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First generation dryers

Cabinet and bed-type dryers (such as kiln, tray, truck tray, rotary, conveyor, and tunnel) fall into this category. Hot air flows over an extensive area of the product to remove water from the surface. These dryers comprise a feeder, heater (gas burner, electric heater, or steam coil heat exchanger), and collector. The final arrangement of these components determines the dryer type.

Cascading rotary dryers, conveyor dryers, and continuous tray dryers (for example, turbo or plate dryers) are the most commonly used today for drying granular or particulate solids. Direct and indirect (steam) heated rotary dryers are used for fish meal (Freshland and others 2000) and solid food wastes, such as for citrus peel and pulp (Saravacos and Kostaropoulos 2002). Multistage dehydrators bring controls to adapt the operating parameters (residence time, airflow, temperature, and humidity), allowing greater energy efficiency (Fellows 2000; Kudra and Mujumdar 2002; Tang and Yang 2004).

Second generation dryers

Whereas spray and drum dryers are intended to dehydrate food slurries and purees for food powders, agglomerates, and flake production, fluidized beds will dry longer-sized food pieces and grains. Spray-drying transforms a fluid feed into droplets by spraying droplets continuously into the hot air to recover dried particles. Droplets can flow in co-current, counter-current, or mixed modes with respect to air. The most common spray dryers are the open- and closed-loop units (Barbosa-Cánovas and Vega-Mercado 1996). Closed-loop dryers are more energy-efficient than open-loop systems and more environmentally sound, due to lower release of hot air and particles. Improved designs of spray dryer chambers, with fewer wall deposit problems, are being achieved using computer simulations (Kudra and Mujumdar 2002).

Modern spray dryers can produce a fine powder with specified particle size and shape (agglomerated, granular, or spherical). Atomization techniques vary according to the type of energy needed to produce droplets, that is, centrifugal, pressure, kinetic, or sonic energy (Masters 1991). Pressure atomizers provide a narrow distribution of droplets (Mermelstein 2001). Continuous spray dryers exist that are adaptable to full automatic control. Today large-scale spray dryers are combined with fluid bed dryers, or

### Table 1—Characteristics of classical drying techniques (Adapted from Okos and others 1992; Crapiste and Rotstein 1997; Fellows 2000; Maroulis and Saravacos 2003; Tang and Yang 2004)

<table>
<thead>
<tr>
<th>Dryer type</th>
<th>Product</th>
<th>Batch (B) or continuous (C)</th>
<th>Size (mm)</th>
<th>Product temp. (°C)</th>
<th>Evaporation capacity (kg/m²·h)</th>
<th>Residence time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabinet and bed dryers</td>
<td>Fruits, vegetables, meat, fish, grains, cereals</td>
<td>B</td>
<td>&gt;5</td>
<td>40–80</td>
<td>5–15</td>
<td>0.5–10 h</td>
</tr>
<tr>
<td>Rotary</td>
<td>Grains and granulated sugar, fish meal, solid food wastes</td>
<td>B/C</td>
<td>0.5–5</td>
<td>60–100</td>
<td>30–100</td>
<td>0.2–1 h</td>
</tr>
<tr>
<td>Drum</td>
<td>Puree, pastes, extracts, syrups</td>
<td>C</td>
<td></td>
<td>80–110</td>
<td>5–30</td>
<td>10–30 s</td>
</tr>
<tr>
<td>Fluidized bed</td>
<td>Grains, granules, vegetable pieces</td>
<td>B/C</td>
<td>0.5–5</td>
<td>60–100</td>
<td>30–90</td>
<td>2–20 min</td>
</tr>
<tr>
<td>Spray</td>
<td>Liquids, tea, coffee, barley, dairy, eggs, fruits</td>
<td>C</td>
<td>&lt;0.5</td>
<td>60–130</td>
<td>4–30*</td>
<td>10–60 s</td>
</tr>
<tr>
<td>Vacuum /freeze</td>
<td>Fruit pieces, coffee, vegetables, dairy, meats</td>
<td>B/C</td>
<td>&gt;5</td>
<td>10–20</td>
<td>1–7</td>
<td>5–24 h</td>
</tr>
<tr>
<td>Pneumatic/ flash</td>
<td>Powders</td>
<td>C</td>
<td>0.5–5</td>
<td>60–120</td>
<td>10–100*</td>
<td>2–20 s</td>
</tr>
</tbody>
</table>

*kg/m³·h

### Table 2—Classification of dehydration methods according to historical development (Vega-Mercado and others 2001)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Drying method</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Cabinet and bed-type dryers</td>
</tr>
<tr>
<td>II</td>
<td>Spray dryers, drum dryers, fluidization</td>
</tr>
<tr>
<td>III</td>
<td>Freeze dehydration, high-vacuum, osmotic dehydration</td>
</tr>
<tr>
<td>IV</td>
<td>Flash dryers, microwaves, RF, combined methods, refractance window, contact sorption drying, high electric field drying</td>
</tr>
</tbody>
</table>

urls and e-mail addresses are active links at www.ift.org
pneumatic dryers, at the bottom of the spray chamber to remove internal moisture under milder drying conditions (Figure 1). Both capital and operating cost improvements have been attained in comparison to spray-drying alone.

Drum dryers, or hollow metal cylinders rotating on horizontal axes, conduct indirect heat (from steam or hot water) through a thin surface (of liquid and pureed food) to produce powdered and flaked ingredients. Drum dryers, single or twin drum, can provide a uniform thickness of film applied to the drum surface. Available commercial drum dryers usually use feed rolls (starches, cereal-based foods, fruit pulps, pastes, and baby foods), nip feeding (for example, yeast and milk drying; R. Simon (Dryers) Ltd. 2000), and dipping, spraying, and splashing (Tang and Yang 2004). Vacuum drum dryers, continuous or batch, are available to produce high-value heat-sensitive products. Drum-dried products include bakery goods, baby foods, pureed vegetables, cooked starch, beverages, cereal, granola, and dairy foods (Feng and others 2003).

Fluidized bed dryers levitate the particulate solids upward into a flowing hot air stream. At least 20 variants exist for the fluidized-bed dryer alone. The process is adequate for small products like whole peas or diced/sliced vegetables, but inappropriate for powders since they would clog up the cyclone, which is used to separate out fine particles (Bahu 1997; Fellows 2000; Tang and Yang 2004). In order to increase air-product contact, systems are equipped with vibrating beds, centrifugal chambers, torus-shaped chambers, or use pulsed fluidization. The use of superheated steam has proven feasible for drying fruits and vegetables, reducing net energy consumption 5 to 10 times (Mujumdar 2003).

For larger particles, the spouted-bed dryer (a special fluidized-bed dryer) is preferable. The intermittent drying concept, or the use of several cycles to apply heat, has proven to enhance energy efficiency and product color in fruits using a spouted bed (Chua and others 2000, 2003). A similar concept is pneumatic and flash-drying, where small particles are transported in a stream of air through a long tube, and recovered in a special cyclone (or cyclone dryer) to increase residence time (Saravacos and Kostaropoulos 2002).

**Figure 1—The combination of spray and fluidized bed drying (Courtesy A&B Process Systems Corp. 2004)**

**Third generation dryers**

Freeze-drying and osmotic dehydration can be included into the same generation because of their unconventional pathways in low-temperature water removal. The freeze-drying process involves rapidly freezing the product and then drying it by direct sublimation of the ice under reduced pressure (< 6 mbar, −20 °C) and radiant heat. Vacuum drying (10 mbar, 8 °C) is another drying alternative for heat-sensitive products, as well as freeze-drying in combination with other methods such as radiant heat or microwaves. Freeze-drying is a lengthy (10 to 40 h) and energy-demanding process, and thus has high operating costs. Although expensive, freeze-drying still operates for certain high-value products maintaining structure, flavor, and aroma. The sublimation process in vegetables, fruits, and ground meat can be speeded up by applying microwaves to the product in rotary trays (Tang and Yang 2004). Both batch and continuous dryers are used commercially to dry many products (vegetables, fruits, meats, dairy products, and entrees). Freeze-dried powdered beverages (such as coffee, tea, apple cider, citrus juices, potato-based mixes, soup mixes, creamer, egg mixes) are some of the components in military combat rations (Army Defense Supply Center Philadelphia 2004). Some of these items have been transported in the NASA Space Shuttle for consumption at the International Space Station. Freeze-dried foods are convenient in that they are light in weight and are utilized for combat rations designed for cold weather conditions (Army Defense Logistics Agency; Army Defense Supply Center Philadelphia 2004).

Osmotic dehydration is the partial removal of water by direct contact of plant or animal tissue with a highly concentrated solution of sugars (sucrose, corn syrups), salts (sodium chloride for vegetable and fish), and sugar/salt mixtures (Lazarides and others 1999). These systems mainly require a storage tank for the osmotic solution and a pump to control the flow rate at the processing tank containing the product. Water removal can be aided with the use of vacuum (Fito 1994) and residual fluid can be removed with a conveyor dryer. A large number of publications recognize the advantages of osmotic dehydration for minimal processing of foods; however, large-scale industrial applications have yet to be achieved (Lazarides and others 1999). Vacuum-impregnation of fruits and vegetables, vacuum-salting of cheese and hams, and combinations of microwave and vacuum, during and after osmotic dehydration, are some of the latest trends on the cutting edge of this technology (Fito and others 2001). Osmotically dried fruits are being used as military rations as well (Army Defense Supply Center Philadelphia 2004).

**Fourth generation dryers**

Different patents and publications have been developed over the years for a myriad of possible drying techniques in search of new products, higher drying capacity, better product quality and quality control, reduced environmental impact, safer operations, better energy efficiency, and lower investment and running costs. Among these technologies, microwave and radio frequency drying have shown the most remarkable progress, although in some cases at a higher cost. Emerging alternatives are drying methods such as refractance window drying (Vega-Mercado and others 2001) and contact sorption drying (Kudra and Mujumdar 2002). Microwave drying occurs due to internal heat produced within the food after the polarization and accelerated rotation of water molecules, which follow an alternating electric field. The most significant frequencies allowed for microwave technology are 915 MHz and 2450 MHz. Microwaves, as well as radio frequencies, can speed
up almost any drying process, allowing the material to dry in 10% or less of the normal drying time (Schiffmann 2001). No microwave industrial application can dry food products alone, but combined with hot air, ambient or force circulation, and/or infrared, the removal of water from a surface can be accelerated. For example, spouted-bed hot air drying combined with microwaves have proven useful for drying diced apples, blueberries, and asparagus when processed at 2450 MHz (Feng and Tang 1998; Nindo and others 2003). Microwaves are commercially used for finish-drying of cookies, biscuits, cereals, and pasta products at the end of the falling rate period (Schiffmann 2001).

Manufacturers report industrial applications such as MIVAC® microwave vacuum-drying (Pitt-Des Moines, Inc. 2000), continuous microwave belt ovens (Linn High Therm GmbH 2004), a microwave cylindrical reactor (Industrial Microwave Systems; Vega-Mercado and others 2001). MIVAC® successfully dehydrates over 100 different fruits, vegetables, and other foods at temperatures below 55 °C (15 to 40 mbar). The 40-ft (12.2-m) vessel contains a conveyor system, a microwave unit, and a radiant heat source. The microwave belt furnace system (Linn High Therm GmbH 2000) uses magnets arranged in a spiral plus a conveyor belt equipped with secondary radiators. Air flows into the oven and moisture is drawn out of the oven by a suction system.

Like microwaves, RF uses electromagnetic energy to heat products, which achieves positive results in terms of time cycle and efficiency. Radiofrequency waves cover the frequency spectrum from 1 to 100 MHz (Schiffmann 1995; Saravacos and Kostaropoulos 2002). RF energy mainly acts through the electrical conductivity of the material due to the presence of ionic species (for example, dissolved salts), providing deeper heating penetration than microwaves into the food material. There are automated RF applications higher in energy efficiency (PSC-Power Systems 1999) used in various post-baking systems (Figure 2) for production of biscuits, crackers, and snack foods. RF and Microwave/RF dryers are expected to find more niche applications, since this technology has proven successful in other industrial areas such as timber production and drying of coated paper (Kudra and Mujumdar 2002).

Refracontance Window (MCD Technologies 2000; Bolland 2000) uses water (95 to 97 °C) to transmit heat into the product being dried. Pureed or thick products are evenly applied to the surface of a plastic conveyor belt moving over circulating water in a shallow trough. When the product reaches lower moisture levels, infrared energy will be refracted such that the amount of heat transmitted through the conveyor will be minimal. At this point, excessive application of heat in the product can be prevented and heat can be recycled. Heat minimization will provide dried foods higher in nutrients and flavors, and with better color retention. Vegetable purées and slices (Nindo and others 2003), algae, fruits, and liquid eggs have been effectively dried using this technology.

Contact sorption drying is another novel method and involves using a carrier (such as maltodextrin) dispersed in the product, which is then fed into different dryers from single- or multi-stage fluidized-bed dryers to counter current spray dryers (Mujumdar 2003). Tutova (1988) suggested that drying with sorbent materials can help slow down and better control the drying process of labile materials. Examples of this technique include drying heat-sensitive foods, antibiotics, amino acids, and even microorganisms in porous food particles (Tutova 1988; Tadayyon and others 1997).

Freezing

Freezing is a unit operation in which the temperature of the food is reduced to below its freezing point, upon which a portion of the water forms ice crystals. Freezing is mainly applied in food preservation for several months to facilitate other nonpreservation processes such as ice cream hardening or form-freezing. For most frozen foods, the industrial target temperature at the center of the product is –18 °C (about 0 °F), as indicated by different standards. Different frozen commodities are found in world markets today that include fruits (whole, pureed, and juice concentrate), vegetables (whole, shredded, pureed, and mixed), fish fillets and seafood (fish cakes, shrimps, and crab meat prepared dishes), meats (carcasses, boxed joints, and ground), baked goods (breads, cakes, and fruit and meat pies), and prepared foods (pizzas, desserts, ice cream, and cook-freeze dishes), among others.

Product specification, that is, its sensory quality at frozen state, size, type of packaging, restrictions in shape, production rate, and final storage temperature, are decisive factors in the selection and operation of a freezer. Other considerations include plant space utilization, operating costs, and capital costs. Product quality assurance depends on the selection of a fast freezing method. The faster the freezing rate, the lower the damage the food will receive due to better crystal distribution and lower unfrozen free water. Fast freezing provides lower food cracking, weight loss, and cell degradation (Fellows 2000).

The speed of freezing can be defined as the speed of movement of the “cold front” between frozen and unfrozen product (Maroulis and Saravacos 2003). Industrial freezers can be grouped based upon the rate of movement of the cold front (Fellows 2000). Still-air and cold-store types are slow freezers (0.2 cm/h); air-blast and plate types are quick freezers (0.5 to 3 cm/h); fluidized-bed types are rapid freezers (5 to 10 cm/h); and cryogenic types are ultra-rapid freezers (10 to 100 cm/h). Freezing time required to achieve an equilibrium temperature condition, where temperature at the center and surface of the product coincides, depends on the freezing rate, heat transfer coefficient, amount of heat removed from the product, air velocity and temperature, and sizing of freezer components (such as fans, evaporator coils, compressor) (Bejarano and Venetucci 1995; Saravacos and Kostaropoulos 2002). In order to maximize freezer efficiency, freezers are insulated with expanded polystyrene, polyurethane, or other materials with low thermal conductivity (Fellows 2000).

Different refrigerants have been used for decades. Ammonia is the most commonly used refrigerant in air and plate freezers at –40 °C (Bejarano and Venetucci 1995), and a mixture of ammonia and brine solution can also be used for belt freezers. The CFCs (chlorofluorocarbons), for example Freon 12, were banned under Montreal protocol and EPA regulations for depleting the atmospheric ozone layer (Bejarano and Venetucci 1995). Nevertheless, ozone-friendly halogenated CFCs, also called HCFCs, were devel-
Table 3—Comparison of freezing methods

<table>
<thead>
<tr>
<th>Freezing method</th>
<th>Heat transfer coeff. (W/m²K)</th>
<th>Freezing times to reach -18 °C (min)</th>
<th>Throughput (kg/h)</th>
<th>Food examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still air</td>
<td>6-9</td>
<td>180-4320</td>
<td>-</td>
<td>Meat carcass</td>
</tr>
<tr>
<td>Blast</td>
<td>25-30</td>
<td>15-20</td>
<td>200-1500</td>
<td>Unpackaged peas</td>
</tr>
<tr>
<td>Spiral belt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(50-75 cm wide belt)</td>
<td>25</td>
<td>12-19</td>
<td>&lt; 3000</td>
<td>Hamburger, fish fingers</td>
</tr>
<tr>
<td>Fluidized bed</td>
<td>90-140</td>
<td>3-4</td>
<td>1000-12,000</td>
<td>French fries</td>
</tr>
<tr>
<td>Immersion (Freon)</td>
<td>500</td>
<td>10-15</td>
<td>90-2700 (batch)</td>
<td>25-kg blocks of fish</td>
</tr>
<tr>
<td>Cryogenic (liquid N₂)</td>
<td>1500</td>
<td>0.9</td>
<td>45-1550</td>
<td>170-g orange juice package</td>
</tr>
</tbody>
</table>

Adapted from Fellows (2000) and Saravacos and Kostaropoulos (2002).

opened as an environmentally friendly alternative. Freon 22 is a fairly used HCFC type of refrigerant.

Industrial freezing methods can be classified into 3 groups: mechanical, cryogenic, and combined mechanical and cryogenic methods (Bejarano and Venetucci 1995). Among the most important mechanical freezers are air freezers (still air, blast-room or -tunnel, fluidized bed, belt, and belt-spiral), plate freezers, and liquid immersion freezers. Cryogenic freezing is based on the direct contact of a cryogenic refrigerant with the food surface. Other combinations of mechanical and cryogenic systems have been found to be an economical alternative to processes alone. Up-to-date general information on technological advances in classical refrigeration methods can be found in different literature sources (Persson and Lönndahl 1993; Bejarano and Venetucci 1995; Cleland and Valentas 1997; Fellows 2000; Saravacos and Kostaropoulos 2002), as well as at different company websites (Advanced Equipment, Inc. 2004; FMC Technologies 2004a; The BOC Group 2004). Table 3 compares heat transfer coefficients, residence times, and capacities achieved for different products.

**Air freezers**

Air blast (or forced air) freezers, which are generally located in tunnels but also in cold rooms, chambers, or cabinets, are among the most commonly used freezers in the food industry (Bejarano and Venetucci 1995). Air is recirculated by fans to provide a counter-current air flow that is parallel or perpendicular to the food. In this way, forced convection increases the heat exchange (that is, the heat transfer coefficient) between the product and the air stream (Ditchev and Richardson 1999). Equipment can be either batch or continuous, using trays in rooms or cabinets, storage rack systems, trolleys stacked with trays pulled by chains, or conveyor belts. Air-blast freezers are flexible for different types of products. However, substantial fan energy is needed to obtain desired air velocity rates of 3 to 6 m/s (Saravacos and Kostaropoulos 2002). Furthermore, significant dehydration of unpackaged foods can occur (2 to 3% weight loss). Some applications include freezing of meat carcasses and storage of already frozen foods from other methods.

In belt freezers, cold air streams are vertically directed through the belt stack in a concurrent flow. A stainless steel moving conveyor belt is moved by 2 drums and, in some systems, continuously receives sprays of a cold brine solution (~40 °C) from underneath. Belts can be positioned straight into different zones, or parallel to each other, making an overall length of 5 to 13 m. Parallel belts can also serve as an elevator system (used in ice cream hardening) to circulate loaded cells up and down. Spiral belt freezers belong to a new generation, where a continuous flexible mesh belt (about 300 m length) stacked into spiral tiers (30 or more tiers) is inside a blast freezing chamber (Figure 3).

Spiral freezers offer long product residence times, small floor-space, automatic loading and unloading (self-stacking belts), and cleaning after each full round. Different designs of spiral belts can vary in air flow, type of belt used, means of belt support, and type of driving mechanism (Persson and Lönndahl 1993). For instance, the GYRoCOMPACT® is one of the most commonly used self-stacking spiral freezers (Higgins 2003). Individually large, quick frozen (IQF) products such as pizzas, cakes, pies, ice cream, hamburgers, chicken portions, and ready meals can be frozen using this equipment. Belts allow freezing of packaged and unpackaged products as well as wet and sticky ones. Cold air, in some cases refrigerated by ammonia, can be directed horizontally or vertically (Bejarano and Venetucci 1995). The belt can pass through a washing station to prevent unnecessary downtime for cleaning (Persson and Lönndahl 1993). Impingement freezing is a current implementation of air feeding, which directs thousands of high-velocity jets of air at the top and bottom surfaces of the product (Bejarano and Venetucci 1995; The BOC Group 2004). This adaptation provides faster freezing rates (maximizing heat transfer coefficient), energy efficiency, minimal dehydration, and package bulging prevention.

In fluidized-bed freezers, small food pieces are contained on a perforated tray or conveyor belt where air (at ~25 °C to ~40 °C for ammonia-based systems) is passed upward at high velocity (2 to 6 m/s) through a bed of food (Saravacos and Kostaropoulos 2002). Generally, the fluidized-bed zone provides a quick crust-freezing,
after which the conveyor belt displaces the food to a second freezing zone for food temperature equilibration. Low air temperature has been found beneficial to avoid product drying; achieving weight losses lower than 1.5 to 2%. The fluidized bed method offers greater air contact, shorter freezing times, simultaneous and uniform freezing at the product surface, and larger production rates (1 to 12 tons/h). Fluidized beds are used for small unpacked IQF food particulates with consistent shape and size (for example, peas, sweet corn kernels, shrimps, strawberries, french fries, meat balls, diced meat and so on) in less than 15 min.

Plate freezers
Thin foods are compressed between vertical or horizontal double-wall plates, inside which refrigerant recirculates. Any unpackaged deformable food (maximum thickness limited to 50 to 70 mm), like filleted fish or beef burgers, can be quickly frozen in vertical plate freezers in batch or continuous form. Liquid slurry can be frozen in plastic bags hung between vertical plates. Horizontal types (Figure 4) are used more for packaged foods in cartons or trays (for example, vegetables), or for products formed in metal molds. Systems can be automated for simultaneous product loading and unloading from conveyors, however, these systems require high capital cost (Cleland and Valentas 1997). This design geometry offers good space utilization and high rates of heat transfer, using lower energy than air systems. A push-through system is used for automatic feeding, which allows continuous operation (DSI Samifi Freezers S.r.l. 2004). Other examples of direct contact freezing are the scraped-surface heat exchangers refrigerated via ammonia, brine, or other refrigerants to freeze liquid or semi-solid foods like ice cream (Heldman 1992).

Liquid immersion freezers
Food is submerged in a cold liquid like propylene glycol/water mixtures, eutectic NaCl brine, glycerol, or calcium chloride (Persson and Löndahl 1993; Saravacos and Kostaropoulos 2002; Scott 2003). CFCs were used in the 1980s before being banned, presenting greater advantages at the time compared to mechanical systems (Bejarano and Venetucci 1995). This method offers high rates of heat transfer. However, care must be taken to remove the liquid from the packaging or product surface (if unpackaged) by rinsing with water, which might warm the product's surface (Scott 2003). Some applications include direct contact of unpackaged tuna fish, film-wrapped meat and poultry, and concentrated orange juice in laminated card-polyethylene cans. Today, new systems using cryogenic liquids such as liquid nitrogen (LN$_2$) or carbon dioxide (LCO$_2$) are available, providing instant crust freezing (Air Products and Chemicals, Inc. 2004; Praxair Technology, Inc. 2004). After crust-freezing, equilibration can then be completed in an air blast freezer.

Cryogenic freezing
This process has revolutionized the frozen foods industry by providing an alternative to the ammonia refrigeration system as well as its maintenance. Food conveyed in a tunnel is directly sprayed with or immersed in cryogenic liquid, which changes to a solid state as heat is absorbed by the food. It provides high rates of heat transfer in small- to medium-sized products. In the surface of some products, crack formation can be observed due to thermal shock and extended residence time in the LN$_2$ immersion bath. Cryogenic freezing is a continuous operation that is 30% lower in capital cost than air, plate, or immersion liquid systems, and consumes less power; however, cryogens are costly and they might balance out in convenience depending upon product volumes and other design factors (Fellows 2000). Cryogens are colorless, odorless, chemically inert, and nontoxic in normal concentrations. The cryogens most commonly used in quick-freeze are LN$_2$ and LCO$_2$ in boiling points –196 °C and –79 °C, respectively (Bimbenet and others 2002). Food surface temperature can reach about –190 °C after LN$_2$ spraying. Cryogenic liquid freezing requires high cryogenic liquid consumption. For example, LN$_2$ can be consumed at 1 to 1.5 kg/kg of product (Saravacos and Kostaropoulos 2002). A new cryogenic process uses a tumbler to “enrobe” (or coat) sauces or seasonings in previously prepared meals (frozen meats, vegetables, rice, or pasta) by mixing liquid nitrogen at a maximum capacity of 1400 kg/h (AGA Gas, Inc. 2004).

Combined cryogenic and mechanical freezing, referred to as cryomechanical systems, provide the optimum balance between freezer operating costs, product weight loss, and product quality loss. Tunnels, belts, and spiral belt freezers incorporate LCO$_2$ and LN$_2$, providing more cooling power and controlling the distribution of the liquid cryogen directly in contact with the product (Praxair Technology, Inc. 2004; Air Products and Chemicals, Inc. 2004). Liquid and vapor are delivered in 2 major steps: (a) surface freezing and (b) equilibrium freezing. Cryomechanical systems provide high freezing speed (in other words, high capacity and better quality) and low product weight loss (0.1 to 1.0%).

Other advances in freezing
Two automatic systems are available that provide improvements in energy consumption and automation: cleaning in place (CIP) and preventive system maintenance. The CIP system is a computerized programmable logic control system that maximizes utilization of water and chemicals. Savings in energy, sanitation crew, maintenance, and cleaning times are all some of the CIP’s advantages. The preventive freezer maintenance system also offers ways to improve energy savings and equipment efficiency in which features like a computerized self defrosting system, variable speed drive motors, temperature sensors, computerized control automation systems, and alarm systems and emergency lights for personnel safety are used in new freezing systems (Persson and Löndahl 1993). Among other technological improvements, new recirculating design systems for cryogenic gases, improvements in wall insulation, and self-stacking units can be named. For example, the LINK Control System is a tool that fully automates, integrates, and controls the entire processing line using speed synchronization products (freezer temperatures, belt speeds, air speeds), a recipe management system (core temperatures, weights), and central data collection (FMC Technologies 2004b).

Figure 4—Plate freezer with a 2-stage compressor and sea water condenser (Courtesy of DSI Samifi Freezers S.r.l. 2004)
Most of the new freezing technologies base their improvements on better equipment efficiency, lower energy costs, maximization of advantages in using ammonia and cryogens as refrigerants, cooling efficiencies, environmental concerns, and equipment flexibility (Bejarano and Venetucci 1995). Like freezing technologies, in-container sterilization, in particular retort sterilization, are and will be providing more convenient shelf stable products with lower energy costs and better equipment efficiency.

**Classical in-container sterilization**

In-container sterilization is a severe thermal treatment of packaged food designed to inactivate all microbial spores, which thus inactivates other spoilage bacteria and enzymes as well and extends product shelf life for months and or/years. During thermal treatment, heat can be supplied using saturated steam, steam/air mixtures, or sprays of hot water. Equipment that provides relative container motion for internal agitation, as well as relative motion of heating (or cooling) medium, provides higher heat transfer. Apart from the thermal treatment itself, previous operations such as automatic headspace adjustment and fill-in weight, exhausting of air, and hot-filling are important for obtaining the desired heat transfer rate and securing product quality. Different automated mechanical fillers such as Solbern fillers and FMC rotary fillers can be found in the market (Downing 1996a; Packaging Technologies 2003). Exhausting removes air from the product, preventing overpressure inside the can and assuring vacuum after cooling. Modern closing machine systems provide mechanical vacuum eliminating the need to exhaust air space (Downing 1996b).

Today, closing machines offer higher closing speeds and automatic sealing for metallic and flexible containers. For example, double-seaming machines operate at speeds higher than 1000 cans/min for particulate foods in light tinplate, deep-drawn aluminum, composite, and plastic containers (Saravacos and Kostaropoulos 2002). Furthermore, fluid and semi-fluid canned foods can be closed at speeds up to 1500 cans/min (Downing 1996b). There also are automated closing machines for glass jars, which reach slower closing speeds in general than comparable-size can containers; particularly due to the fragility of glass. Moreover, sealing machines have also been optimized to close polymeric retortable pouches or trays. Pouch closing machines can seal around 50 to 100 pouches/min (Packaging Technologies and Inspection LLC 2004) and some tray conveying systems can close 60 containers/min (Raque Food Systems LLC 2004). Vacuum packaging chambers for flexible pouches and trays are also available in the market (Koch 2003; Packaging Technologies 2003; Reiser 2004).

The level of vacuum in a container after the sterilization process can be tested on-line with pressure vacuum monitors (also called dud detectors), which are based on proximity technology. Operating on an electromagnetic impulse, these monitors check the extent of the depression of the jar or can lid center (that is, the distance from the lid to the sensor), detecting up to 2000 containers/min online (Care Controls 2000; TapTone 2003). In some cases, X-ray sensors can be used for vacuum detection in jars and cans (TapTone 2003). Automated equipment has also been developed for on-line container inspection of double-seam defects in cans, height of fill, liquid leaks, and missing labels (Food Master 2004).

Food products are being sterilized in different types of containers such as metallic cans (steel or aluminum), glass jars or bottles, plastic materials, flexible pouches, and rigid trays. Today, cans received are internally coated with universal types of coatings for general use (Barron and Burcham 2003), instead of enamels used for specific types of foods. There are different options for hermetic vacuum-sealing of glass containers used for sterilized low-acid foods, namely, the pry-off (side seal), lug (twist-off), and PT (pressure/twist-off) types. Steam-flow cappers are used to seal the glass jars caps, holding them in place to receive the applied overpressure during sterilization (Ramaswamy and Chen 2004).

US military rations in the form of meals-ready-to-eat (MREs) in retortable pouches and institutional trays are finding more applications and are competing with different canned products that have a position in the market (Blakistone 2003). Some foods used in the 1969 Apollo moon mission were packed in retortable pouches (Downing 1996a). Retortable pouches were approved for sterilization of low-acid foods by the FDA/USDA in 1977, but commercial use was first seen in England and Japan 10 years earlier (Downing 1996a). Several retort-pouched foods were developed in Japan during the mid-1980s, such as sauces, soups, seasonings, cereals, and desserts (Yamaguchi 1990). Preformed pouches can be either foil-based laminates (for example, polyester/nylon/foil/cast polypropylene) or nonfoil (for example, polyester/nylon/ethylene vinyl alcohol), as well as co-extruded without the use of an adhesive for laminate construction (Blakistone 2003). During pouch sterilization, seal integrity is one of the most important critical points of control (Yamaguchi 1990). The large consumer market in the United States offers, for example, pouched tuna fish, and is opening opportunities for different entrees such as pet foods, chipped beef, wild rice, and boiled peanuts, in pouches that come with 3-side seals or stand-up versions (Figure 5). Other incoming features include pouches with zippered and pour spouts (Pyramid 2004).

In modern canning, retorts are automated and equipped with PLC (programmable logic controllers) or sequential event controllers. Microprocessor controllers use product-specific software and store processing programs for a range of canned foods. There are standard hardware and software platforms accepted and approved by the FDA and USDA, such as ICON3® (Stock America, Inc. 2003) used for control of critical processes. Most retorts sold today have sophisticated controls that can optimize the time, temperature, and pressure of the process during preheating, processing, and cooling. Some control systems can calculate thermal process lethality and, therefore, can make process time adjustments in the event of an unplanned decrease of process temperature (Hart-English 2003). Selected variables during processing are temperature (of raw material, cooling water, and steam), time of processing, and rates of heating and cooling. Thermal processing modeling software is also available for batch, continuous hydrostatic, and continuous rotary pressure operations (FMC Technologies 2004b). Furthermore, time/temperature integrators can be attached as labels to food packages to monitor the entire temperature history of the product, indicating with an easily measurable time/temperature-dependent change the temperature history and quality sta-

**Figure 5—Rertot pouches loaded in retort chamber trays (Courtesy of Profile Packaging, Inc. 2004)**
tus of the food. Automated filling, loading, unloading, and conveying systems are available for cans, jars, and pouches (Allpax Products, Inc. 2003; Profile Packaging, Inc. 2004; Stork Food and Dairy Systems BV 2004).

Batch sterilizers are earlier than continuous sterilization commercial systems (Hardt-English 2003) and are used in many small- and medium-sized food processing plants because of their low cost and simple operation. Batch retorts are suitable for treatment of seasonal raw materials or for low production volumes (Saravacos and Kostaropoulos 2002). Still retorts (water or steam), batch rotary sterilizers, crateless retorts, and retorts for glass and flexible containers are the most widely used types for batch sterilization (Downing 1996a). Immersion retorts are useful for products requiring gentle agitation and a short process to maintain quality (Hardt-English 2003).

Continuous in-container sterilization systems, generally used for medium- to larger-size production volumes, are the current trend for in-container sterilization due to advantages over the batch process. Higher production rate, lower labor cost, more accurate process control, and improved food product quality are among the advantages claimed for continuous systems (Gould 1996; Saravacos and Kostaropoulos 2002). The 2 main continuous systems commonly used are the rotary cooker/coolers and hydrostatic sterilizers. Both concepts were introduced in the early 1950s (Downing 1996a). These and other types of retorts, such as the steam and water retorts, are flexible for making quick changes in the container material, dimensions, and so on (Hardt-English 2003). Other in-container sterilizers have also found several applications at industry level. Circulating water and steam sterilizers, track flow sterilizers, "Flash 18" sterilizers, and flame sterilizers are some examples that provide faster heat transfer rates, resulting in improved food quality and safety of processed food products. The following paragraphs will describe some general and innovative features of batch and continuous in-container sterilizers. For further information on novel in-container sterilization, the reader is referred to Hardt-English (2003), Blakistone (2003), Saravacos and Kostaropoulos (2002), Larousse and Brown (1997), and Downing (1996a,b). Table 4 shows examples of capacities in different types of retorts.

### Batch in-container sterilizers

Within this group, still retorts have the same working principle as ordinary laboratory autoclaves. Several retort units can be placed in a plant either vertically or horizontally, and a well-managed cook room can have up to 100 retorts operating at full production (Hardt-English 2003). The system can be arranged to automatically, or manually, operate continuous loading and unloading. Vertical retorts generally use 3 or 4 crates (baskets), which are then loaded into the retort by chain hoists. In horizontal retorts, cans are placed in trucks or trolleys that are then moved on special tracks. Heating can be provided using steam spreaders, that is, perforated pipes generally distributed at the bottom, or water sprays. These systems are used for most vegetables and many fruits (Gould 1996). Special horizontal models feature 2 doors, a product-entrance door and a finished-product door, facing the storage area. Batch rotary horizontal sterilizers provide axial rotation of the cans, using a helical track on the wall. Process time is reduced (Downing 1996a) due to an increase in convective heat transfer inside the can; especially in fluid foods where the headspace air bubble provides agitation. Modern systems can be operated at temperatures above 121 °C and regulated using digital programmers.

Crateless retorts are vertical retorts that avoid crate or truck loading and unloading. Cans are loaded from the top when the retort is filled with heated water, which has a cushioning effect. Figure 6 shows the operating sequence of a semi-continuous system that uses a series of crateless retorts. Cans of any size can be sterilized in this system at temperatures up to 132 °C (270 °F), but other packages may suffer significant damage during loading and unloading (Hardt-English 2003). This type of retort offers high line speed, one-man operation, easy maintenance, and automatic control; it can be used for low-acid vegetables, tomatoes, pet food, fish, and meat products (Malo, Inc. 2004).

Glass and flexible packages (polymeric trays and pouches) are processed in hot water under an overriding pressure from air or steam pressure supplied to the retort, which surpasses the amount of pressure exerted by the heating medium at a certain temperature (Blakistone 2003). Overpressure prevents lids from popping up.

### Table 4 — Capacities for batch and continuous in-container sterilizers — some examples (Adapted from Saravacos and Kostaropoulos 2002)

<table>
<thead>
<tr>
<th>Equipment type</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still retorts (vertical or horizontal)</td>
<td>1000 Nr 2 cans (307 × 409 in.)</td>
</tr>
<tr>
<td>Batch rotary sterilizers</td>
<td>400 Nr 10 cans (603 × 700 in.)</td>
</tr>
<tr>
<td>Continuous rotary cooker/coolers</td>
<td>600 cans Nr 10 (603 × 700 in.)</td>
</tr>
<tr>
<td>Continuous hydrostatic sterilizers</td>
<td>5000 Nr 2 cans</td>
</tr>
<tr>
<td>Track flow sterilizers</td>
<td>120000 cans/h (each line holder carries up to 35 Nr 2 cans)</td>
</tr>
<tr>
<td>Cushioning water</td>
<td>15 cans/h Nr 2-1/2 cans (401 × 411 in.)</td>
</tr>
</tbody>
</table>

![Figure 6 — Crateless retort system (Courtesy of Malo, Inc. 2004)](image-url)
off jars, glass breakage due to air/vapor internal pressures, and controls flexible package sealing integrity and potential ballooning (Hardt-English 2003). Foods in rigid polymer trays or flexible pouches heat more rapidly owing to the thinner material and smaller cross-section of the container (Fellows 2000). Glass and flexible containers use the same types of retorts as metal cans with special arrangements of air piping, valves, and racking systems (for example, cascading retorts, water retorts, water spray retorts, water immersion, or steam/air retorts) (Yamaguchi 1990; Hardt-English 2003; Blakistone 2003; Packaging Technologies and Inspection LLC 2004).

Water immersion systems, in particular, re-use water preheated in the upper storage tank within several cycles and are capable of maintaining the overpressure needed for the nonmetallic packaging. Steam/water spray systems have no restrictions on air pressure. The heat-to-cool transition is easy and no danger of a pressure drop exists that could affect package integrity (Blakistone 2003). Systems that control ramping of temperature and pressure during heating and cooling reduce the impact on pouch integrity.

**Continuous in-container sterilizers (ICS)**

Systems have been developed that arrange rotary sterilizers automatically in continuous form, providing high capacity and faster sterilization due to rotation of the cans. The rotary cooker/cooler (FMC) carries cans on a spiral turning reel, which are conveyed through different shells. Temperature cycles include heating, holding, and cooling in 2 or 3 horizontal pressure shells. Single-sized cans are first carried over the top two-thirds of the reel, then fall off the reel, and roll around the bottom third of the shell. In each shell, self-rotary valves control the pressure zone. The rotary system improves significantly the heat transfer to the canned product and reduces the processing time operating at temperatures up to 130 °C (Hardt-English 2003). Foods like tomatoes, apricot halves, asparagus, fish, minced meat, and evaporated milk are actually processed using this system.

Another type of continuous system is the hydrostatic sterilizer. In this system, towers 10 to 25 m tall operate under pressure similar to steam pressure, which are maintained by water legs (columns), eliminating the need for closed pressure vessels and pressure locks (Figure 7). The system is divided into 4 main chambers: (a) a hydrostatic pressure “come-up” feed leg, (b) a sterilizing chamber, (c) hydrostatic discharge leg, and (d) a cooling section. Heavy-duty conveyor chains are available for large numbers of cans allocated in rows situated “end to end” and can have capacities up to 2000 cans/min (120000 cans/h). Alternatively, some systems move pallets of containers. In some systems, cans or jars of different sizes can be processed in parallel at different processing times by having several chain lines to convey the containers (Hardt-English 2003). Automated operations (loading, processing, cooling, and unloading) and efficient use of floor space are some of the advantages of hydrostatic sterilizers. The main disadvantage is that the system requires a high initial investment.

**Other in-container sterilizers**

Alternative concepts can often improve product quality. However, when these concepts are in the initial stages of development, they can not compete with better throughput systems with conventional and optimized systems. One alternative type is the flame sterilizer, in which cans are preheated with steam at atmospheric pressure and exposed to flames of gas burners at 1200 to 1800 °C while rotating rapidly (Ramswamy and Chen 2004). Small cans containing solid or viscous food products (such as mushrooms, sweet corn, and green beans), packed without a fluid medium, undergo a high-temperature/short-time process due to the high heat transfer rates obtained (Fellows 2000). Another type is the “Flash 18” sterilizer, in which a viscous food product is brought to a sterilizing temperature prior to can filling through steam injected into a pressure chamber (18 psig) or by using a scraped-surface heat exchanger. The product is discharged into nonsterile cans, which are closed and held at the processing temperature (for example, 124 °C) for a predetermined time in the pressure chamber. Finally, cans are released to the atmospheric pressure and cooled using water sprays. Glass and flexible packages can also be used.

Combinations of hot-water sprays, can rotation or agitation, and recirculation of steam or hot water provide overpressure thermal processing and allow flexibility of different types of containers. For example, a special horizontal pressure sterilizer, the Stock Rotomat, is also useful for certain packages such as trays of different sizes and shapes (Stock America, Inc. 2003). Crates loaded with cans or other packages rotate while packages are heated by circulating hot water or water sprays. The Stork-Lagarde has implemented a cooling system using cold carbon dioxide produced from dry ice (Saravacos and Kostaropoulos 2002).

A long serpentine pipe (or duct) of rectangular cross-section acting as a track for rolling cans can be used for sterilization purposes. This type of system is called the track-flow sterilizer (Downing 1996; Saravacos and Kostaropoulos 2002). Water is heated by steam injection to achieve a can rolling speed of about 200 rpm. The serpentine pipe has a cooling zone where cold water replaces the hot water in the pipe. Two types of track-flow sterilizers are applied: (a) the Hydroflow system, consisting of metallic tracks guiding the cans to different zones in the sterilizer and (b) the Hydrolock system, in which cans roll in a pressurized chamber following a serpentine track. The containers enter via a rotary paddle wheel with spring-loaded sealing bars (Ramswamy and Chen 2004).

**Microwave and RF sterilization**

The main idea behind using electromagnetic waves as part of a
sterilization system is that, by reducing the come-up time, the product quality improves. Microwave sterilizers can significantly reduce come-up times, achieving the same lethality level as the conventional retort (121 to 129 °C); even so, major US manufacturers claim they cannot afford this option, but the benefit of a microwave system could justify the additional expense (Schiffmann 2001). Research efforts such as heat uniformity and microbial challenge studies are being made in order to obtain FDA approval of dielectric heating technologies. Fiber optic sensors have been found adequate for measuring temperatures in the food during microwave heating, since they do not interfere with microwave fields and provide comparable accuracy to MIG thermometers. Chemical markers made of whey protein gels have been studied for validation of sterilization processes using dielectric heating, as presented by different researchers (Prakash and others 1997; Lau and others 2003; Wang and others 2004); other biological indicators are being developed as well (Prakash and others 1997; Mateu and others 1997). Promising processes mostly rely on combinations with conventional heating such as steam and hot water. For example, a microwave system called the Microwave-Circulated Water Combination (MCWC) consists of a pressurized vessel which receives overriding air pressure for processing of meal trays; to regulate this process, the vessel is also equipped with a water circulation system to improve temperature uniformity and edge-heating (Guan and others 2003). The MCWC system has been validated for sterilization of macaroni-and-cheese products using inoculated pack studies with Clostridium sporogenes PA 3679 (Guan and others 2003). Other studies have been performed in a pilot-scale RF system (27.12 MHz) in 6-lb (2.724-kg) polymeric trays using a whey protein chemical marker to compare relative uniform heating with a retort system (Wang and others 2003). Further challenges in microwave and RF sterilization technology include understanding the effects of food formulation on heating patterns, by measuring the dielectric properties of a selected food, and the effects of equipment design factors at the selected frequency.

Final remarks

Classical technologies such as drying, freezing, and in-container sterilization will continue to play an important role in food preservation worldwide. The key to continuous improvement will be their adaptation to global market demands by maximizing technical resources and providing economic benefits to industry. Joint ventures among academic organizations, equipment suppliers, and food manufacturers will promote the development of energy-efficient automated and controlled systems, which will reduce processing costs and increase throughputs. Software programs for equipment selection, increased databases on current worldwide equipment and equipment part suppliers, PLC systems or sequential event controllers, cleaning-in-place systems, preventive system maintenance, and other integral process systems for automation and control of the entire process line are now offered by manufacturers of classical technology.

Different generations of food dehydrators are providing greater intensification of drying rates within specified limits of product quality by establishing different drying zones (multi-stage dehydration), increasing air/product contact using fluidized beds (or spouted beds or flash-drying), using intermittent drying, applying microwaves or radiofrequencies during the falling-rate period of drying, and using carriers in the feeds (contact sorption drying). Improved drying processes offer dried food pieces with better controlled water activity and sensory attributes. Powders dried up to specified particle size distribution and shapes, as well as freeze- and vacuum-dried foods, are available in the marketplace.

Current freezing systems are more flexible and faster, incorporating a wider range of foods. Freezing equipment provides higher rates of heat transfer by adapting high velocity jets of air, and cold sprays of brine solutions or cryogenic refrigerants. Similar to drying, freezing equipment can be arranged in different stages for an initial quick (or instant) crust-freezing followed by food temperature equilibration. Self-stacking spiral-belt freezers, automatic loading and unloading systems in continuous-plate freezers, cryomechanical systems, and self-defrosting systems are improving the operating costs of freezing technology as well as lowering product weight and quality loss.

Modern retorts include equipment automation through software platforms, on-line critical point control, automated loading and conveying options, and flexibility in packaging materials as well as sizes and shapes. Container filling, headspace adjustment, exhausting, closing, and defect monitoring operations for metallic, glass, and flexible retort packages are thus increased in speed. Batch and continuous systems can reach temperatures up to 130 °C, significantly reducing the processing time. Retortable pouches sterilized in overriding pressure systems are already expanding to commercial applications, which in the near future will provide more foods with desirable “just-cooked” characteristics.

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