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Second Edition

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Contents

Table 1.2. *(Continued)*

Crop	Temperature (°C)	Temperature (°F)	Humidity (%)	Storage life[a]	Water content[b]	Specific heat[b] (cal/g/°K)
Radish, spring, topped	0	32	95+	3–4 weeks	94	0.96
winter	0	32	98	6 months	—	—
Rhubarb	0	32	98	2–3 weeks	95	0.96
Rutabagas	0	32	98	2–4 months	89	0.91
Salsify, topped	0	32	98	2–4 months	79	0.83
Southern peas	3–5	38–42	95+	1 week	—	—
Spinach	0	32	95+	10–14 days	93	0.94
Squash, summer	10	50	95	1 week	94	0.95
winter	10–15	50–60	60	[d]	85	0.88
Sweet corn	0	32	95+	4–6 days	74	0.79
Sweet potatoes	13	55	90	4–6 months	68	0.75
Tomatoes, unripe	[d]	[d]	90	[d]	93	0.94
ripe	2–7	35–45	90	3–5 days	94	0.95
Turnip	0	32	95	2–4 months	91	0.93
Turnip greens	0	32	95	10–14 days	90	0.92
Water chestnuts	0	32	[d]	10 months	—	—
Watercress	0	32	95+	4–7 days	93	0.95
Watermelon	7–15	45–60	80–90	2 weeks	93	0.94
Yam	16	61	60 or 100	[d]	—	—

Data from Ryall and Lipton (1979) and Lutz and Hardenburg (1968).

[a]Storage life given refers to quality rating of "good", and thus allows for a subsequent marketing period of somewhat higher temperature. This table is intended as a quick guide only; for details, consult Ryall and Lipton (1979).

[b]From Lutz and Hardenburg, 1968. Water content rounded to nearest whole percent. Formula for specific heat above freezing: 0.008 (water content as %) + 0.20.

[c]See Chapter 8.

[d]See Ryall and Lipton (1979).

its limit in air at a given temperature. The produce must have higher quality after a given time in CA storage than it would have had if stored in air. Although CA storage does not stop deterioration, it lengthens storage life from a few days to as much as several months, depending on the item involved.

In general, CA storage is beneficial for vegetables that deteriorate rapidly or those that will complete ripening after harvest. According to Ryall and Lipton (1979), no one mixture of gases is suitable under all circumstances. Even members of the same botanical family differ greatly in their tolerance to low O_2 or high CO_2. For instance, cauliflower is injured during one week's storage at 5°C in 10% CO_2, whereas broccoli remains in excellent condition in that atmosphere. Many vegetables do well under a controlled atmosphere of 2–3% O_2 and 5% CO_2. However, specific recommendations and cautions must be determined for each crop over a wide range of gas mixtures, temperatures, and time periods. Readers can refer to Ryall and Lipton (1979) for more detailed information.

DEHYDRATION

Dehydration is probably the oldest method of preserving foods. Removal of water from foods is primarily accomplished by application of heat, but new methods employing other sources of energy also are used (Van Arsdel *et al.* 1973; Charm 1971; Hall 1980). As with canning and freezing, preparation of foods prior to drying greatly affects the quality of the finished product. Foods are dehydrated to protect against spoilage by microorganisms and to reduce the costs of packaging, handling, storing, and transporting.

Several methods of drying are used industrially: forced-air drying, drum drying, spray drying, vacuum drying, and freeze-drying. Continuous belt conveyor driers have increasingly replaced tray and tunnel driers in recent years. In the late 1960s, because of the high cost of freeze-drying, the fragility of the end products, and poor stability of color and flavor, California Vegetable Concentrates Company, a division of General Foods Corp., introduced a combination of air drying and freeze-drying, which they called Aire Freeze. In this process the vegetable pieces are air-dried to about 50% moisture, then freeze-dried to 2–3% moisture. A broad line of air-freeze-dried vegetables, including crosscut green beans, celery, corn, bell peppers, and pimientos, is now commercially available. Recently, solar dehydration of foods has been of interest to agriculture (Guceri 1983; Knorr 1983).

Mechanism of Drying

The mechanism of drying has been the subject of scientific study for many years. The external factors related to it, such as air temperature, pressure, humidity, and velocity, are governed by relatively simple and well-known laws, but this is not so for the internal transfer of moisture. The following brief description of a typical sequence of physical events as a piece of vegetable tissue is dried can do no more than suggest how the leading theories are related to the observed phenomena.

As water evaporates from the wet surface, the diameter of superficial water-filled pores and capillaries diminishes and solid structural elements pull closer together under the influence of surface tension. The effect spreads into deeper layers of tissue and eventually all the way to the center. Volume shrinkage is nearly equal to the volume of water evaporated, and the drying rate per unit of surface remains constant. Structural elements of the body begin to deform by crumpling or folding so as to occupy less space as additional water is removed by evaporation at the surface, but increasing resistance to deformation is encountered and the water meniscus in capillaries begins to recede into the body. Water vapor also moves to the surface by molecular diffusion through the air in the open capillaries. The thick layers of water that wedge apart long flexible molecular chains in the wet solid begin to release the most loosely held water molecules into a diffusional flow of water in the direction of lower water concentration—that is, toward the surface. The progressive thinning of the thick water layers continues until the remaining water, averaging only about one molecule deep, is left adsorbed on the internal surface—not uniformly, but preferentially at the more highly polar groupings in the underlying solid structure. The structural elements, therefore, continue to be drawn closer together and more volume shrinkage takes place, although by a smaller amount than the volume of water lost. In the final phase, water molecules adsorbed on the internal surface of solid constituents move by a process of activated diffusion along the solid fibrils or lamellae in the direction of lower surface-spreading potential, equivalent to lower vapor pressure. In this process a water molecule that by chance receives a larger than average impetus in its continuous thermal vibration may jump from its absorption site to a nearby vacant site. On the average, there will be more vacant sites in the direction of lower vapor pressure. The process can continue, but with increasing difficulty, until equilibrium with the surrounding humid air has been approached.

Use of a solution of a sulfite (sodium sulfite or metabisulfite) on cut vegetables before drying has been standard practice in the British Commonwealth countries and the United States. In addition to improving storage stability greatly, the presence of a small amount of sulfite in a blanched, cut vegetable makes it possible to increase the drying temperature, thus shortening the drying time and correspondingly increasing the drier capacity, without exceeding a tolerable small degree of heat damage. Sulfite use has received considerable scrutiny throughout the food industry in recent years, and many manufacturers are searching for alternative methods of producing high-quality dehydrated products.

It is a prime requirement of any vegetable dehydration process that no opportunity exist for the development of bacterial toxins by *Clostridium* spp. and other causative organisms that may be present. Such toxin formation is most likely to occur when a moist product, usually with some soil contamination, is given a heat treatment followed by prolonged holding under moderately warm conditions without access to air. Thorough washing and proper blanching are required to obtain a satisfactorily low level of the poison-producing organisms and of bacteria generally. The second requirement of a vegetable dehydration process is the absence of pathogenic bacteria such as *Salmonella* sp. and *Staphylococcus aureus*. The third requirement is maintenance of a reasonably low general bacteriological content so that no decomposition or undesirable odors or flavors develop in processing or in product reconstitution (Tressler *et al.* 1968; Tressler and Joslyn 1971).

Rehydration

The quality of the finished dried product is reflected not only in its texture, flavor, and color but also in its ability to rehydrate as closely as possible to the raw material. This rehydration efficiency is determined in part by preparation and in part by the method of drying.

Dehydrators

The majority of foods are dried in dehydrators, and it is the advances in engineering technology that are responsible for the vast increase in production of dried foods (Van Arsdel *et al.* 1973).

Moving-air dehydrators, in which the air moves either counter to or parallel with the flow of the product, are widely used in drying fruits and vegetables. Temperatures of the moving air can vary in different parts of the dehydrator, the temperatures used depending upon the food being dried. The product is contained on either wooden trays, in stacks, on stainless steel trays, or on moving belts. In many dehydrator plants, moving-air drying is the first stage in the drying process. Removal of the last 2–3% moisture is done in bins in which cooler air is passed through the product. Carrots are blanched prior to dehydration. Onions and garlic are peeled and dried without blanching.

Drying of liquids or semiliquids is usually done in spray or drum driers, or by the foam-mat process. Liquids may be concentrated first by removing a portion of the moisture with heat under vacuum. Vegetables are generally dried to levels of 3–4% moisture. The rate of drying for most products is faster with fluidized-bed drying and foam-mat drying than with other methods, and the rehydration characteristics of the dried products are improved.

The principles of osmotic pressure changes have been recently applied in a reverse osmosis drying process. In this case, sugar and pressure are used to remove water from the foods. This process, developed by the USDA Research Laboratory at Albany, California, results in products of exceptional quality with respect to color and texture; as yet the process is too expensive for large-scale commercial application. Refinements in the technology may reduce its cost, allowing it to be more commonly used.

Commercial Applications

A wide variety of dried foods is now on the retail market, and many more are dried for remanufacturing purposes. For example, most of the dehydrated garlic and onions are used as seasoning for such products as canned tomatoes, tomato ketchup, tomato sauce, and soups. Achievements in the technology of dehydration have permitted commercial production of high-quality food items that previously were not amenable to drying. In particular, this applies to potato products. Alteration of the potato granule to prevent crystallization of the starch molecules has resulted in the production of dried mashed potatoes that rehydrate into a very favorable product.

Dehydration is used also to convert waste materials into animal feed. Solids from tomato-processing plants, for example, can be dried and incorporated into animal feed. As the disposal of food-processing wastes becomes more and more complex, food processors are exploring methods for recovering by-products from the waste material, and drying is certainly one of the major methods of obtaining such by-products.

FREEZE-DRYING

The principles of freeze-drying are rather simple. The product is frozen, and in the frozen state it is placed in a chamber (Fig. 1.5) under a high vacuum (at least 150 μm of mercury). The water goes directly from ice to the vapor phase, and then is condensed on refrigerated coils. Since the structure of the food is altered by the process, it picks up moisture very rapidly; therefore, a vapor-proof container must be used for packaging of freeze-dried foods. Some foods may be precooked and then freeze-dried; others may be blanched and then freeze-dried; some may be freeze-dried directly.

The reason that freeze-drying is not more widely available at the present time is the cost of the process. Only products with high intrinsic value, such as mushrooms, green asparagus, and parsley, are freeze-dried. As work progresses on developing a continuous freeze-drying unit or more advantageous ways of obtaining heat transfer from the drying phase, the process will become more economical and production will increase. The advantage of freeze-dried foods over other types is the reduction of weight by removal

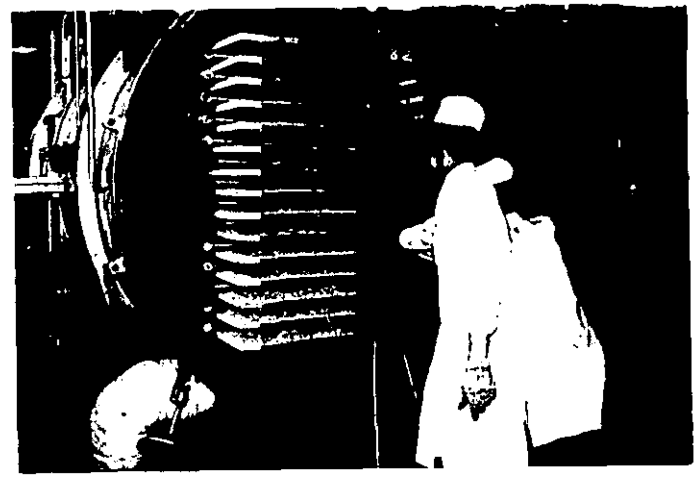

FIG. 1.5. Atlas freeze-drying chamber. (Courtesy ATLAS, Copenhagen, Denmark.)

of water and retention of quality. For certain foods, such as bell peppers, pimiento, and others, a common commercial practice is to remove a part of the moisture in the prepared raw produce in a dehydrator, followed by freeze-drying. This two-stage method greatly reduces the cost of production without significant loss of quality in the finished product.

A detailed discussion of freeze-drying is presented in Chapter 9.

PICKLING AND FERMENTING

Pickled food may be defined as a food to which an edible acid, for example, lactic acid or acetic acid in the form of vinegar, has been added. A fermented food is a food in which the acid is produced from sugar in the food product by the fermentation of lactic acid bacteria. Both pickled and fermented foods are preserved primarily by acidification. (On the other hand, wines are produced by the action of certain yeasts on grape juice, producing ethanol.)

Spanish-style olives, Sicilian-style olives, and sauerkraut are still produced solely by fermentation. Some cucumber pickles are produced by fermentation in the presence of spices and salt that are added before fermentation begins. This is called the genuine dill fermentation (Pederson 1979), but it is rapidly being replaced by salt stock and fresh-pack pickling methods in which fermentation does not occur and acid is added directly to the product in the final container.

A wide variety of vegetables are pickled commercially. Pickling is usually combined with some type of heat treatment in the final container to prevent secondary fermentation and subsequent spoilage. Heating acidified products must be done carefully so that changes in texture do not occur. Some products (e.g., artichokes and onions) cannot be processed without acidification; hence, these are called acidified-canned products, but in essence they are pickled or acidified products. A recent development in the pickled food industry has been the process for making the fresh-pack or pasteurized cucumbers and other vegetable pickles. In this process cucumbers, for example, are packed directly into jars either in longitudinal slices or in quarters. These are then covered with the brine, which is made of salt and vinegar, preferably containing some lactic acid, and seasonings. The product is then heated so that the internal temperature of the cucumbers reaches 71°C, at which it is held for 1 min. It is then cooled and stored for several days for equilibrium of the brine and the food product to be reached. Since there is residual sugar in cucumbers that could be fermented by lactic acid bacteria, the heating step is necessary to destroy the lactic acid bacteria that are normally associated with cucumbers. This heating also destroys the enzymes of the cucumber itself.

Storage of cucumbers, olives, and cauliflower in bulk in high concentrations of salt until they can be packed into individual consumer size containers is practiced by most processors. Work has been done at the University of California—Davis on the use of benzoic acid instead of high concentrations of salt for bulk storage (Vaughn *et al.* 1969). With the exception of fresh-pack vegetables and bulk storage with preservative, there have been few new methods in the pickling and fermented industries in recent years. Product-handling equipment, closing machines, and sorting machines have all been improved, but there are few new products.

Vinegar Production

Vinegar is formed by oxidation of wine by the acetic acid bacteria *Acetobacter* sp. to acetic acid (Dave and Vaughn 1969). This is an aerobic process requiring large amounts of oxygen, which is just the opposite of fermentation. Vinegar is one of the widely used condiments in pickled foods and in tomato ketchup. There is a continuing demand for biologically produced acetic acid vinegar for pickling.

New techniques in vinegar manufacture have stemmed primarily from development of the submerged oxidation system in which air is forced into the liquid. The use of this process for commercial manufacturing of vinegar was delayed because a critical concentration of oxygen could not be maintained in the solution. The acetic acid bacteria under these conditions are very sensitive to a lack of oxygen. Since they grow rapidly aerobically, they can rapidly deplete the dissolved oxygen, and if the oxygen is not supplied in sufficient quantities, the culture of acetic acid bacteria will die. New devices for oxygen distribution in submerged oxidation equipment have over-

come this difficulty, and submerged oxidation is now a commercial reality. For best results, alcoholic fermentation should be completed before acetic acid formation is started, i.e., all the fermentable sugars should be used up.

Vinegar is produced from apple cider, pineapple wine, grape wine, and malt wine. Wine vinegar and rice vinegar are the main types of vinegar produced in many countries. Some vinegars have herbs (tarragon) or other flavoring materials added. The traditional procedure in vinegar making is to expose the cider or wine to air by aging it in partially filled containers exposed to air. To speed up the process, the cider or wine is passed through a column of beechwood shavings, oak chips, corn cobs, or other porous material impregnated with *Acetobacter* sp. with a counter-current of air. Today closed tank or generator processing with a continuous introduction of oxygen is widely used. Control of the temperature and nutrients for the acetic acid bacteria is important to successful formation of vinegar. Vinegar must contain at least 4% acetic acid, although acetic oxidations can produce as much as 10%. Some vinegar is aged in wood containers to attain additional quality. However, the demand for high-quality vinegar is comparatively small. The major demand is for distilled (white) vinegar.

RADIATION PRESERVATION

Radiation preservation of foods was first carried out at the Massachusetts Institute of Technology in 1943. Since that time, there have been many trials and experiments on radiation preservation of foods using various types of ionizing radiations. These studies have been conducted in many research institutes and universities all over the world. The Food and Drug Administration has currently approved the use of ionizing radiation for the following purposes: control insects and slow growth and ripening of fruits and vegetables with a dose limit up to 1 kilogray (kGy); kill insects and control microorganisms in dried herbs, spices, teas, and seasonings with up to 30 kGy; control *Trichinella spiralis* in pork with a dose ranging between 0.3 to 1.0 kGy; inhibit sprout development in white potatoes with 50 to 150 gray; control insects in wheat and wheat flour with 200 to 500 gray (Lecos 1986).

At first, it was thought that ionizing radiation could be used to destroy essentially all microorganisms in foods, thereby rendering products sterile, just as in canned foods. However, the large doses of ionizing radiation required to sterilize most foods often creates undesirable side effects such as off-flavors, vitamin destruction, and quality defects. These adverse effects have been demonstrated at dosages of 20 kilogray or higher. The severity of these effects prompted exploration of the use of low-level ionizing radiation at levels of 1 kilogray or less as a means of pasteurizing foods.

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9

Vegetable Dehydration

L. P. Somogyi and B. S. Luh

Dehydration is an ancient method for preserving food. It lowers the costs of packaging, storing, and transportation by reducing both the weight and volume of the final product. Sun drying of certain fruits, such as apricots and peaches is common, whereas there is only limited application of sun drying with vegetables, except for a small quantity of home-dried mushrooms and experimental use of solar driers for carrots, celery, etc.

The U.S. vegetable-dehydration industry may be divided into four broad groups: (a) onions and garlic, almost exclusively in California; (b) potatoes in Idaho, Washington, Oregon, and a few other states; (c) all other vegetable products, almost exclusively in California; (d) freeze drying of certain high-value crops, mainly in California and Oregon.

Dehydrated vegetables are used in dry soup mixes, canned soups and sauces, frozen entrees, processed meats, baby foods, dairy products, and seasoning blends.

A comprehensive treatment of vegetable dehydration was presented by Feinberg (1973). Literature on freeze drying of foods has been reviewed by Burke and Decareau (1964), King (1970) and Rey (1972). Definitions frequently used in dehydration terminology were summarized by Somogyi and Luh (1986).

GENERAL CONSIDERATIONS

Temperature and Humidity

About 1000 Btus (252 kcal) of heat are absorbed when 1 lb (0.45 kg) of moisture is evaporated. The resultant cooling effect permits the drying of delicate food materials in high-temperature air without scorching. While the material is still high in moisture content, its temperature will be many degrees lower than that of the air flowing past it. As the surface dries, the rate of drying slows, the cooling effect decreases, and the temperature of the material approaches that of the surrounding air.

The relative humidity of air used for drying is a critical factor. Its ability to hold more moisture may be increased by either dehumidifying the air or by heating it and thus increasing its evaporative capacity. Wet-bulb depression, as determined by a psychrometer, and the velocity of air passing through or over the material to be dried are important external factors controlling the rate of dehydration.

Drying times may be greatly shortened by reducing the dimensions of the drying piece. Spray drying, in which the individual droplets may be only a few micrometers in diameter, is very rapid. The final product particle size thus represents a compromise between the need for rapid drying and the consumer's requirements for certain particle sizes.

Unit Loading

In tray driers the density of loading on the trays has a marked effect on drying rate. In many respects, increasing the load of wet material on a tray is analogous to increasing the thickness of a wet piece; it reduces the drying rate.

Cut vegetables are commonly loaded on trays in layers ranging from perhaps only a single piece deep to well over 1 in. (2.54 cm) deep. Loading per square foot (929 cm^2) of tray may range from less than 1 lb (0.45 kg) to as much as 3–4 lb (1.36–1.8 kg). In a well-conducted operation, careful attention is given to obtaining a uniform spread of the cut material as well as controlling total weight on the trays. In a conveyor drier, special devices are used to obtain uniform loading on the belt surface.

Conveyor driers are ordinarily designed to be loaded with a relatively thick layer of the wet material, which is treated with through-flow air, i.e., air that passes perpendicularly, up or down, through the horizontal layer of material instead of parallel to its surface.

A nomograph or alignment chart can sometimes be used to describe drying behavior. Such an empirical expression can serve to summarize the results of a large number of drying experiments, and represents the general drying behavior of the commodity in question. Van Arsdel *et al.* (1951) described several extensive experiments on vegetable dehydration and correlated the results by means of a series of nomographic charts.

By combining the indications of one of these nomographs with the physical laws of drier operation, many useful conclusions can be drawn about design and operating problems, such as the relative merits of different drier configurations; optimum loading of trays; optimum ratio between lengths of primary and secondary drying stages of a two-stage tunnel drier; the best proportion of recirculation of the drying air; and the time–temperature experience of a typical piece of material passing through the dryer.

Heat Damage

A common problem with dehydrated vegetables is the color change called *browning*. Browning may be caused by heat damage during dehydration or by poor storage conditions. If the degree of browning is not great, color change may be the only noticeable effect. When the change proceeds further, the flavor, rehydration capacity, and nutrient content may also be adversely affected.

Water is necessary for some deteriorative reactions. Consequently, the rate of browning reaches a maximum at some intermediate moisture content during drying, often in the range of about 15–20% moisture (Labuza *et al.* 1970). As complete dryness is approached, browning during storage becomes less severe; at moisture contents of 1–2% most dehydrated foods are stable for a long time, even at elevated storage temperatures. However, other types of quality deterioration, such as lipid oxidation can occur even at very low moisture content.

Enzyme Inactivation

Vegetables contain catalase, peroxidase, polyphenoloxidase, and many other enzymes. At the time of cutting and peeling, enzymatic reactions are accelerated and discoloration will often occur. Discoloration in cut potatoes is caused by the action of polyphenoloxidase in the presence of oxygen.

Enzymes can be inactivated by heating or acidification to low pH values. Inactivation of enzymes by heating is called blanching. It can be done by immersing the food in hot water at 95–100°C for a few minutes or exposing it to steam. Details on blanching of vegetables are presented in Chapters 5 and 8.

If fresh vegetables are not blanched, enzymatic deterioration of dehydrated products may take place during processing or storage and after reconstitution. Flavor changes resulting from fat oxidation may take place during storage. Browning reactions may occur if the dried product is stored at temperatures higher than 20°C and when the moisture content is higher than 5%.

Sulfuring

Although dried fruits are commonly treated with sulfur dioxide gas (SO_2) to retard browning, this treatment is impractical with vegetables. Instead, treatment with sulfite solutions is preferred as the most practical method of controlling the absorption of sulfur. The application of these treatments before drying is a common practice for cabbage, potatoes, and carrots (Salunkhe *et al.* 1974). Specifications of U.S. procurement agencies now require a range of 200–500 ppm SO_2 in dehydrated diced potatoes; 200–400 ppm in potato granules; 200–500 ppm in diced sweet potatoes; 500–1000 ppm in diced carrots; and 1500–2500 ppm in cabbage shreds (Roberts and McWeeny 1972).

In addition to improving storage stability, the presence of a small amount of sulfite in blanched, cut vegetables makes it possible to increase the drying temperature, thus shortening the drying time and increasing the drier capacity without exceeding the tolerance for heat damage. Sulfur dioxide also retards loss of ascorbic acid and carotene during blanching and dehydration.

Sulfites are generally recognized as safe (GRAS) as chemical preservatives and are known to be metabolized to sulfate and excreted in the urine without any obvious pathological results (Pintauro *et al.* 1983). Recent studies indicate that a small subset of sulfite-sensitive individuals of the asthmatic population cannot tolerate foods that have been treated with sulfites (Taylor and Bush 1986). Presently, The Center for Science in the Public Interest (CSPI) is petitioning the FDA to have sulfites removed from the GRAS list (Nolan 1983).

The most common and least expensive method to prevent enzymatic browning in fresh prepared vegetables is the use of sulfiting agents. Somogyi and Luh (1986) reviewed possible alternatives for sulfites in dehydrated products. Perhaps the best alternative to sulfiting agents is the use of ascorbic acid or erythorbic acid as a browning inhibitor. Blends of citric/ascorbic, or citric/erythorbic, acids are also effective and somewhat less expensive. These compounds can be applied to prepared vegetables by immersion in a water solution containing 1% citric acid and 0.5–1% ascorbic (or erythorbic) acid for 30–45 seconds (Nolan 1983).

Rehydration

The rehydration of dehydrated foods frequently is difficult or unsatisfactory. The process of rehydration after drying is not a simple reversal of the drying mechanism. Not only are some of the changes produced by drying irreversible, but also the swelling of outside layers as water is reabsorbed puts severe stresses on the softened outer layers. Previously crushed and crumpled structures are unable to come back to their original configurations, and solutes in the tissue leach out into the rehydration water instead of remaining in the tissue.

Irreversible changes of the colloidal components of vegetable tissue occur if the material is held for a period of time at high temperature, even if the exposure is insufficient to produce browning or scorching. The elasticity of cell walls and the swelling power of starch gel, both important for good rehydration, are reduced by heat treatment.

SELECTION OF A DRYING METHOD

Selection of a drying method for a given food product is determined by quality requirements, raw material characteristics, and economic factors. The quality required in a finished product, and its necessary physical characteristics, are determined by its end use. The method selected should be the least expensive one that provides the needed quality and other features of the product. A drying method may be prohibitively expensive for a cheap product, but quite reasonable in cost for an expensive one. A single food commodity can sometimes be worked into several different end uses by judicious choice of drying method.

Most dehydrated vegetables are processed by the forced-air drying. A disadvantage of air-dried products is their low rate of rehydration. However, depending on the particular use of the dehydrated vegetables, slow rehydration may not be of critical importance. Large quantities of carrots, onions, garlic, potatoes, and other vegetables are forced air-dried. If the food to be dried is highly susceptible to browning and other deteriorative changes, then other drying methods should be considered. Drum drying is used for some products such as potato flakes and tomato flakes.

In freeze drying, food pieces are first frozen; drying occurs with mild heating in a vacuum chamber as ice evaporates from a receding ice interface within the pieces. Product shrinkage is negligible, heat-induced changes are minimal, and the dry material is porous and readily rehydrated. However, freeze drying is an expensive way to evaporate water; it is justified only when the material is highly sensitive to heat or when the particular properties imparted to the product justify the higher cost for a given end use. In addition, freeze-dried vegetables are highly demanding with regards to packaging; if adequate packaging is not provided, their quality quickly deteriorates (Villota *et al.* 1980). Nominal quantities of such vegetables as chives and mushrooms are freeze-dried. King (1970) reviewed recent developments in food dehydration technology and the advantages of low-temperature dehydration and freeze-drying processes.

For purees or flowable suspensions, other drying techniques are used. Spray drying is the most important method for dehydration of liquid food products. Among vegetable substances, concentrated tomato puree is commercially spray-dried. Drum drying, a high-temperature short-time method, is an inexpensive way to dry pureed foods. Drum drying is successfully used for drying mashed white potatoes and tomato concentrates.

Costs of Dehydration

A wide variety of methods is available for drying food products, each with a definite effect on the quality and physical properties of the product. Costs vary with drying methods, and they vary widely for different products made by the same drying method. A simplified cost picture for products that are easily dried was summarized by Brown *et al.* (1973).

Flick (1977) compared costs of producing and distributing frozen, freeze-dried, and compressed freeze-dried peas. Although frozen peas are the least costly item to manufacture, its cost advantage disappears if the cost associated with one month of home storage is included. In that case, compressed freeze-dried peas is as equally cost-effective as its frozen counterpart.

Supplying Heat to Driers

Heating systems used in forced-air driers are of two basic types: direct and indirect. In the direct system, heat is applied directly to the wet solid or liquid material by the heating medium, usually a hot gas. The passage of the gas also provides a medium to help carry away the vapors removed from the material. In the indirect system, heat is transferred from steam, hot combustion gases, or possibly other hot substances, by conduction through a metal surface to the air used for drying. Gas or fuel oil is commonly used in direct-heating systems; steam, waste gases from boilers or furnaces, or air streams heated by the combustion of gas, fuel oil, coal, or any available combustible material can be used in a heat exchanger to provide indirect heating.

Solar Drying

Because of the tightening supplies and increasing costs of various forms of energy, the utilization of solar energy for drying vegetables has been evaluated. The use of wind and radiant solar energy in combination for drying vegetables can help promote conservation of food and energy resources (Wagner *et al.* 1981).

A two-stage batch solar-drying process has been developed in Florida. It involves use of an enclosed solar collector/hot-air drier with transparent covers and planar reflector mounted above and beneath to increase solar radiation to the food compartment. The equipment was tested with diced carrots and sliced parsley. Most of the moisture was evaporated during the solar stage and drying was completed overnight with a low flow of air heated by fossil energy sources (Wagner *et al.* 1979). Different procedures have been investigated by Bolin *et al.* (1980) for using solar radiation to accelerate dehydration. Bolin and Salunkhe (1982) reviewed the literature on the application and economics of food dehydration by solar energy.

Mahmood *et al.* (1981) described four models of solar dehydrators and compared the resulting products with sun-dried vegetables. Bitter gourd, cabbage, paprika, coriander, mint, okra, and spinach were tested. Drying time and temperature, relative humidity, microbial load, and rehydration characteristics of the finished products were determined for each method of drying. In general, the solar dehydrators provided better results than open sun drying.

TYPES OF DRIERS

The common kinds of vegetable-drying equipment are tray, tunnel, continuous conveyor-belt, belt-trough, air-lift, fluidized-bed, spray, drum and vacuum shelf. Dehydration equipment was thoroughly reviewed by Van Arsdel *et al.* (1973A), Somogyi and Luh (1986), and Levine (1977).

Air drying of vegetables is still the most widely used method. In the early days, tunnel and cabinet driers were in general use, but continuous conveyor-belt dryers and belt-trough dryers are rapidly replacing these devices.

Tunnel Driers

Despite the increasing popularity of continuous driers, tunnel driers are still used in the United States because of their simplicity and great versatility. Foods in pieces of almost any size and shape can, so long as they are solids, be successfully dried in a truck-and-tray tunnel.

A tunnel drier is basically a truck-and-tray batch drier. Truckloads of freshly prepared material are moved at intervals into one end of the long, closely fitting enclosure. The whole string of trucks is periodically advanced, while the dried truckloads are removed at the other end of the tunnel. Hot air is supplied to the tunnel in any of several different ways, depending on the design of the drier; for example, there are counterflow, concurrent or parallel-flow, center exhaust, multistage, and compartment arrangements.

In operation, the prepared wet material is loaded in a thin, uniform layer on the drying trays, which are stacked on shelves one above the other on a low-bed truck or dolly. The trays, made of wood or light metal, with thin slat or open-mesh bottoms, are designed so that air can pass between them. Loaded trucks are moved, one at a time, into the "wet end" of the drier. A close-fitting passageway constitutes the tunnel, forcing air to flow mainly between the trays. A single tunnel may accommodate as few as 5 or 6 trucks, or as many as 15 in a maximum working length of about 15 m. The overall length, including space for fan and recirculation port, may be 4.6–6.1 m longer than that of the drying section.

Tunnel-drying characteristics are strongly influenced by general design and arrangement, especially the direction of progression of the trucks relative to the air flow. Air flow may be directed either parallel to the direction of truck movement or transverse to it. In the more common types of tunnel design, the main air flow is parallel to the direction of truck movement. It may be in the same direction (concurrent or parallel-flow) or in the opposite direction (counterflow), or it may be partly one and partly the other, as in various types of multistage driers. Figure 9.1 illustrates a simple concurrent tunnel; Fig. 9.2 shows a simple counterflow tunnel. A more complex counterflow tunnel, designed to allow a portion of the drying air to be recirculated, is depicted in Fig. 9.3.

In a concurrent tunnel very rapid initial drying of the material takes place, causing a high moisture gradient within each piece, rapid setting of the outer layers after only a little shrinkage, and formation of internal splits or porosity as the internal flesh finally dries and shrinks. Final drying stages are very slow because the material is approaching dryness and the drying air is relatively cool and moist. In a counterflow tunnel, on the other hand, the best drying conditions exist as the material approaches dryness. Unless the evaporative load is very light, the initial stages of drying take place in much cooler and more humid air, internal moisture gradients are not so steep, and more nearly unhindered and complete volume shrinkage can take place.

Several other tunnel arrangements have been used to take advantage both of the high wet-end evaporative capacity of the concurrent design and the good final-drying capability of the counterflow design. The combination generally preferred consists of a concurrent wet end and a counterflow dry end. In some designs, trucks are moved straight through a single long tunnel, which is divided into sections by one or more movable partitions. Another design, known as center exhaust, dispenses with partitions and relies upon the placement of the air-circulating fan, heater, and dampers to divide the air flow in the desired way. In some successful installations, a multiple bank of concurrent first-stage tunnels is connected by trackage and switching arrangements with a second bank of counterflow finishing tunnels; any given truck may be routed into whichever tunnel happens to be scheduled for the next one-step advance. Rodda and Gentry (1969) described construction of tunnel driers.

Continuous Conveyor Driers

The through-flow continuous conveyor drier represents the completely mechanized development of equipment for drying pieces of a food material in warm circulating air. Conveyor driers (Fig. 9.4) are being used in more and more food dehydration plants to dry beet, carrot, onion, potato, and

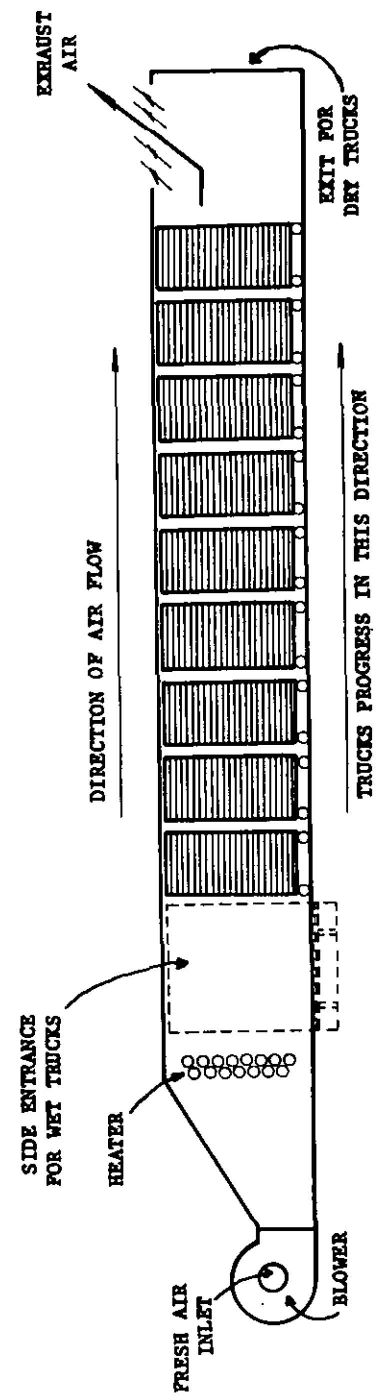

FIG. 9.1. Simple concurrent tunnel drier (elevation). (From Brown *et al.* 1973.)

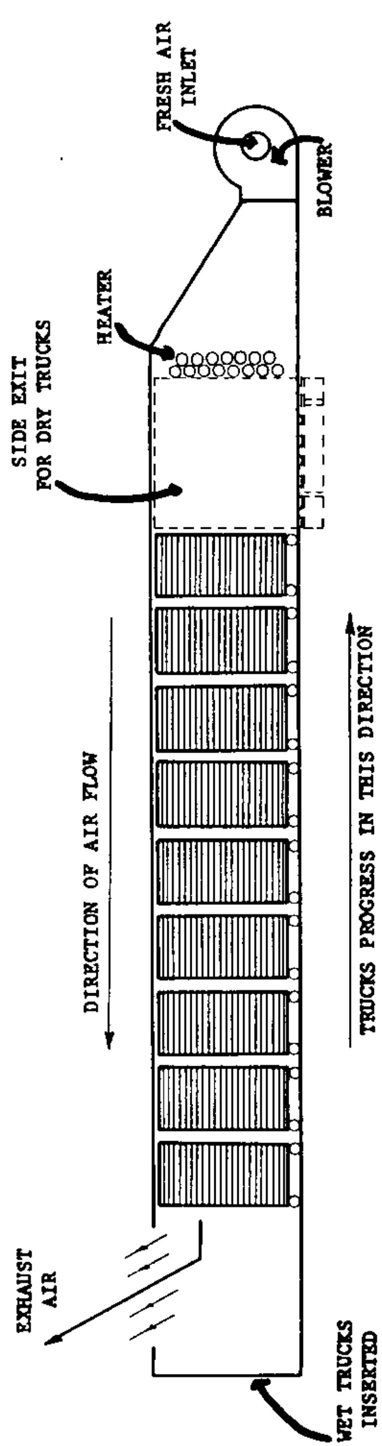

FIG. 9.2. Simple counterflow tunnel drier (elevation). (From Brown *et al.* 1973.)

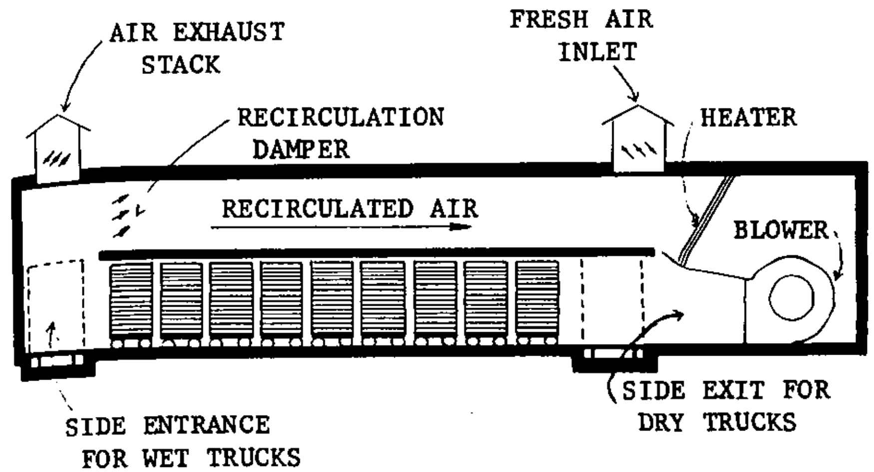

FIG. 9.3. Side-entrance counterflow tunnel drier with variable air recirculation. (From Brown *et al.* 1973.)

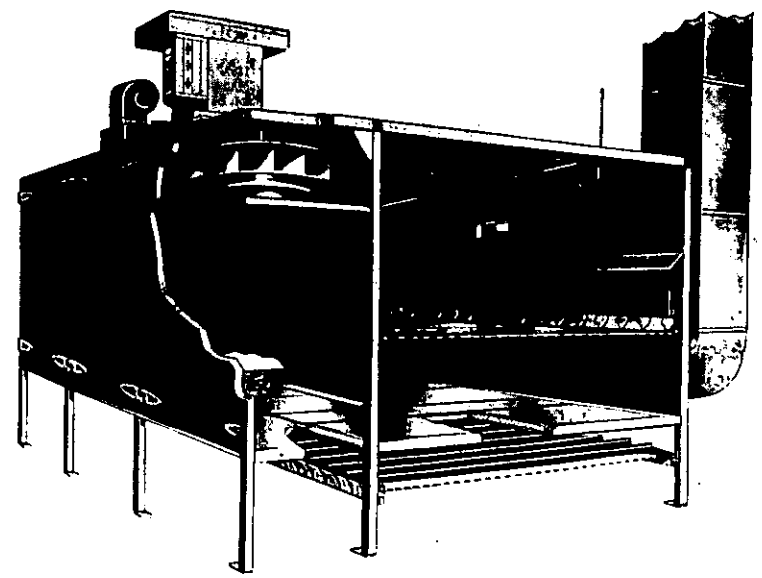

FIG. 9.4. Interior view of a single conveyor drier. (Courtesy Proctor and Schwartz, Philadelphia.)

sweet potato pieces, which have conventionally been dried on trays in tunnels. The primary reason for the change is the substantial saving in the cost of moving prepared food into and out of the drier and of maintaining the drying surface in good condition. The conveyor drier is best adapted to the large-scale drying of a single commodity for the whole operating season. It is not well suited to operations in which the raw material or the drying conditions are changed frequently, because of the complexity of producing a fully satisfactory product during the many hours of startup and shutdown.

A diagrammatic elevation and cross section of a widely used type of conveyor drier is shown in Fig. 9.5. Wet material supplied to the spreader device at the left is loaded evenly and in a relatively deep layer (7.6–15.2 cm) on the surface of a slowly moving conveyor belt. This may be fabricated of woven metal mesh, but more often the belt consists of a succession of flat, hinged, or interlocking, perforated plates, each as long as the width of the conveyor and usually no more than 15–20 cm wide. The working surface of a single stage of the conveyor may be 9–18 m long and 1.8–3.0 m wide; usually at least two stages are combined in series into a single drying operation. The belt extends beyond the body of the machine at both ends to provide for the loading and unloading operations, and returns within the body. The hot drying air flows through the layer of wet material and through the meshes or perforations in the conveyor, generally upward in the first section and downward in succeeding sections. The drier is designed to produce up-through and down-through flow in alternate sections in order to improve the uniformity of drying. Flow is always down-through in the last one or two sections, to prevent lightweight, nearly dry pieces from blowing out of the bed. This through-flow of air is a highly effective method.

Several variations in the basic design of the continuous-conveyor drier have proved useful. For example, sectionalizing the drier makes it possible to control air temperature, humidity, and velocity independently in several stages to give optimum output and quality. Construction of the drier as two separate conveyors in series makes it possible to discharge the partly dry material at the end of the first stage, mix it, and repile it in a deeper layer for its passage through the second stage. This is an important feature. Not only does mixing aid in making a uniform product, but repiling makes possible a reduction in the floor space required.

To save space, axial-flow fans are ordinarily used. Two or three such fans may all discharge into the common plenum above or below the belt. A large proportion of the air passing through the layer of moist material recirculates into the fan; part of it may be diverted by dampers into the next section, to be replaced by heated fresh air. The intense turbulence in the plenum effectually equalizes the air conditions within the section.

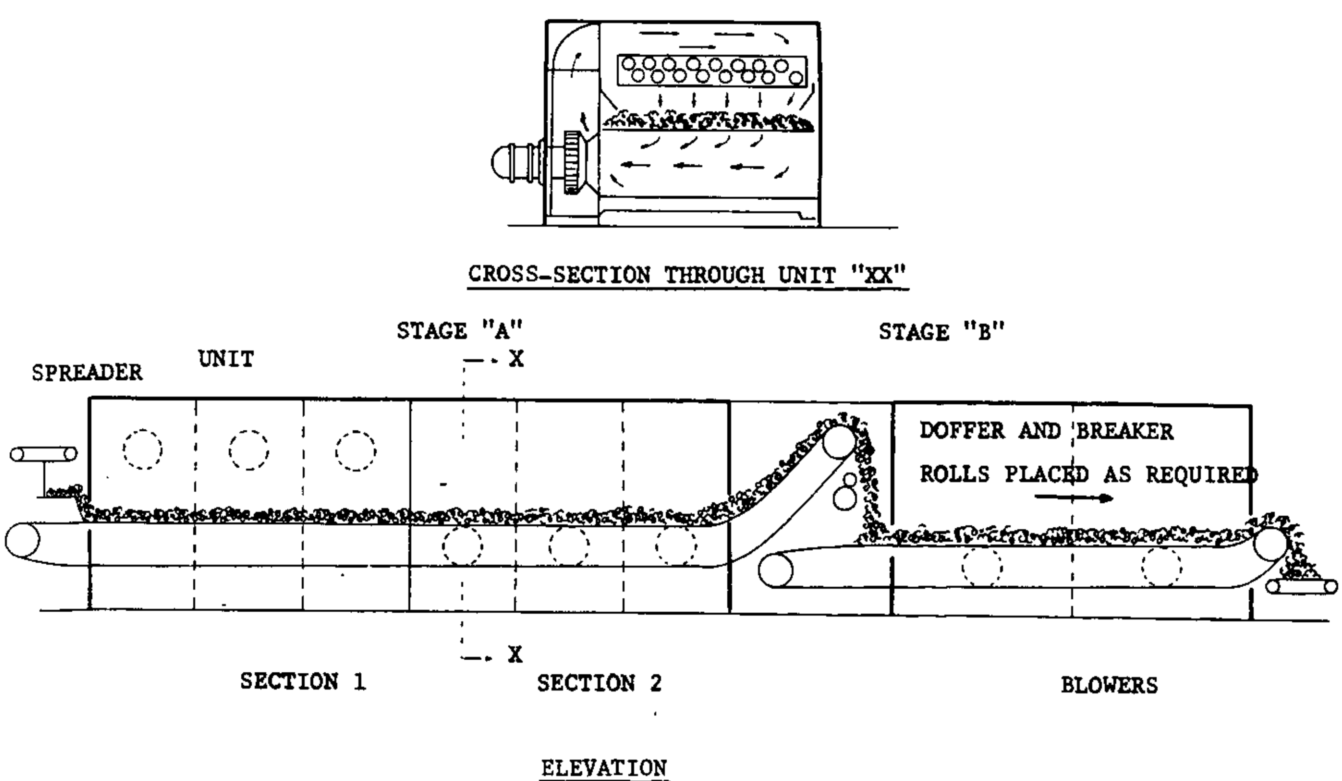

FIG. 9.5. Diagram of two-stage continuous conveyor drier. (From Brown *et al.* 1973.)

Space or cost considerations may dictate the use of high-pressure steam heat and extended-surface transfer coils, but many conveyor dehydrators for vegetables employ direct heating by combustion of natural gas in the circulating air.

Drying conditions for vegetable material vary from first-stage temperatures of 93–127°C in the first section and 71–104°C in the second, to second-stage temperatures of 54–82°C. Satisfactory drying conditions for a particular raw material can be determined experimentally in pilot tests.

Care must be taken to avoid either crushing or matting the wet material on the bolt or creating thick or thin spots. Thick spots receive too little air and remain wet, while in a lightly loaded area the product may be blown aside, leaving a hole through which much of the air can escape; surrounding material for several feet on every side will receive too little air and will dry too slowly.

Some soft, starchy or sugary materials may benefit by being subjected first to very rapid surface drying in such equipment as the belt-trough drier, so that the working surfaces of the conveyor drier will remain clean and free of sticky buildup. Automatic brushing of the return side of the conveyor removes most adhering pieces of product, but scrupulous manual cleanup should be carried out each time the drier is shut down. Dust and light fragments of product, which invariably accumulate within and around the drier, must be cleaned out frequently.

Pneumatic Conveying Driers

In pneumatic conveying driers, powders or granular materials are dried while suspended in a stream of heated air. Such driers are not used extensively as the sole drying equipment for a food material, but are valuable in specific instances. Parsley is sometimes dried in this type of drier. As the material entering must be conveyable in an air stream, the incoming material usually is predried in another way to a moisture level below 40%.

A pneumatic conveying drier is often integrated with a spray drier to provide a second stage of drying. The product obtained directly from the spray drier is normally low enough in moisture content for the commercial market, but special requirements may call for a lower-moisture product. In such cases, product from the spray drier is fed into a duct with a fresh supply of heated, dry air, leading to a cyclone collector where the product—now lower in moisture by a few percent—is removed.

Pneumatic conveying driers have found extensive use in the potato-granule industry. Here, the feed ordinarily enters the first drier at 35–40% moisture, and the product is discharged from the cyclone at a moisture content in the range of 11–13% (Schanhals *et al.* 1963).

Another kind of pneumatic conveying drier is used for the finish drying of potato granules to a final moisture content of 6%. This is a fluidized-bed drier, originally developed by Neel *et al.* (1954). The fluidized-bed drier resembles a long box or trough with a bottom formed from woven stainless-steel cloth or porous ceramic such as sintered aluminum oxide. Hot air is admitted to a plenum chamber below the porous surface. Moist potato granules (11–13% moisture) are fed on top of the porous surface and heated air is fed up through the layer of granules. When the air flow is properly adjusted, the bed of granules is completely fluidized and has many of the physical properties of a liquid. Addition of a constant-rate feeding device at one end of the trough and an overflow wire at the opposite end is all that is needed to make a simple and effective continuous drier for the finish drying of potato granules. Similar equipment is also used for the cooling of potato granules before packing.

Belt-Trough Driers

The belt-trough drier is a continuous through-flow drier with characteristics that make it useful in drying a variety of materials, particularly cut vegetables.

As shown in Fig. 9.6, a belt-trough drier consists essentially of an endless, closely woven, metal-mesh conveyor belt the width of the drier and supported between two horizontal rolls with a great deal of slack so that it hangs freely. The upper run hangs down only far enough to form a moderately deep trough, and the slack in this run rests lightly on a flat-surfaced hot-air grate and a third supporting roll. When the belt is driven slowly by means of its supporting rolls, the bed of material slowly turns over, continuously exposing new surfaces within the bed to the blast of hot, dry air coming up through the grate at the bottom of the trough. Because of dynamic considerations, the trough bottom is slanted at an angle of about 15–20°; thus, the material at the bottom of the bed moves up a gentle slope, works to the top of the bed, and slowly works cross and down again on the opposite side. The entire belt assembly is also tilted slightly toward one end. The result is that the material in the bed feeds slowly in a generally helical path toward the downside; operation is made continuous by feeding fresh material to the raised end and removing the dried material at the low end.

Drying air is delivered at a volume high enough to support, but not fluidize, the material in the bed. Material in the drier is thus gently and continuously moved by the air flowing through it and turning action of the conveyor belt.

The standard belt-trough drier, which has a bed 4 ft (1.2 m) wide and 10 ft (3.0 m) long, evaporates 1000 lb (454 kg) of water per hour, and can

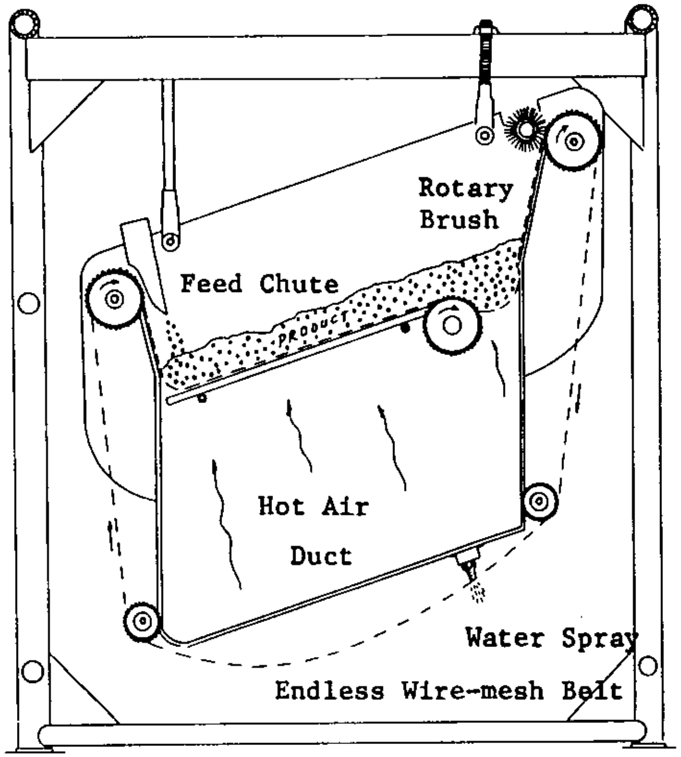

FIG. 9.6. Design of a belt-trough drier. (From Brown *et al.* 1973.)

reduce feed material to half its original weight at the rate of 1 ton/hr. Air leaving the bed in the drier is nearly saturated, indicating efficient use of heat.

The belt-trough drier was originally developed to meet the needs of the dehydrofreezing process in which it is essential that each piece of food material be dried to very nearly the same moisture level. This uniformity is also advantageous when belt-trough driers are used for the major portion of the drying.

It has been shown that belt-trough driers can make dehydrated vegetables of better quality than those produced by more convenient air driers. However, the belt-trough drier, because of the partial suspension of pieces in the air stream, requires reasonable uniformity in the size and shape of pieces. The optimum would be spheres of uniform size, like peas, which are processed commercially in belt-trough driers. Also, blanched potatoes, red and green peppers, onions, and pimientos, cut by a dicer, can be dried satisfactorily.

Bin Driers

Bin driers are used in the drying of piece-form vegetable products to complete the drying operation after most of the moisture has been removed in a tunnel drier or its equivalent. Typically, a bin drier would be used to reduce the moisture content of a partially dried cut vegetable from about 10–15% down to about 3–6%. Bin dryers are widely used for this purpose because they can remove a small amount of tightly bound moisture from the pieces more economically and with less heat damage than any other type of dehydrator. The long time required, ranging up to as much as 36 hr in some cases, does not entail much cost because the equipment tied up is relatively inexpensive.

Bin drying also serves several other purposes. The product discharged from the main drying tunnel or conveyor may range widely in moisture content, containing decided "wet spots" and "dry spots." The redistribution of pieces of the material as the bin is loaded, and the long holding of the entire batch in warm flowing air, help to bring about substantial, controlled equalization of the moisture. The capacity and operating flexibility of tunnel and conveyor driers are improved when bins are used for final drying. The bins themselves also serve as storage reservoirs to maintain a smooth flow of product in a plant.

Simple in construction and operation, a typical bin drier consists essentially of a metal or wooden box equipped with an air inlet at the bottom and a wire-mesh or false bottom. Warm, dry air is passed up through the nearly dry product piled on top of the deck. Typical interior dimensions are 3-4 ft (0.9–1.2 m) wide, 5-8 ft (1.5–2.4 m) long, and 5-6 ft (1.5–1.8 m) deep although larger bins have been used successfully.

Product is usually moved into fixed (stationary) bins by conveyor. The bottom of a fixed bin opens to discharge the product onto a conveyor beneath it. These require less total floor space, labor, and maintenance, and can be larger in size, than portable bins. The latter, on the other hand, have greater flexibility and convenience of operation, are less expensive to construct, reduce the handling and conveying of material (thus minimizing breakage of brittle product and consequent production of fines), and are easily cleaned.

Several types of continuously operating finishing bins have been proposed. Stack or column driers are used routinely for large-scale grain drying. However, the irregular and distorted shapes of the individual pieces of dry cut vegetables invariably cause arching, jamming, and failure to feed smoothly and uniformly down through columns designed like grain driers, even with the assistance of vibrators. This difficulty appears to have been overcome in one recent design that is essentially no more than a very slowly moving conveyor carrying a deep bed of the product above a warm air grate, with an opening at the end of the conveyor. An unloading device continuously rakes small portions of the dried product onto the discharge conveyor. This, therefore, makes the finishing bin basically the last stage of a continuous conveyor drier system.

Bin-drying conditions for vegetable pieces have not been closely defined. For onion slices the recommended incoming air temperature falls within the range of 100–130°F (38–54°C), while for potato dice, the temperature may be somewhat higher, up to about 140°F (60°C). In humid producing areas, dehumidification of the drying air may be necessary.

Spray Driers

In spray drying, the fluid to be dried is dispersed into a stream of heated air. The dry particles are separated from the air and collected, and the moist, cooled air is exhausted. Different types of spray driers are manufactured, with various combinations of atomizing devices, air-flow patterns, heating systems, and collecting systems. These are needed to meet the requirements imposed by the different materials that are spray-dried.

Spray drying of liquids or purees is preferred to other drying methods for several reasons, mainly product quality. With some feed materials, no other drying method has been able to yield a satisfactory product at an acceptable cost. Materials that are easily damaged by heat or oxidation can frequently be handled in a properly designed and operated spray drier. Some foods when dried yield powders that are hygroscopic as well as thermoplastic, but if a spray drier is designed to inject cool and/or dry air as needed to cope with these problems, satisfactory products can be collected. Desired characteristics in the dry powder may point to spray drying as the method of choice.

Drum Driers

A drum drier comprises one or more hollow rolls (drums) so fitted that a heating medium—usually steam, but occasionally water or a special high-temperature heat-transfer liquid—can be circulated through them. The drums are mounted to rotate about the symmetrical axis and are customarily driven with a variable-speed drive. Some type of feeding device is used to apply a thin, uniform layer of the material to be dried on the hot drum surface. A knife or doctor blade is also fitted to the drum at an appropriate location. The feed material applied on the periphery is dried as the heated drum rotates toward the doctor blade, which scrapes the thin layer of dry material from the drum surface.

Drum driers are classified as single-drum, double-drum and twin-drum. A single-drum drier has only one roll. A double-drum drier has two rolls, which rotate toward each other at the top (Fig. 9.7). The spacing between

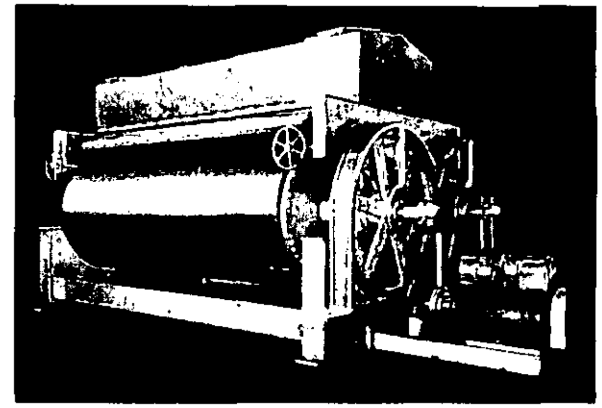

FIG. 9.7. Atmospheric double-drum drier with exhaust system and cool-air blast to aid removal of sheet. (Courtesy Blaw-Knox Food and Chemical Equipment, Buffalo, NY.)

the two rolls is carefully adjusted to control the thickness of the feed layer applied to the drums. Although similar in appearance to the double-drum drier, the two drums of a twin-drum drier rotate away from each other at the top and are not spaced close together.

Drum driers are fitted with hoods to exhaust the water vapor evolved during the drying operation. The entire drier may be enclosed so that it can be operated under vacuum. A vacuum drum drier is used only for heat-sensitive products that must be dried at lower temperatures than is practical at atmospheric pressure. In the food industry, the atmospheric drum drier is most commonly used.

The need to apply a uniform layer of materials differing widely in characteristics gives rise to a variety of feed application devices. A single-drum drier is conventionally fed from beneath. In the simplest form, the drum merely dips into a pan of the feed material, which may be constantly stirred to assure uniformity. Feeds that cannot tolerate prolonged exposure to heat may be dip-fed from a very small pan constantly supplied with fresh material. When a dip feed is unsatisfactory, devices can be used to splash or spray the feed material onto the drum, using a spreading knife to apply a uniform layer. A small, unheated auxiliary roll has been used to assure a uniform layer of tomato paste on single-drum driers.

Feeding arrangements for double-drum driers are usually simple. Clear liquids that are not too viscous are fed from a perforated pipe located above the trough formed between the two drums of the drier. For viscous liquids, or for those containing appreciable amounts of suspended matter, the feeder may consist of an oscillating pipe that deposits the feed along the trough formed between the two drums of the drier. Twin-drum driers are fed by dip or splash systems located beneath the drums, or by flow systems located above the drums.

Only single-drum and double-drum driers have been employed extensively in drying vegetables. Large quantities of mashed potato flakes are now dried on specially designed single-drum driers. The potato-flake drier has four auxiliary small rolls, driven at the same surface speed as the main roll, located around the periphery of the main roll. The smaller rolls, part of the feeding system, are used to apply and reapply the mashed potato to the drying drum. Double-drum driers are used commercially in California for the drying of tomato paste. Spadaro and Patton (1961) developed a continuous pilot plant process for making precooked, dehydrated sweet potato flakes. Nair (1963) reported on commercial production of precooked sweet potato flakes by a drum-drying process.

Special techniques are required to drum-dry tomato puree and other products containing large amounts of sugars. The sugars in these materials will be sticky and may be molten when the sheet is ready to be peeled from the drum. If a simple doctor blade is used to remove such materials from the drum, the product sheet wrinkles and adheres to itself to form crimped sheets or sticks of product. Such forms are not easily dispersed for subsequent use and are unsatisfactory in physical properties. Many devices have been employed to circumvent this difficulty. Such devices have a common purpose of cooling and solidifying the product in sheet form. A cool-air blast from beneath the sheet is frequently used to support and cool the sheet as it is peeled from the drum. Perforated rolls with air flowing outward through the perforations, or rolls formed from wire mesh, are also used to support and cool the product. Internally cooled auxiliary rolls may also be used to aid in handling the product sheet. The quality of such drum-dried products has, however, often been no better than marginal. The trend has been toward spray drying and other methods to make products of high quality at an acceptable cost.

Freeze Driers

The equipment needed in a freeze-drying plant varies with the type of foods to be processed and the capacity of daily output. Essential operations are preparation, freezing, freeze drying, and packaging (Rowe 1971).

A typical freeze drier is shown in Fig. 9.8. The unit's primary components are a drying chamber, cold tray, evacuating system, a circulating system for heating and/or cooling, refrigerators, and an operation panel. Freeze-drying and the properties of freeze-dried foods are discussed in detail in the next two sections.

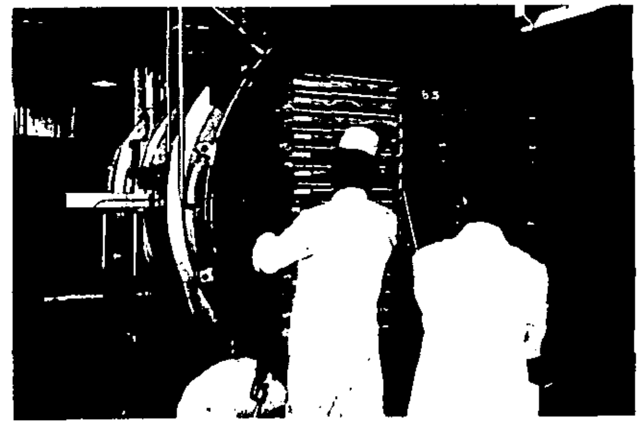

FIG. 9.8. Atlas vacuum contact dehydration cabinet used to freeze-dry foods. (Courtesy Dragon Gate Food Corp., Taiwan.)

FREEZE-DRYING PROCESS

The freeze-drying process consists of removing moisture from foods in the frozen state by sublimation under high vacuum. The low temperature used in the process inhibits undesirable chemical and biochemical reactions and minimizes loss of volatile aromatic compounds. The dried product is light in weight and can be stored in airtight containers for long periods without refrigeration. Freeze drying causes very little shrinkage of the product, and consequently allows nearly complete rehydration. Because of the absence of free liquid water during freeze drying, there is no migration of dissolved solutes carried by capillary liquid flow and no spattering or undesired frothing resulting from liquid entrainment in the water vapor.

The important steps in making freeze-dried products include raw-material selection, grading, size separation, washing, peeling or removal of undesirable parts, sorting, slicing, blanching, freezing, freeze drying, inspection, screening, packaging, and marketing. In this section, only the freezing and freeze-drying (drying) steps are discussed.

Freezing

In the manufacture of freeze-dried products, the raw material is pretreated and frozen before drying. The freezing points of some important vegetables are presented in Table 9.1. The moisture content, specific heat, and latent heat of sublimation of some common vegetables are presented in Table 9.2. A higher moisture content is associated with a higher specific

Table 9.1. Freezing Point of Vegetables

Vegetable	Freezing point (°C)	Vegetable	Freezing point (°C)
Artichoke, Jerusaleum	−2.5	Lima beans (shelled)	−2.0
Asparagus	−2.0	Mushrooms	−1.5
Cabbage	−0.5	Olives	−1.5
Carrots	−2.5	Onions	0.0
Cauliflower	−3.0	Peppers	0.0
Celery	−2.0	Potatoes	−1.5
Corn	−1.5	Pumpkin	0.0
Cucumber	0.0	Spinach	0.0
Garlic	−3.5	Sweet potatoes	−2.0
Green peas	−1.0	Sugar beets	−3.0
Green peas (shelled)	−2.0	Tomatoes	0.0
Leeks	−1.5	Wasabi (mustard)	−3.0

Source: Takano and Tadano (1962).

heat and latent heat of sublimation. There are two methods of freezing, namely, prefreezing and self-freezing. In each case, the moisture in the raw material should be converted to very fine ice crystals. Freezing results in a change in elasticity and moisture-keeping ability of the raw material. If the raw material is frozen at a temperatue higher than 14°F (−10°C), ice crystals will be formed slowly, and the crystals will be coarse and large. The food texture will be damaged by the coarse ice crystals. In addition, denaturation of the cell membrane or protein components may occur, and enzymatic reactions may continue to take place until the raw material is completely frozen.

Table 9.2. Specific Heat and Moisture Content of Selected Vegetables

Vegetable	Moisture (%)	Specific heat (kcal/kg) Before freezing	Specific heat (kcal/kg) After freezing	Latent heat (cal/g)
Cabbage	92	0.94	0.47	73
Carrots	88	0.90	0.46	70
Celery	94	0.95	0.48	75
Sweet corn	74	0.79	0.42	59
Cucumber	96	0.97	0.49	76
Eggplant	93	0.94	0.48	73
Onions	88	0.90	0.46	69
Peas, green	74	0.79	0.42	59
Potatoes	78	0.82	0.43	62
Spinach	93	0.94	0.48	73
Sweet potatoes	69	0.75	0.40	54
Tomatoes	95	0.95	0.48	74

Source: Takano and Tadano (1962).

Self-Freezing. The majority of blanched vegetables can be frozen by direct evaporation of moisture from their surfaces. In this process, the latent heat of vaporization is drawn from the material, causing a decrease in temperature. The reduction in pressure must be sufficiently rapid to accomplish self-freezing. Deformation and foaming, which may occur during evaporation, may be minimized by adjusting the vacuum at a fixed level. The process cannot be adapted to products requiring very good shape and appearance. It can only be utilized in freeze-drying powdered products (taro, egg, etc.).

Prefreezing. Another process for freezing the raw material before sublimation is prefreezing. Such freezing can be accomplished by (a) cold-air blast, (b) immersion in cold brine, (c) contact with cold metal plates, and (d) spraying with supercooled liquid nitrogen or Freon or dipping in the refrigerants. For better texture in the final products, the quick-freezing process is preferred. In general, vegetables start to form ice crystals at a relatively high temperature and can be prefrozen easily.

The freezing speed may affect the texture of the final freeze-dried product. For example, asparagus frozen at −22°F (−30°C) for 15 min showed better elasticity and water retention than that frozen at −4°F (−20°C). For large-scale production, raw materials may be stored in the frozen state. In a blast freezer, cold air is continuously circulated in the refrigerated room and it may dehydrate the exposed surface of the product. Thus, the frozen vegetables should be freeze-dried as soon as possible. This is particularly important for materials that are not blanched.

Drying

After pretreatment and freezing, the raw materials are sent to a freeze drier. The temperature is maintained below the triple point of the constituent aqueous solution so that water vapor can be sublimated from the frozen solution. There is a direct transfer from the solid state to a vapor without passing through the liquid phase. The heat required to sublimate a given quantity of ice at any temperature is equivalent to the heat of fusion of ice and the heat of vaporization of water plus the heat necessary to raise the temperature of the ice to its melting point. The quantity of heat required is the same whether the process is carried out slowly at ordinary pressures or rapidly under a high vacuum. Since the vapor pressure of ice increases with temperature, the higher the temperature is, the faster the drying process and the lower the cost will be. Obviously, the food should not reach 0°C until nearly all the water has been removed, because ice melts at this temperature.

It is necessary to remove the vapor evolved when drying at very low pressure. This can be done either by condensation, pumping, or absorption with a desiccant. In order to condense the water vapor, the temperature of the condensing medium must be below that of the frozen product being dried. This is costly because of the amount of heat to be extracted from the vapor and the relatively low efficiency of refrigeration machines operating at low temperature.

The apparent activation energy of water-removal rates during the falling-rate stages of drying is in the range of 7–12 kcal/g-mole, corresponding closely to the latent heat of vaporization of water (10 kcal/g-mole), which characterizes the dependence of vapor pressure upon temperature. The apparent activation energies of nonenzymatic browning reactions are close to 30 kcal/g-mole. Because of the higher activation energy for the browning reaction, the amount of browning for a given amount of dehydration is much less at lower temperatures.

At sufficiently low temperature and partial pressure of water vapor, drying will occur by sublimation rather than evaporation. Freeze driers are operated under high vacuum (0.1–1 mm Hg) and supplied with enough heat for sublimation.

Low-temperature drying processes inherently give slow rates of drying because of the limits imposed upon the driving forces of temperature and water-vapor partial-pressure difference for heat and mass transfer. The main problem is to achieve more rapid drying while preserving good product quality. The latent heat of sublimation must travel from the heat source to the surface of the material being dried by an external heat-transfer process. This heat is then conveyed by an internal heat-transfer process to the point within the material where vaporization of water actually takes place. The water vapor generated must reach the outer surface of the material by an internal mass-transfer process and must then travel by an external mass-transfer process to the moisture sink (condenser). These processes act in series with one another. Any one of them or a combination can be the principal rate-limiting step, depending on the design and operation condition of the dehydration device and the characteristics of the material being dried. Efforts to accomplish more rapid drying must be directed toward improving those heat- and mass-transfer coefficients, and to increasing the interfacial area per unit product volume.

Heat- and Mass-Transfer Coefficients. The external heat- and mass-transfer coefficients are accelerated considerably under vaccuum-drying conditions by high-velocity jets issuing from the surface of the material and by rarefaction shock waves. Usually, it is easier to achieve high external heat- and mass-transfer coefficients than it is to achieve high internal coefficients. Therefore, it is more economical to build and operate drying equipment in such a way that the external resistance does not limit the rate significantly. The external heat- and mass-transfer coefficients should be just high enough to give this condition (King 1970).

Internal heat transfer occurs by conduction, while internal mass transfer at low moisture content takes place by viscous flow or bulk diffusion of water vapor. The bulk gas diffusivity is inversely proportional to the pressure; thus vacuum drying is useful for accelerating drying rates in low-temperature processes. Because product shrinkage is quite low during freeze drying, the limiting internal resistance under vacuum conditions is most often heat transfer rather than mass transfer.

Wet-Weight Load. The weight load on a unit area of drying tray is an important factor influencing the drying time in a freeze drier. Because the raw material is dried from the outer to the inner layer, the thicker the raw material is, the longer it takes to complete the process. For this reason, raw materials are usually sliced to 0.25–0.75 in. (6–19 mm) in thickness.

The wet-weight load on the drying tray per unit area differs from one heating system to another. It also varies according to the kind of product to be dried. On an industrial scale, if the drying time for one cycle is 6–8 hr, the load will be set at 1.5–2.0 lb/ft^2 (7–9 kg/m^2). In Table 9.3, freeze-drying times for several vegetables at various thickness levels are listed. The thickness of the food, the plate temperature, vacuum in the chamber, and the temperature of the condenser are important factors affecting the drying time.

Drying Temperature. Several types of heating systems can be used to supply the heat energy needed for sublimation of frozen foods to form freeze-dried foods.

An accelerated freeze-drying (AFD) method was developed in Scotland (Hanson 1961). The characteristic feature of the AFD method is to supply

Table 9.3. Typical Wet-Weight Loading and Drying Time in Freeze Drier

Raw material	Drying ratio[a]	Loading (kg/m^2)	Drying time (hr)
Broad beans	4.5:1	7.3	8.5
Brussels sprouts	8.6:1	9.8	9.0
Cabbage	13.2:1	9.8	9.5
Carrots (diced)	10.0:1	9.8	9.0
Cauliflower	11.0:1	7.3	8.5
French beans	10.0:1	9.8	8.5
Peas	4.6:1	9.8	8.0
Potato chips	5.0:1	7.3	8.0
Strawberries	15.0:1	8.5	9.0

Source: Hanson (1961)
[a]The ratio of initial weight:final weight.

color stability is best at a product moisture content slightly higher. Oxidation of carotene and lycopene is most severe below this value. The color and odor stability of green peppers is better at a moisture context of 1.6%, the monolayer value, than above or below this value. The color of precooked freeze-dried carrots is best at 5.8% moisture, which is considerably above the monolayer value of 1.8% for this product; however, ascorbic acid is lost at this high value.

The lower the moisture content of a dehydrated product, the longer its storage life at high temperatures. Lowering the moisture content of cabbage, for example, from 5 to 3% doubles its storage life at 37°C. Accelerated freeze-drying gives products with quite low moisture contents, and most foods can now be packed with moisture contents of 1–2%. The storage life of such freeze-dried foods is three or four times longer than air-dried foods of 5 or 6% moisture content.

Mircoorganisms. Freeze-dried products, except those pasteurized during pretreatments, contain the same microorganisms that are present before drying. When dried in a mixed state with protein or sugar, microorganisms can survive freeze drying. For example, *Pseudomonas campestis* will die completely in 10 days when dried on a glass plate, but if dried with cabbage seeds it will survive more than a year. Kimura (1964B) reviewed the microorganisms in freeze-dried products, discussing the drying and death rate of *Staphylococcus* and *Micrococcus*. He reported that death rates are proportional to the square root of the oxygen concentration. Except for those that cannot form spores, microorganisms can multiply and reproduce when moisture content in freeze-dried foods is increased.

In general, when the moisture content in foods is below 8%, microorganisms do not grow; when moisture content is above 18%, some microorganisms may reproduce gradually. Ohta and Nakano (1963) measured total bacterial counts in marketed powdered food. They showed that the kinds and number of microorganisms in the products varied with the method of manufacture and packaging and with storage conditions. If the packaging materials are poor, and sanitation in the plants is not carefully controlled, contamination of products with microorganisms will occur.

Vaughn (1970) studied bacteria in dehydrated onions and garlic. He stated that a tolerance requirement for *E. coli* in dehydrated onions and garlic is unnecessary, since onions and garlic contain antimicrobial substances toxic to *E. coli*.

Dehydrated foods made by freeze-drying or vacuum-drying processes may be irradiated with ultraviolet light to decrease bacterial counts. Ethylene oxide has also been used for the pasteurization of freeze-dried cocoa powder, soybean powder and curry powder. Complete pasteurization can be obtained. Tsuruta *et al.* (1963) and Tsuruta (1968) treated such products

with 14 mg/liter ethylene oxide at 20°C for 24 hr; they reported that it was possible to kill 99% of molds and bacteria by this treatment. For gas pasteurization, propylene oxide, chloropicrin, and ethylene dibromide may also be used. These are effective as insecticides, and their killing mechanisms are believed to be due to destruction of the biologically active site of proteins, such as -COOH, -NH_2, -SH, and -OH groups. Each reagent is different in its rate of vaporization, rate of permeation, adsorption into foods, and killing effect. Therefore, they may be used in mixture to make best use of their individual characteristics.

Freeze-dried mushrooms are pasteurized by fumigation in Europe and Japan, but since the reagent is very toxic, safety precautions should be taken. Li *et al.* (1974) conducted experiments to ascertain whether microwave heating could be used to reduce the total bacterial count as well as the moisture content of dehydrated mushrooms. Table 9.7 shows the total bacterial counts of both freeze-dried and hot air-dried samples after exposure to 2450-MHz microwave irradiation. Total bacterial counts were reduced by microwave irradiation, considerably more so for hot air-dried samples than freeze-dried ones. The microwave treatment did not affect palatability of freeze-dried mushrooms.

Packaging Materials

Cartons, cans, glass containers, and pouches can be used to package dehydrated foods. The final package should be inexpensive, attractive in appearance, and as nearly insect- and moisture-proof as possible.

Cartons. Most dried vegetables are packed in paper cartons lined with some moisture-proof material (e.g., waxed paper, paper parchment) or, preferably, in high-density polyethylene bags that are heat-sealed and placed in cartons. Cartons are overwrapped with tightly fitting lithographed paper, waxed paper, cellulose film, or aluminum foil. Cartons are usually

Table 9.7. Effect of Exposure to Microwave Irradiation (2450 MHz) on Total Bacterial Counts of Freeze-Dried and Hot Air-Dried Mushrooms

	Freeze dried		Hot-air dried	
Exposure time (sec)	Bacterial counts/g	Survival (%)	Bacterial counts/g	Survival (%)
0 (control)	1.0×10^6	100	2.4×10^6	100.0
20	3.8×10^5	38	3.6×10^5	15.0
30	2.1×10^5	21	3.3×10^5	13.8
45	3.0×10^5	30	1.3×10^5	5.4
60	3.0×10^5	30	1.2×10^5	5.0

Source: Li *et al.* (1974).

filled, sealed, and wrapped by standard, readily obtainable automatic machinery.

To destroy all insect life, dehydrated vegetables may be fumigated with methyl bromide as they come off the drying trays, while they are still hot and before insects have had an opportunity to lay their eggs on them; sometimes, they are fumigated after carton packaging,

Two serious objections to cartons for packaging of dehydrated vegetables are their susceptibility to later insect infestation and to penetration of moisture. Pliofilm inner linings, however, can be made practically watertight but not insect-proof. Newly hatched larvae of the Mediterranean meal moth apparently can enter by openings so small as to escape detection by the unaided eye.

As some dried vegetables, owing to higher drying ratios (water content to solids), must bring a higher price than dried fruit, it would seem a justifiable precaution to use insect-proof packages, even at slightly higher packaging cost.

At the time of packing, dried vegetables should not be above 4% moisture, and in some cases a maximum of 3% is preferable.

Cans. An ideal container for dehydrated vegetables is the key-top can such as is used for canned meats and (formerly) for coffee. If the cans are reinforced to prevent collapse under vacuum, or if the cans are tightly filled—as they should be—so that the dried product will support the walls, the filled cans may be sealed under a high vacuum. The vacuum protects against oxidative changes and will kill insect life or prevent its development.

In one method, cans are filled with product, the first seaming operation is applied, and the cans are then heated in live steam for 6–8 min, to be quickly followed by the second sealing operation. After the first sealing operation and during heating, air escapes from the cans; following the second sealing and subsequent cooling, a considerable (but incomplete) vacuum develops. If this method is used, the packer must be certain that the product, before packing, is free of insect life, particularly eggs.

Friction-top cans of the type used for paints are usually insect-proof and reasonably moisture-proof. They have been used very successfully for dried vegetables.

Powdered vegetables should be packed only in airtight tin or glass containers to prevent not only insect infestation but also absorption of moisture with consequent caking. Also, such powders are very susceptible to oxidative changes; hence, exclusion of air as in a vacuum-sealed tin or jar is desirable.

Dehydrated vegetables can also be packed in 5-gal. (18.9-liter) cans of rectangular shape. These cans are filled through a rather small circular opening in the top, which is then sealed by soldering a circular piece of tin over the opening. These containers protect dried products well.

Glass Containers. Glass jars are moisture- and insect-proof. Some can be sealed under vacuum, and they are preferable to other types for dehydrated foods. One great advantage of glass is the visibility of the product; another is the resealability of most glass jars. However, the greater weight and fragility of these containers are disadvantages. Lightweight, rigid plastic jars have appeared in retail trade for such low-density products as dehydrated parsley.

Pouches. Plastic pouches, laminated pouches, and aluminum–film combination pouches may be used for packaging dehydrated vegetables. The selection of packaging materials for each kind of product depends on the length of storage time, justifiable packaging cost, and the quality required of the dehydrated product. Chapter 3 has more information on this type of packaging.

Packagings for Freeze-Dried Products. Freeze- or vacuum-dried foods should be kept in airtight containers made from a material that is impermeable to oxygen and light. Transparent packaging materials are usually unsuitable for this purpose. Because freeze-dried products are fragile, the packaging materials should protect them from mechanical damage (Taylor 1961).

Metal cans meet these criteria and are suitable for freeze-dried foods. Despite their expense, metal cans are extensively used for packaging freeze-dried foods when long-term storage (2 years or more) is of prime concern. Glass containers can also be used. When closed tightly, they can be considered similar in value to metal cans; however, the heavy weight and light-transparent properties of glass present a problem. Commercially, glass is rarely used as a packaging container for freeze-dried foods except for instant coffee or tea and condiments such as freeze-dried chives. Today, aluminum–film combination pouches are widely used instead of metal and glass containers for packaging freeze-dried products. From the point of view of weight and price, they are most desirable as packaging materials. Single, thin plastic films are undesirable because of their high water-vapor permeability as well as gas and light transmission rates. Plastic films are inexpensive and can be easily heat-sealed. They are usually used in laminated form.

Syn and Luh (1965) studied packaging of freeze-dried green asparagus in laminate and aluminum–film combination pouches. The product was packed under air or nitrogen in plastic-laminated (Mylar–saran–polyethylene) or aluminum–film combination (AFC) pouches and tested for storage stability at 0, 20, and 37°C. Samples packed in AFC pouches and stored at 0 and 20°C showed good rehydratability (Fig. 9.12) after 11 months of storage, whereas samples in laminated pouches stored at 20 and 37°C declined in rehydration capacity with storage. Ascorbic acid retention and serum color darkening served as reliable measures of quality changes in the product. Organoleptic evaluation showed that samples packed in AFC pouches under nitrogen and stored at 10 and 20°C received considerably higher flavor scores than those stored at 37°C (Table 9.8). The plastic-laminated packs, because of their permeability to moisture and oxygen, were inferior to AFC packs for quality retention.

Luh and Eidels (1969) compared the color of freeze-dried mushrooms packed in plastic-laminated pouches and AFC pouches. The samples in plastic-laminated pouches darkened faster than those packed in AFC pouches. This was apparently due to the permeability of the former to air. For products packed in AFC pouches, the rate of darkening was slightly faster at 30 than at 20°C.

Daoud and Luh (1967) tested the storage stability of freeze-dried red bell peppers (*Capsicum annuum*, cul. 'California Wonder'). The raw materials were cored, cut into 1.0- to 1.5-in. squares, frozen at −26°C, and freeze-dried to 2.8% moisture content. The freeze-dried product was packed in Mylar–saran–polyethylene plastic-laminated and AFC pouches under nitrogen and stored up to 12 months in the dark at 0, 20, and 30°C. In plastic-

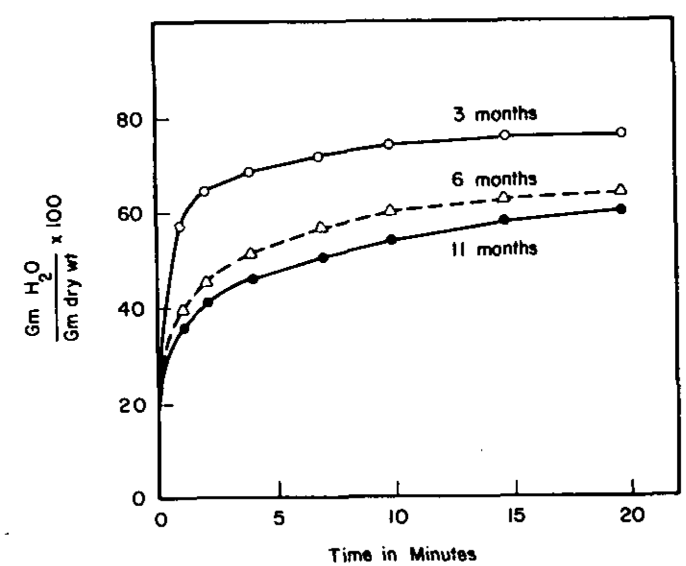

FIG. 9.12. Rehydration curves for freeze-dried asparagus packed under nitrogen in aluminum-film combination pouches and stored at 20°C. (From Syn and Luh 1965.)

Table 9.8. Effect of Packaging Material and Storage Temperature on Organoleptic Evaluation of Freeze-Dried Asparagus After 11 Months of Storage[a]

Packaging material	Storage temp. (°C)	Average organoleptic score[b]: Aroma	Visual color	Flavor
Aluminum film combination	0	8.4	8.6	8.2
Aluminum film combination	20	6.6	7.2	7.1
Mylar-saran-polyethylene	20	4.0	4.4	3.9
Aluminum film combination	37	2.3	2.0	2.0
Mylar-saran-polyethylene	37	2.2	2.9	2.1
LSD at 95% probability level		1.6	1.7	1.7

Source: Syn and Luh (1965).
[a]All samples were packaged under nitrogen. Samples were rehydrated by boiling for 10 min in 1% NaCl solution before evaluation.
[b]Evaluations were based on a hedonic scale of 1 to 10 as follows: excellent, 9-10; good, 7-8; fair, 5-6; poor, 3-4; and very poor, 1-2.

laminated pouches, the moisture content increased in 12 months from 2.8 to 9.7% at 0°C and to 10.8% at 20°C. The AFC pouch was effective in protecting the peppers from moisture, oxygen, and light; storage changes in the product were evaluated by ascorbic acid retention, formation of water-soluble pigments, and decrease in organoleptic scores. Products packed in an atmosphere of nitrogen or under vacuum retained acceptable flavor characteristics for 48 weeks when the temperature did not exceed 4°C.

The following laminates are used for packaging of freeze-dried foods: aluminum foil + polyethylene; cellophane + polyethylene + aluminum foil + polyethylene; paper + polyethylene + aluminum foil + paper + polyethylene; and cellophane + polyethylene + aluminum foil + paper + polyethylene. The laminates differ in water-vapor permeability depending on the nature and order of the plastic layers in the laminates.

In-Package Dessicants and Compression

Use of in-package dessicants to bring moisture content to 2% or lower should permit storage of dehydrated vegetables for extended time without significant loss of vitamins. Fumed silicas at a concentration of 1–2% are recommended in powdered food to prevent agglomerating or caking of spray-dried tomato powder (Salunkhe *et al.* 1974).

Dried vegetables can be compressed into dense bricks or cylinders. These may be wrapped in any suitable manner, for example, in paper with an outer aluminum foil wrap, in cellophane or plastic, or in cartons or cans. If compressed to high density, the products are fairly resistant to insect attack or represent a substantial saving of space. Compression technology utilizes a hydraulic press to reduce product volumes to as little as one-sixteenth of the original volume. Carrots, green beans, spinach, cabbage, and celery have been suggested as suitable for utilizing this new process (Anon. 1982).

Recommended Packaging Practices

Because freeze-dried foods are very hygroscopic, the humidity of the packaging environment is very important. The ideal relative humidity (RH) for the packaging room is about 10%. If the packaging operation proceeds very smoothly and quickly, a 20% RH is good enough; the limiting relative humidity is 40%. A lower temperature in the environment is preferred for packaging. For best efficiency of the operators, the room should be at 20–25°C. Attention should be paid to water vapor from respiration of workers and to their body heat. Naturally, direct sunlight must be avoided.

There are several methods for adjusting humidity, but the best method for keeping packaging rooms at 20% RH is dehumidifying through the use of absorbents. Because of its power to absorb moisture and its ability to regenerate, lithium chloride is commonly used as an absorbent.

Dust is another problem to be considered in packaging rooms. The number of dust particles should be maintained below $400/cm^3$. Various dust-collecting instruments (e.g., cyclones, bag filters, cyclone scrapers, electric dust collectors) are available. A bag filter can be used in the packaging of dehydrated foods; this device is used in combination with a dehumidifier to remove dust, microorganisms, and moisture.

When metal cans and glass jars are used, there is no problem in packaging powdered foods. The shape of solid foods must be protected from mechanical shock during transport. Shock-absorbing materials such as paper with plaits, plastics, or foamed plastics may be used. When flexible-film bags are used for packaging dehydrated products, weight or shock in transport may cause the film to break or develop pinholes. This will allow deterioration by the absorption of moisture. For this reason, a shock-aborbing device may be used, or the bags sealed with air or nitrogen gas to make them resistant to shock.

As noted earlier, dehydrated foods, especially freeze-dried products, containing lipids and fat-soluble components are easily oxidized. Therefore, whatever packaging material is used, the oxygen in the container must be replaced with nitrogen gas. The residual oxygen should be below 2%.

In-package dessicants may be used to lower the moisture content of packaged dehydrated foods. The compounds usually used are lime, activated charcoal, silica gel, etc., sealed in permeable bags. However, use of in-package dessicants is not a widespread commercial practice.

The recommended practices to achieve good packaging of dehydrated foods may be summarized as follows:

- Maintain a 20% RH (40% RH is limiting tolerance) and a temperature of about 20°C in the packing room.
- Avoid dust and direct sunlight.
- Fill container with gas or shock-absorbing material to avoid shock damage and/or breakage in transport.
- Use an in-package dessicant and seal the container with an inert gas or oxygen-absorbing agent to reduce moisture absorption and oxidation.

QUALITY CONTROL

As in the production of other foods, it is highly desirable that operations in a dehydration plant be monitored by laboratory examination of finished products. The most important routine tests are moisture and SO_2 determinations, behavior on rehydration, and cooking of representative samples.

Moisture may be determined in about 10 min with an OHAUS balance (OHAUS Scale Corp., Union, NJ), which uses an infrared lamp and a calibrated dial to indicate weight loss (moisture) in powdered foods. The current standard AOAC vacuum-oven method should be used for calibration. The Karl Fischer titration method is also recommended for moisture determinations on low-moisture products (Joslyn 1970).

Sulfur dioxide residue can be determined by the Monier–Williams method, in which SO_2 is removed by distillation in the presence of HCl and subsequently determined in the distillate by titration (AOAC 1984). The Monier-Williams technique has a detection limit of 50 ppm. The ion-chromatographic technique recommended by Sullivan and Smith (1985) is accurate to 1 ppm, and the analysis time is reduced from 2–3 hr to 25 min.

The particle-size distribution, an important characteristic of powdered products in particular, is determined by a screen analysis. In this procedure, the product is shaken for a specified time (usually 3–5 min) through a series of standard sieves and the residue on each size sieve is determined.

The enzymes peroxidase and catalase have been used as indicators of blanching adequacy prior to dehydration. A variety of methods has been recommended for detection of peroxidase and catalase activity by Cruess (1958) and Joslyn (1970). Some vegetables such as green peas may be over-blanched when peroxidase is used as indicator. Lipoxygenase has been proposed as a new indicator to determine the effectiveness of blanching (Anon. 1984). It takes less than half the heat to destroy lipoxygenase as it does to destroy peroxidase.

Rehydration tests are of considerable value. A 50-g sample taken from tray, bin, or final package is placed in a beaker or jar. For such products as peas, potatoes, corn, and sweet potatoes about 200 ml of cold water is added; for other vegetables, 300–500 ml depending on the drying ratio avoids storage whenever possible. In the plant, beets are prepared in the same manner for dehydration as for canning. However, blanching may not be necessary, and the addition of sulfite has not been found to be beneficial in extending storage life of dehydrated beets. As betanin, the red pigment of beets, is water soluble, such operations as blanching, cutting, and washing should be controlled (Twigg 1957).

The washed, peeled, blanched, and diced beets may be dehydrated in tunnel driers on trays, in continuous conveyor-belt dehydrators, or in belt-trough driers. Relatively high initial air temperatures of 93–99°C may be used, with a maximum second-stage temperature of 71°C. The material is taken from the driers at about 11% moisture and may be finished in bin dryers at 63°C to a final moisture content of 5%.

Howard (1945) found that dehydrated beets dried to a moisture level of 2.4% were of good quality after 48 weeks storage at 38°C. Beets dried to a moisture level of 7% were inedible after 48 weeks at 38°C.

Air-dried 0.95-cm beet cubes may take 45–55 min in boiling water to reconstitute. Explosive puff-drying is used commercially by one company to make quick-cooking beet dice. The dice are blanched for 8 min, hot air-dried to about 45% moisture, then exploded after being heated at 45 psig (3.2 kg/cm^2) steam pressure. The exploded product, which has lost about 5% moisture, is then finish-dried in tray, continuous belt, or belt-trough driers, with air at 94 liters/sec and a temperature of 66°C dry bulb (Cording *et al.* 1963).

Cabbage

The successful preparation of compressed, shelf-stable, dehydrated cabbage (*Brassica oleracea* L.), suitable for use in cole slaw, has been reported by Andres (1977). In this process, fresh cabbage (after washing, coring, and shredding) is blanched to eliminate enzymatic degradation using a hot-air blanching method in a bin air drier. The initial temperature of 93°C is lowered slowly (15 min) to 55°C. Air drying at 55°C is continued until a moisture content of 5% is reached. Before compression, the air-dried cabbage is remoisturized to about 13% using a water mist, then held for 1 hr for equilibration. The remoisturized cabbage then is compressed into 9-cm-diameter disks using pressures between 7.0 and 14.0 kg/cm^2. Disks are then redried in a vacuum oven to less than 5% moisture to assure stability in storage. The disks have approximately the same diameter as a No. 2½ can. Freeze drying was evaluated, but it was found that air drying produced a superior product at a lower cost.

Carrots

Carrots (*Daucus carota* L.) require a long growing season, and their harvesting period is limited. Therefore, if an extension of the dehydrating period after harvest is desired, carrots must be stored. Fortunately, they are readily stored at a temperature close to 0°C. The relative humidity of the storage facilities should be 95% or higher. Well-ventilated underground cellars have proved to be satisfactory for storing carrots. In California, the planting of carrots can be scheduled so that a continuous year-round harvest at prime maturity is possible.

'Imperator' and 'Red Cored Chantenay' are the two principal cultivars of carrots grown in the United States. Practically all the dehydrated carrots currently produced in this country are processed in California from the 'Imperator' or 'Golden Spike' cultivars.

High solids and freedom from woody fiber are desired qualities of carrots to be dehydrated. Dehydration firms may require that raw carrots meet their own specifications or U.S. No. 1 grade (carrots must be orange colored throughout and free from rot, dirt, sunburn, green cores, pithy cores, dry rot or other diseases, or injuries caused by insects, freezing, oil spray, or mechanical damage). Carrots grown for dehydration are larger, more mature, and higher in carotene and solids than fresh-market carrots.

Preparation and Drying Methods. A flow sheet for preparation of dehydrated diced carrots is given in Fig. 9.15. Carrots are first dry-washed in a rotating, slatted cylinder, which removes dirt, trash, and undersized carrots. This dry wash is followed by high-pressure water washing.

Steam or lye methods can be used for peeling. Steam peeling requires about 30 sec at 100 psig (7.0 kg/cm^2), or longer periods at lower pressures. Lye peeling requires about 4 min in 5% lye solution at 99°C. Peeling must be followed by thorough washing with high-pressure water sprays to remove softened peel and any carryover lye. An automatic sorter divides the peeled carrots into large-diameter roots for dicing and smaller-diameter roots for cross-cut slices. Both sizes then pass through automatic topping machines that remove the green crown of the vegetables. Peeled carrots pass over an inspection belt where they are trimmed to remove defects and discolored areas.

Diced carrots are sold in various commercial sizes: $\frac{1}{16} \times \frac{3}{8} \times \frac{3}{8}$ in. (0.16 × 0.95 × 0.95 cm); $\frac{1}{16} \times \frac{1}{4} \times \frac{1}{4}$ in. (0.16 × 0.64 × 0.64 cm); and $\frac{3}{8} \times \frac{3}{8} \times \frac{3}{8}$ in (0.95 × 0.95 × 0.95 cm). Military specifications require half-dice, $\frac{3}{8} \times \frac{3}{8} \times \frac{3}{16}$ in. (0.95 × 0.95 × 0.48 cm) (U.S. Dep. Defense 1962). Cross-cuts—slices made at right angles to the long axis of the carrot—are also currently produced for commercial use in such items as beef stew. Immediately after cutting, the dice are blanched by spreading on a continuous stainless-steel mesh belt at a loading of about 4 lb/ft^2 (1.8 kg/0.1 m^2) and heating in flowing steam for 6–8 min. Adequacy of blanching should be periodically checked by the peroxidase test.

A sulfite solution of 0.9–1.0% concentration, or sufficient to give a concentration of 500–1000 ppm SO_2 in the final product, is sprayed over the

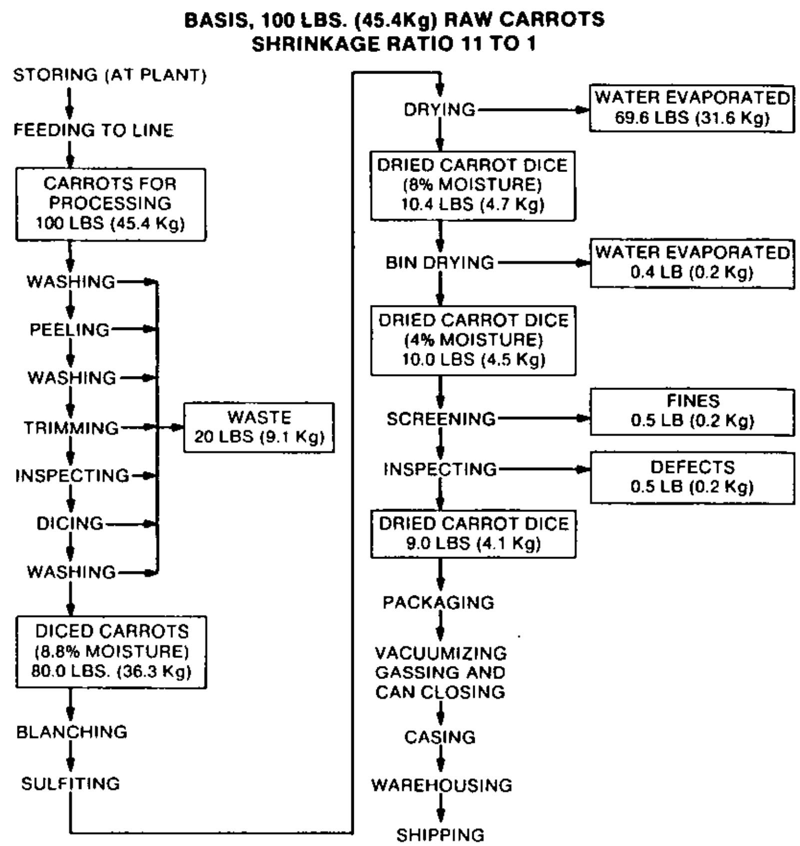

FIG. 9.15. Flow sheet for dehydration of diced carrots. (From Feinberg 1973.)

dice at the discharge end of the blancher. Hendel *et al.* (1953) reported that careless application of sulfite may result in leaching losses of 5–12% of the dry product weight. Alternatively, the blanched dice can be sprayed or coated with a 2.5% cornstarch suspension at 79°C. This latter procedure is now used commercially. Early experiments showed that storage life of starch-coated diced dehydrated carrots sealed in cellophane bags and stored at 29°C was four to six times longer than blanched and sulfited dice stored under similar conditions (Masure *et al.* 1950). Dehydrated carrots that are not starch-coated should be nitrogen-packed to assure good stability. Carotene is easily oxidized, and carrots packed in air, even though blanched and sulfited, lose much of their carotene in a few months (Table 9.9). This oxidation results in loss of color and development of a haylike flavor and an off-odor resembling violets.

The blanched–sulfited or blanched–starched dice are spread onto trays at

Table 9.9. Loss of Carotene in Dehydrated Carrots Stored in Cellophane at 29°C Expressed as Percentages of Initial Content

Processing treatment	Initial carotene content (ppm)	Carotene as % of initial content after storage for			
		1 mo.	3 mo.	6 mo.	9 mo.
Unblanched	1047	52.1	85.8	91.8	93.9
Blanched only	1265	34.2	60.1	70.2	77.4
Blanched and sulfited	1290	32.8	58.8	74.5	81.9
Blanched and starched sprayed	1292	15.0	28.4	36.4	50.1
Control[a]	1290	2.5	6.4	2.7	1.0

Source: Feinberg (1973).
[a]Blanched and sulfited sample, stored in nitrogen at −34°C.

a loading rate of about 0.6 kg/0.1 m^2. Carrots are dried in tunnels or on continuous conveyors to a final moisture content of about 4%. The use of drying-rate nomographs facilitates drier design and estimation of expected drying time for carrot pieces on trays under a wide range of tunnel drying conditions; these have been published by Lazar and Brown (1947).

Single-stage, counterflow tunnels have also been successfully used for drying carrots. Air temperature at the hot end of such tunnels is 71°C. After about 7 hr drying time, the moisture content is reduced from 88 to 8%. An additional 7 hr drying time in drying bins with an air inlet temperature of approximately 60°C is required to bring the moisture content down to 4%. Some dehydrated diced carrots have been commercially produced in continuous belt-trough driers. With this type of equipment, 95% of the original moisture of the carrot can be removed in 50 min.

For military use, dehydrated carrot dice or slices are packed in No. 10 cans. The air in the container is exhausted and replaced with nitrogen or carbon dioxide so that the gas in the sealed container is less than 2% oxygen.

Turkot *et al.* (1965) described a process for dehydrating quick-cooking puffed carrot dice as follows:

> The dice are steam-blanched for 4 min, dipped in a solution containing about ½% each of sodium bisulfite and citric acid, and fed to the first-stage dryer. This is a conventional continuous-belt, steam-heated, hot-air dryer, which reduces moisture content of the dice to approximately 25%. The partially dried dice are next screened to separate small pieces, which are sent directly to the final dryer. These small pieces will rehydrate quickly enough so that they need not be explosive puffed. The remaining dice are conveyed to the feed hopper of the puffing guns. The guns discharge puffed dice into a sloping discharge tunnel from which they are conveyed to the hopper of the feeder for the squeezing rolls. After squeezing, the dice are fed (along with the small pieces) into

the final dryer, which discharges product at about 4% moisture. Following manual inspection for removal of defective pieces, the dice are weighed into fiber drums and taken to storage.

The squeezing step after puffing and before final drying increases the bulk density from about 18 to about 24 lb/ft^3 (8.1 to 10.9 kg/0.03 m^3). This operation reduces packaging and shipping costs. Compressed pieces rehydrate just as rapidly as the uncompressed material.

Stephens and McLemore (1969) prepared a carrot flake with a good typical carrot flavor on rehydration. In their process, fresh, unpeeled carrots were cooked, comminuted, made into a puree, and dried for 35 sec on a double-drum drier set at 0.01-in. (0.25-mm) clearance between drums having a working steam pressure of 30 psig (2.1 kg/cm^2). Flakes prepared from the dried product and canned with nitrogen in the headspace retained good quality for 24 months at 20°C. Carrot flakes are used for dry soup and sauce mixes, canned soup, baby food, and as a coloring agent for specialty foods.

For better quality, carrots are freeze-dried. As carrots have a high sugar content, it has been found that very low temperatures are necessary in order to ensure complete freezing; a temperature of −33°C is desirable, requiring an absolute pressure of about 0.2 mm Hg. If the vacuum equipment attached to the drier is not capable of producing a vacuum of this order, it is necessary to freeze the material in some form of blast freezer before it is placed in the drying cabinet.

Effect of Processing Variables. Blanched pieces of air-dried and freeze-dried carrot were examined histologically by Pendlington and Ward (1962). Total cell collapse was common in all of the air-dried vegetable tissue. The freeze-dried tissue showed no cell collapse, but considerable cell wall rupture.

The effect of processing variables on the cell structure and physical characteristics of carrots were determined by Rahman *et al.* (1971). The phloem portion of fresh carrots was subjected to one of the following treatments: blanching; cooking for 10 min; freezing at −17.8°C to −34.4°C (blast freezing) or −195°C (liquid nitrogen immersion); freeze drying; compressing after freeze drying at approximately 1500 psi (105 kg/cm^2). The treated carrots were tested for (1) texture by means of an Allo-Kramer shear press; (2) water-holding capacity by centrifuging at 500, 1000, 1500, 2000 and 2500 rpm; and (3) histological changes by microscopic observation of the tissue structure. Of all the treatments, freezing temperature was the most critical factor affecting carrot cell structure. Freezing at −17.8 or −34.4°C resulted in considerable disruption of the cellular structure, whereas it was minimal at −195°C. Carrots frozen at −195°C showed firmer texture as well as higher water-holding capacity than the rest. A significant correlation coefficient was established between shear press values and percentage weight loss measured by centrifugation. This suggests that the latter may be used as an objective test for measuring textural changes in processed carrots.

Shibasaki *et al.* (1964) determined the hygroscopicity of freeze-dried vacuum-dried, and hot air-dried carrots. Freeze-dried carrots had the highest hygroscopicity. When freeze-dried carrots were stored at various relative humidities, their hygroscopicity decreased during storage, especially at high relative humidities.

Ayers *et al.* (1964) reported the formation of an off-odor in accelerated freeze-dried carrots stored in the presence of oxygen. A systematic analysis revealed that the compounds mainly responsible for the off-odor were α- and β-ionones and β-ionone-5,6-epoxide.

Carrot volatiles were investigated by Heatherbell *et al.* (1971) and Heatherbell and Wrolstad (1971). According to their reports, freeze drying resulted in an approximate 75% loss of the total volatile content. Twenty-three volatile compounds were identified in the raw carrots. Differences in volatile composition among canned, freeze-dried, and raw carrots were quantitative rather than qualitative.

Shibasaki and Asano (1965) freeze-dried carrots at −20, −78.5, and −195.5°C. The freeze-dried carrots were compared with heat-dried and vacuum-dried carrots. Carrots frozen at −20°C showed no appreciable changes in quality. Rehydration was better with the freeze-dried carrots than with the vacuum-dried ones.

Lewin and Mateles (1962) made a preliminary investigation on freeze drying without vacuum. Frozen diced carrots were dehydrated in a flow of desiccated air. Dehydration was rapid when the air temperature was approximately −4 to −1°C. Although drying rates were greater at 60°C than at freezing temperature, products dried at the high temperature lacked flavor and odor, and showed more distortion and shrinkage than freeze-dried carrots. Freeze drying without vacuum offers certain advantages over any other dehydration method. Color, odor, and flavor are maintained relatively well, since temperatures are kept low.

Changes in carotenoids in freeze-dried carrot powders stored at different water activities (a_w 0.0–7.3) were reported by Arya *et al.* (1979). The carrots were blanched prior to drying and the dried products were packed in paper–aluminum foil–polyethylene laminates and kept at room temperature. Carotenoids were found to be more stable in the range of 0.32–0.57 a_w; maximum stability was near 0.43 a_w. Dipping in a salt solution (5%), sodium metabisulfate (0.1%), and Embanox (0.1%) significantly reduced the rate of carotenoid destruction and nonenzymatic browning of dehydrated carrots.

Celery

Dehydrated celery (*Apium graveolens dulce* L.) is commercially available as ⅜-in. (0.95-cm) stalk dice, stalk and leaf flakes, stalk and leaf granules, and powder. These various products are used in dry soup mixes, broth base for canned tuna, poultry stuffings, potato salad, canned stewed tomatoes, and camping and survival packs. Celery usually is dehydrated by conventional methods. Dehydrated celery products rehydrate very poorly under the usual rehydration conditions. For example, rehydration by conventional procedures restores less than one-third of the weight of fresh cross-cut ¼-in. (0.6-cm) slices, and the individual pieces do not regain their original shape or form.

Celery may be classed by color as either green or golden. Green celery is divided into 'Utah' and 'Pascal' cultivars and several subcultivars. 'Pascal' cultivars are favored for dehydration.

Celery is a relatively perishable commodity. For storage of 2–3 months, it should be kept at −0.5 to 0°C. As is true for most vegetables to be dehydrated, moving the produce directly from field to plant is the most desirable practice.

Prior to dicing and slicing, celery is inspected and thoroughly washed. Then it is fed through mechanical cutters that remove any desired portion of the stalk from the celery head and divert it to the manufacture of either celery stalk dice or to celery stalk and leaf flakes. The leafy portion of the celery is cut to specified size, and the leaves are separated from the stalk portion. At this point the two streams of material are diverted, the stalks being conveyed to dicing equipment and the leaves to slicers. Sulfite-bisulfite solution is sprayed over the dice to give a final SO_2 content of 500–1000 ppm.

To dry celery in a two-stage tunnel drier system, initial dry-bulb temperatures of 82°C in the hot end of the first stage (parallel-flow) and 54°C in the second stage (counterflow) have been recommended.

A technique using superheated steam, which produced puffed celery in a shorter time at lower costs than tunnel drying, was described by Sullivan and Cording (1969). Stalks were cut into 3/16-in. (0.48-cm) slices and blanched for 6 min in 0.5% sodium bicarbonate to give a higher pH and preserve the green color. After blanching, the slices were dipped for 0.5 min in a 0.2% sodium bisulfite solution. Following air drying to 35–50% moisture, the slices were held overnight at 3°C in plastic bags to equilibrate the remaining moisture. The slices were then exploded from the pressure chamber at 35 psig (2.5 kg/cm^2) and returned to the drier for final drying to 4% moisture.

To improve the texture of dehydrated celery. Shipman *et al.* (1972) recommended an 18-hr soaking of ¼-in. (0.6-cm) cross-cut fresh celery stalks in aqueous glycerol solution prior to dehydration. The glycerol-treated products were subsequently air-dried to approximately 4% moisture; when rehydrated, the textural characteristics of the product approached those of fresh celery.

Sliced celery—⅛-in. (0.3-cm) slices cut at right angles to the stalk—contains string lengths of ⅛ in. (0.3 cm). Compared with dehydrated diced celery—having ⅜-in. (0.95-cm) string lengths—dehydrated sliced celery has substantially better texture and faster rehydration rate.

Wilson (1965) dehydrated celery by the explosion-puffing technique. After blanching and freezing, celery was partially dried to 65–66% moisture and exploded at 30 psi (2.1 kg/cm^2). Freezing and puffing reduced total drying time by approximately half. Puffing improved the texture, appearance, and degree of rehydration over that of conventionally dehydrated celery, although fiber toughness remained about the same. Freezing and puffing further improved the texture and appearance to approximate that of freshly boiled celery, and increased the degree of rehydration two- to threefold over that of celery receiving only the puffing treatment. Taste panel ratings indicated increased acceptance with an increase in the degree of rehydration or coefficient of weight restoration.

Neubert *et al.* (1968) in studies on celery rehydration found that swirling agitation produced by moving a screen in a reciprocating, rotary motion was the only method that resulted in good rehydration of conventionally dried celery.

Neumann (1972) treated celery before air drying with either sucrose, dextrose, sorbitol, or glycerol. Such pretreated dried celery had better reconstitution characteristics (e.g., increased weight, larger size, fuller shape, and a crisper, more tender texture) than dried, untreated celery.

Because of its high water content, celery undergoes an unusually great amount of shrinkage during freeze drying. This shrinkage is accompanied by unusually severe deformation. Freeze-dried celery rehydrates to a mushy, unacceptable product due mostly to tissue damage during freezing.

Corn

Almost any variety of corn (*Zea mays* L.) suitable for canning or freezing should prove satisfactory for dehydrating. Yellow cultivars such as 'Golden Cross Bantam' are preferred. Watson *et al.* (1979) found that the 'Jubilee' cultivars scored highest in taste panel tests over several other dehydrated products.

Corn should be harvested when still tender and the kernels full of "milk." The ears are mechanically harvested, quickly hauled to the processing plant, and automatically dehusked and desilked. The kernels are cut from the cob and blanched for 2 min in atmospheric steam. The blanched corn is either dipped into, or sprayed with, a sulfite–bisulfite solution adjusted to a pH of about 6.7 and of sufficient concentration to produce a residual SO_2 content of approximately 2000 ppm in the final dried product.

A high concentration of sulfur dioxide in the dried product is an important factor determining sensory quality and storage stability (Nelson *et al.* 1954; Watson *et al.* 1979). Von Loesecke (1955) reported that carotenoids of sweet corn tend to bleach on storage and that this bleaching was believed to be due to selective absorption of sulfur dioxide by the kernels. However, Wilson and MacKinney (1961) found no demonstrable change in carotenoid content after storage of sulfited and unsulfited dehydrated sweet corn prepared from raw material of various maturities. Hayes *et al.* (1956) reported that puncturing the kernels before exposure to sulfite solution resulted in more than 50% increase in the uptake of sulfur dioxide in the dried product.

Sweet corn may be dried in tray-tunnel driers or continuous-belt driers. In a two-stage tunnel-drying system, a dry-bulb temperature of 82°C for air entering the first (parallel flow) stage and 74°C for air entering the second (counterflow) stage has been recommended. The partially dried kernels may be taken from the second stage and dried to a final moisture content of 5% in a bin drier. Pieces of cob, silk, or kernel fragments may be removed by aspiration after drying. The belt-trough drier should be useful for air drying corn.

Garlic

Virtually all U.S. garlic production is in California. To meet the increasing interest in gourmet cooking and prepared foods, the production of garlic has increased markedly in recent years.

The principal garlic cultivars grown for dehydration are 'California Late' (Pink or Italian), 'California Early' (White or Mexican), and 'Creole.' Because of the problem of nematode transmission in the planting stock, there is an increasing tendency to use stock that has been inspected and certified by a state agency to be free from disease and pests. As garlic is an expensive crop to grow, most acreage for dehydration is grown on a contract basis.

Garlic (*Allium sativum*) is propagated vegetatively by planting individual garlic cloves. The harvest season in California is from May to August. Garlic bulbs are extremely delicate and bruise easily, losing quality. Caution must be taken during harvest to ensure gentle handling. The first harvesting step is to mow the fields and cut off the dried tops of the garlic bulbs close to the ground. After the field is sprinkled to soften the soil, the roots are mechanically undercut with a sharp blade pushed through the soil below the garlic bulbs. The bulbs are then carefully scooped up and deposited on soft ground. Bulbs are loaded into sacks by hand after sorting out damaged ones in the field.

After grading, garlic is brought to the dehydration plant in 100-lb (45-kg) open-mesh bags or in large bulk bins holding about 1000 lb (454 kg). Garlic stores well under a wide range of temperatures, so that controlled-temperature storage usually is not necessary. At temperatures near 4.5°C garlic tends to sprout, so long storage near this temperature should be avoided. When the relative humidity is higher than 70%, mold may grow on garlic bulbs.

Garlic bulbs, which consist of 6 to 36 cloves, are broken into individual cloves by passing them between rubber-covered rollers that exert just enough pressure to crack the bulb without crushing the cloves. The loose "paper-shell" is removed by screening and aspirating. The cloves are then washed in a flood washer at which time the root stubs are floated off. Garlic is sliced and dehydrated in a manner similar to that used for onions, which is described in a later section. After drying, the pink skin that adheres tightly to fresh cloves can be removed by screening and air-aspiration. Garlic is commercially dried to about 6.5% moisture.

Dehydrated garlic is sold commercially as powder, as granules, or in sliced, chopped, or minced form. Packaging is similar to that used for onions. It is widely used in the formulation of spice mixtures for luncheon meats, salad dressings, sauce, soup mixes, garlic salt, pet foods, etc.

Green Beans

Green beans (*Phaseolus vulgaris* L.) may be dehydrated soon after harvesting, or frozen and held for dehydration at more convenient times. These two operations may be performed at the same plant, or a separate freezing plant may prepare beans for delivery to a dehydration plant.

Beans are delivered to the processor in bulk bins, dumped, graded for size, sorted for defects, and mechanically snipped to remove the pod ends. These operations are the same as those customarily performed in canning and freezing green beans. The beans are washed, either before or after these operations. Sizing of beans according to diameter by automatic graders is a routine operation in processing. Sizes 1, 2, and 3 have been found to rehydrate poorly, while sizes 6 or larger are usually fibrous. Sizes 4 and 5 ($^{21}/_{64}$ in. (0.8 cm) to, but not including, $^{27}/_{64}$ in. (1.1 cm) thick) yield a good rehydrated product both in appearance and quality, and are specified in current military specifications for this item.

The snipped pods are cut transversely into segments approximately 1 in. (2.54 cm) long for cross-cut beans or transversely into 1½-in. (3.81-cm) segments, and then sliced lengthwise for French style. The cut beans are steam-blanched for about 4 min and promptly cooled with water sprays. A sulfite–bisulfite solution is sprayed over the blanched material to produce a sulfur dioxide content of about 500 ppm in the final-dried product. Blanched, sulfited cut beans are frozen for later dehydration.

U.S. military procurement specifications for dehydrated green beans require that "the product [cross-cut dehydrated green beans] shall rehydrate and cook to approximately the original [cut] from . . . when 1 oz [28.4 g] of the dehydrated product is added to 16 fluid ounces [473 ml] of distilled water, brought slowly to a boil in 20 minutes and simmered for such time as necessary—not to exceed 30 minutes—to produce a tender product. The rehydration of the product . . . one part yields seven to eight parts by weight of reconstituted and cooked beans" (U.S. Dep. Defense 1966).

"Precooked" dehydrated green beans—prepared by extending the blanching operation until the beans have been completely cooked, then freezing and dehydrating them—have been successfully manufactured. This product is ready to serve after the addition of boiling water and a 15-min holding time.

Freeze drying of blanched green beans has been reported by Foda *et al.* (1967). In a comparative study of the effects of processing on the chemical and organoleptic characteristics of green beans, they found that beans blanched in sodium bicarbonate solutions and then dehydrated contained more chlorophyll and less carotene and ascorbic acid than beans blanched in water or steam. Freeze-dried beans reconstituted rapidly, in either cold or hot water, to a shape and size similar to fresh beans. Beans packed in metal containers were generally higher in quality than those packed in either polyethylene bags or paper cartons.

Horseradish

Horseradish (*Armoracia lapathifolia* Gilib) is grown mainly in Missouri, Illinois, Wisconsin, and California. The yield of roots is about 3 tons/acre. The 'Malineer Kren' and 'Bohemian' cultivars are of better quality than common or "regular" horseradish (Knott 1949).

Horseradish plants are topped before harvesting, and the roots are removed by plowing. The roots can be held for 10 months under cold storage at 0°C and a relative humidity over 95%. They are frequently stored in cool cellars or in trenches lined with clean, dry straw and covered with soil and straw to protect the roots from freezing. Horseradish roots should be stored in the dark because they turn green upon exposure to light.

The pungency of grated horseradish is due to a volatile oil produced by enzymatic hydrolysis of a glucoside. The glucoside has been reported to be sinigrin, which yields allyl isothiocyanate upon hydrolysis by the enzyme myrosin (Jacobs 1951). The enzyme and substrate are distinctly separated in the plant cell. When the plant tissue is cut, bruised, or crushed, the enzyme and substrate can react to liberate various end products. In the case of horseradish, no pungent or flavorful oil is produced until the appropriate enzymatic action takes place. If the horseradish root is blanched or cooked, the natural enzymes are destroyed and no flavor-producing substances can

be formed in subsequent slicing or grinding. For this reason, when horseradish is dehydrated, the enzymes must not be destroyed by blanching or inhibited by sulfiting.

Crushing of the plant tissue must be kept to a minimum during the predrying operations so that the formation of volatile allyl isothiocyanate and other flavorful components, and their subsequent loss during drying, is minimized. When the horseradish root is sliced for drying, only a small proportion of cells are broken. The dried slices are ground into a powder or into small granules. Although the grinding ruptures the plant cells, liberating enzyme and substrate, no allyl isothiocyanate is formed, since the enzyme reaction requires water. For this reason, dried horseradish powder is almost tasteless, yet when mixed with water and allowed to stand a few minutes, it becomes extremely pungent.

Horseradish roots must be thoroughly washed by high-pressure sprays and scoured with stiff brushes or other mechanical means because they are not peeled before drying. The roots are sliced about ¼ in. (0.6 cm) thick and tray-dried. Two-stage tunnels have been recommended, the first stage being parallel flow with a relatively low inlet temperature of about 66°C; an inlet temperature of about 57°C can be used in the secondary counterflow stage. The slices are removed at about 7–8% moisture content and are dried to a final moisture content of 5% in a bin drier. The dried slices are then milled into a powder or granules. Horseradish powder is used as an ingredient for cocktail and fish sauces, horseradish mustard, or horseradish dressings.

Mushrooms

Approximately two-thirds of the U.S. mushroom-growing and -processing industry is located in Pennsylvania, New York, Delaware, and Maryland. In recent years, California and Oregon have become important mushroom-producing states.

The cultivated white mushroom, *Agaricus bisporus*, is also referred to as *Agaricus campestris* L. or *Psalliota campestris*.

References on air drying of mushrooms (Cruess and MacKinney, 1943; Von Loesecke, 1955; Lambert, 1963; Cruess and Mrak, 1942) recommend the following practices: (a) use only cultivated mushrooms (*A. bisporus*); (b) wash thoroughly; (c) dry either whole or diced; (d) blanch in steam or boiling water for 2–5 min; and (e) dry to about 5% moisture, using a finishing temperature of not more than 66°C. Cruess and Mrak (1942) stated that unblanched dried mushrooms, while more attractive in appearance, were inferior in flavor and cooking quality to blanched ones.

After the first "pinhead" mushrooms appear in a mushroom bed, the crop goes through a characteristic cycle. Batches of mushrooms appear in sudden outbreaks at invervals of approximately 10 days to 2 weeks. These outbreaks are called "flushes" or "breaks" and are followed by periods in which only a few mushrooms appear on the bed. A mushroom crop consists of 4 or 5 breaks during a 2- to 3-month period. When production becomes so small as to be uneconomical, the mushroom beds are cleaned and new beds prepared.

Komanowsky *et al.*, (1970) found that discoloration in air-dried mushrooms increased drastically as the raw material came from successively later breaks. This was thought to be related to increasing tyrosine content in the mushrooms from the first to the fourth break.

To reduce the bacterial count on fresh mushrooms (more than 1 million/g tissue), Komanowsky *et al.* (1970) reversed the usual procedure for air drying vegetables. Instead of a first-stage at high temperature (e.g., 77°C) and finishing at a lower temperature (60°C), they found that treating mushroom slices for 5–10 min in solutions of 400 ppm Cl_2 and 300 ppm SO_2, then drying at 43°C for 4 hr, followed by a second-stage drying for 1 hr at 77°C produced a dried product with attractive light color and a bacterial count of less than 7000/g. An end product with good flavor and stability, and a better color and shape, was obtained by dehydrating mushrooms unblanched.

Freeze-Dried Mushrooms. Mushrooms are one of the important vegetables preserved by freeze drying. Fang *et al.* (1971) studied the effects of blanching, chemical treatments, and freezing methods on the quality of freeze-dried mushrooms. In their experiments, mushrooms were cut into slices about 5 mm thick. The polyphenoloxidase activity in the sliced mushrooms was inhibited by (a) dipping in sodium metabisulfite solution 200 ppm SO_2; (b) dipping in 2% NaCl solution; or (c) blanching in boiling water for 2 min, followed by evaporative cooling. The products were frozen with Freon-12 at −30°C for 60 sec, then dried to 3% moisture in a Stokes freeze drier. The freeze-dried product made by the Freon-dipping process was better in texture than that made by a slow-freezing process. Blanching the fresh mushrooms in boiling water for 2 min before freezing resulted in a lighter color in the freeze-dried product after rehydration than did the dipping treatments; however, the blanched product was less attractive in flavor and texture. The blanching process, furthermore, caused considerable loss of water-soluble solids and ascorbic acid.

Luh and Eidels (1969) reported on the storage stability and chemical changes in freeze-dried mushroom slices packed in plastic-laminated and aluminum–film combination (AFC) pouches. The effects of steam blanching and sulfite treatment on the quality of the freeze-dried products were compared. The untreated samples were darker in color than the blanched samples, and the latter darker than the sulfite-treated samples. In all cases, the color was more intense after 8 months of storage than after 2 months. An increase in storage temperature and time caused an increase in color intensity of the rehydration water. For better quality retention, it is desirable to pack freeze-dried mushrooms in aluminum-foil combination pouches under nitrogen and to store the product at 20°C or lower.

Yeh (1971) compared mushroom slices made by air drying with those made by freeze drying (Fig. 9.16) and concluded that unblanched air-dried mushrooms were inferior in texture to freeze-dried mushrooms. Freeze-dried mushrooms also rehydrated better and quicker than air-dried ones. The unblanched mushrooms, both air-dried and freeze-dried, showed rapid discoloration after rehydration. Shear press values and sensory scores of dried mushrooms obtained in this study are presented in Fig. 9.17. In a review of the techniques and problems of freeze drying, Namizaki (1968) reported that the maximum surface temperature permissible for sliced mushrooms of 15-mm thickness without damaging their quality is 82°C.

Commercial Process for Making Freeze-Dried Mushroom Slices. The procedure for freeze drying mushrooms used by one commercial plant involves the following steps in sequence: delivery of fresh mushrooms, washing, bleaching, slicing, sorting, freezing, freeze drying, and packaging. After harvest, mushrooms should be processed promptly, preferably within 3 hr; otherwise, one may not get a product of superior quality. Thorough soaking in water by spraying with water from a full-cone nozzle sprayer at 20–30 lb (9–13.6 kg) pressure is advisable. Because harvested mushrooms may change color as a result of enzymatic browning, a sodium metabisulfite

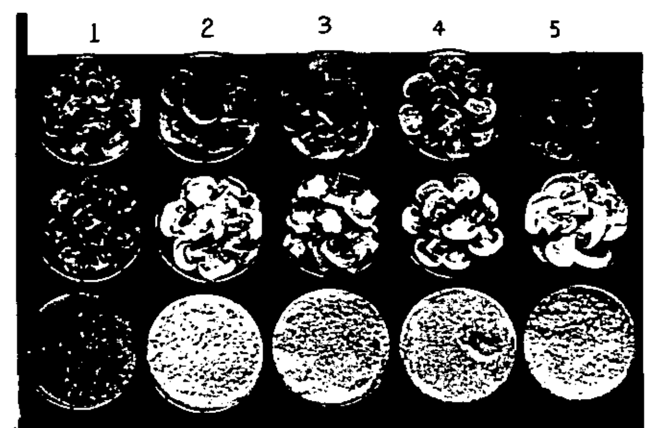

FIG. 9.16. Mushrooms dried by various methods. 1—blanched air-dried; 2 and 3—unblanched air-dried; 4—blanched freeze-dried; and 5—unblanched freeze-dried. *Top row*—rehydrated in 25°C water for 1 hr; *middle row*—dried mushrooms; and *bottom row*—mushroom powder. (From Yeh 1971.)

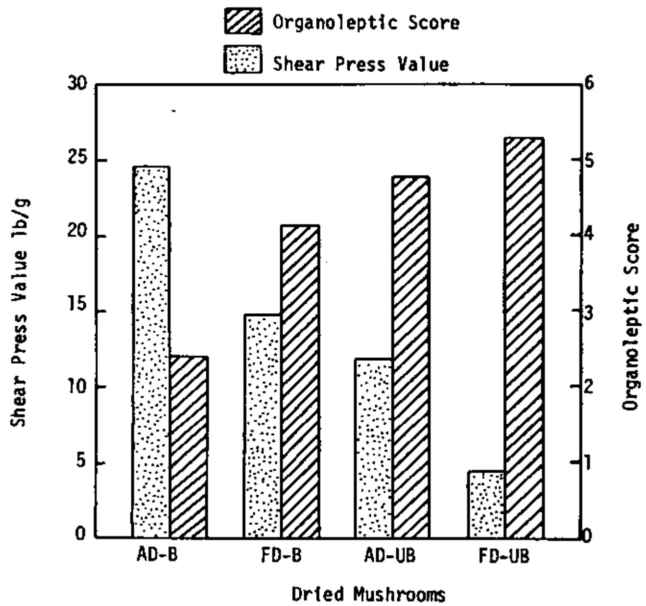

FIG. 9.17. Shear press values and organoleptic scores of mushrooms dried by various methods. AD-B, air-dried blanched; FD-B, freeze-dried blanched; AD-UB, air-dried unblanched; and FD-UB, freeze-dried unblanched. (From Yeh 1971.)

is sometimes added to the wash water to bleach the mushrooms. In general, the SO_2 content is limited to 200 ppm in the product. Some buyers do not allow the use of sodium metabisulfite.

Slicing mushrooms by machine causes crushing, damage, and loss of product. In places where labor is comparatively less expensive, mushrooms are sliced by a hand-operated slicer. The thickness of the mushroom slice is adjusted to 5 mm. Broken and undesirable slices are removed in a sorting operation. Loading sliced mushrooms onto trays is a critical step. If the load is not uniform, burning or incomplete drying of a part of the product will occur. Trays are usually 0.35 m^2 (3.76 ft^2), and the load on each tray is about 3 kg. In general, a layer 1 cm thick is preferred. The mushroom slices on trays are sent to a cold room for freezing. The faster the raw material is frozen, the better the quality of the final product will be. When the slices reach −25 to −30°C, they may be sent to the chamber for freeze drying. It usually takes 4–6 hr to complete the freezing process. When the ice on the surface of the mushroom slices disappears, application of heat can be started. Typical temperature changes during freeze drying of mushrooms are presented in Fig. 9.18.

The freeze-dried product obtained by this process contains about 3% moisture. Some buyers require the total bacterial count to be under

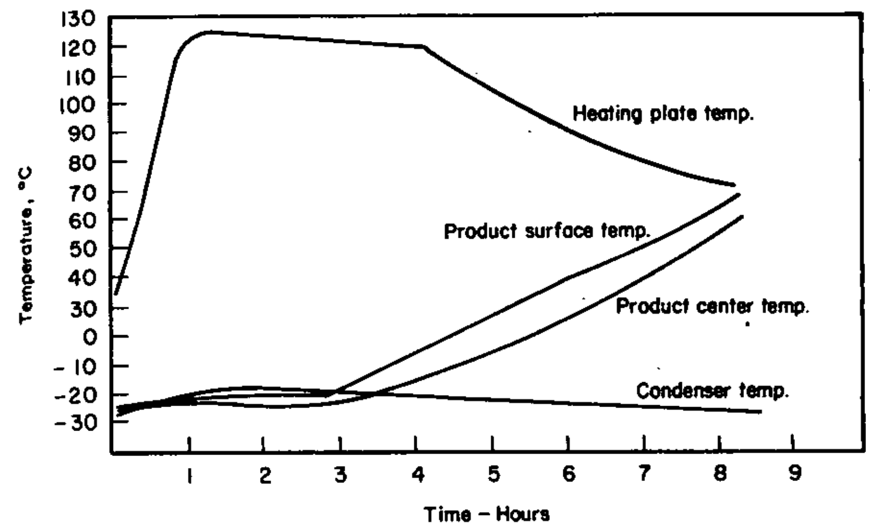

FIG. 9.18. Temperature changes during freeze drying of mushrooms. (Courtesy Dragon Gate Food Corp.)

100,000/g. From 12 kg of raw mushrooms, 1 kg of freeze-dried product is obtained. After reconstitution, 1 kg of the freeze-dried product yields 8 kg of reconstituted product. The freeze-dried product is usually packed in air-tight and moisture-proof containers under nitrogen. Steel drums with enamelled lining, aluminum cans, or aluminum-foil combination pouches can be used for packaging.

Production in Foreign Countries. Most of the commercial dried mushrooms of the world are derived from species of *Boletus,* a thick, fleshy mushroom with pores on the underside of the cap instead of the gills characteristic of *A. bisporus.*

Substantial quantities of mushrooms are imported to the United States; imports are estimated at about 1 million lb (454,000 kg) dried product per year. About 80% of these come from Chile (*Boletus luteus*) and Japan (*Lentinus edodes*). Smaller quantities of air-dried *Boletus edulis* are imported from West Germany, Rumania, and other countries. Both *A. bisporus* and *L. edodes* are cultivated mushrooms.

In Europe, the most important of the wild mushrooms for drying is *B. edulis.* In the dried form, it is used as an ingredient for dry soup mixes. The production of this species has dropped during the past few years.

Boletus luteus is the most important mushroom in South America for drying. A thriving dried-mushroom industry has developed in Chile as a by-product of the government program for reforestation. *Boletus luteus* appears to grow luxuriantly in young pine forests, reaching a production peak about 5 years after the trees are planted. When the forests are about 15 years old, mushroom production drops to an uneconomical level. Mushrooms are collected and sundried to about 15–20% moisture. These predried mushrooms are packed in burlap bags, held for a short time in temporary warehouses, and then taken to a central drying plant. Here the mushrooms are fumigated, cleaned by screening and aspiration, and sorted to remove dirt and foreign matter. This cleaning operation is a dry process, and no wet wash is used. The mushrooms are then sliced, spread on trays, and tunnel-dried. The drying cycle applied in Chile is reported to begin with a relatively low air temperature of about 49°C, increasing to a final drying temperature of 71°C. The final moisture content is approximately 10%.

During the predrying process, *B. luteus* develops soluble brown pigments and a strong flavor quite different from that associated with the cultivated *A. bisporus*. This color and flavor make *B. luteus* products unsuitable for light or cream-colored dishes; when used in other dishes, however, the flavor and texture of these dried mushrooms are pleasing to many people.

Onions

There are more than 250 members of the genus *Allium*, the onion family. Two of these, onions (*A. cepa*) and garlic (*A. sativum*), have been important dehydrated vegetables for many years. The recent growth in popularity of dehydrated soups and specialty items has stimulated increased production of dehydrated green onions and leeks (*A. porrus*).

The major onion-producing countries of the world are the United States, Egypt, Japan, Taiwan, Turkey, Italy, and Sudan; these account for approximately 60% of the reported world commercial onion crop.

The convenience and quality of today's commercial dehydrated onion products have earned them a large market. Tomato catsup contains about 1% fresh onion equivalent by weight, and chili sauce contains up to 4%. The U.S. catsup and chili sauce industries use approximately 1 million lb (454,000 kg) of dehydrated onion annually; more than 500,000 lb (227,000 kg) are used annually in comminuted meat products. Although some dehydrated onion is sold in small containers in retail stores, most goes for institutional use and remanufacture. Sauces, soups, mayonnaise, salad dressing, pickles, and pet food contain dehydrated onions as a component.

Good-quality raw material assumes a special importance in the production of dehydrated onions. Commercial plants have reported shrinkage ratios ranging from 7:1 to 17:1. This wide range may be caused by differences in (a) solids content of onions, which varies with cultivar and cultural practices; (b) deterioration of onions in storage; (c) damage from sunburn caused by leaving the harvested onions exposed to the sun; (d) rain damage either to harvested onions or to onions still in the ground; (e) maturity of onions at harvest; and (f) processing methods.

Raw-Material Characteristics and Cultivars. Onions to be dehydrated should be high in solids content. Common onion cultivars range from 5 to 20% solids content (Stephenson 1950). The cost of processing per pound of dehydrated product is largely determined by the total solids content.

Larger bulbs are desired for economy in field harvesting and plant preparation. The neck and roots must be trimmed off during processing; thus a full-globe to tall-globe shape is preferred over the flat or flat-globe shape to permit greater efficiency in rooting and topping.

The onion should be high in pungency because the dehydrated product is primarily used as a flavoring agent, and some of its pungency is lost during the dehydration process. The residual pungency of the dehydrated product is determined by the original pungency of the raw material and the skill employed in processing. Enzymatic action responsible for the characteristic odor and flavor of onions also forms pyruvic acid. Determination of pyruvic acid in freshly prepared onion juice constitutes a fairly reliable, simple, and convenient estimate of at least one aspect of onion flavor intensity in the raw material (Schwimmer and Guadagni 1962).

Bulbs should have white flesh and preferably a white skin. Yellow and red cultivars have been used commercially, although they are usually less desirable. Only 15% of the onions grown in the United States are white onions, and of these only one-third are pungent cultivars considered desirable for dehydration. Good-quality bulbs can be kept in common storage for 2 or 3 months with a minimum of rot, shrinkage, or sprouting.

An onion dehydration plant should be located within economical hauling distance of sufficient raw material to supply its needs over a long operating season. The cultivars chosen should meet as many as possible of the quality requirements just listed.

'Southport White Globe' is the cultivar most widely used for dehydration. In central California it is seeded from November 1 through April and harvested from July through October. It can be held in common storage through December. This cultivar is considered to be midseason to late. It is high in pungency and solids. 'White Creole' is grown in the Imperial Valley of California for dehydration. It is very early-maturing, high in solids, and stores well.

The introduction of male-sterile onion cultivars in recent years has made economically practicable the production of hybrid onions. One of these, 'Dehydrator Hybrid,' is an early cultivar grown commercially for dehydration in southern California and the Imperial Valley.

Harvesting, Curing, and Storage. A tractor with specially designed knives goes through onion fields several days before the harvesting operation to cut the roots several inches under the onion bulbs. This practice speeds up the drying process and also helps increase the solids content through absorption of sugar in the tops back into the bulb.

While onion bulbs are still in the soil and after the tops have dried down, mechanical cutters remove the dry tops near the neck of bulbs. This prepares onions for digging and loading so that only clean onion bulbs are brought to the plant.

Onion bulbs are dug up by a special digger that lifts them out of the ground, conveys them to the back of the machine, and deposits them on the top of the bed, taking care to avoid bruising them. After digging, a bulk loader moves through the field and mechanically picks up the onions from the beds and then conveys them past as many as 20 inspectors, who remove any dirt clods or defective onions, and on to cleaning rolls. The onions are inspected again, loaded into bulk trucks or trailer units holding up to 22,700 kg, and hauled to the plant.

At the plant the truck is tilted with a large hydraulic lift, and the contents gently roll out. The onions are cleaned for any remaining trash or tops and conveyed to large bins for final curing and storage. Onions can be size-graded in the field or at the plant.

Desired storage conditions are 0–4.5°C and a maximum relative humidity of 75%, although steady maintenance of these conditions may be economically difficult to justify. Yamaguchi *et al.* (1957) stored 'Southport White Globe' onion bulbs for 4 months at constant temperatures ranging from 0 to 40°C. They concluded that storage at 0, 2, and 30°C resulted in the highest yield of sound onions, while intermediate storage temperatures from 10 to 20°C gave the lowest yield of both bulbs and dry flakes.

Dehydration Process. Preparation of dehydrated onion begins with sorting, washing, and peeling the bulbs. Roots and tops may be cut from onion bulbs before or after peeling. Onions may be peeled by passing them through revolving high-pressure washers, which remove most of the outer skin. In another method, onions are peeled by conveying them through a flame peeler, which burns off the outer "paper-shell" and hair roots. This method is little used today.

Slices (made by specially designed high-speed cutters), approximately ⅛ in. (0.3 cm) thick and cut at right angles to the vertical axis of the onion, dry much faster than "slabs"—slices cut parallel to the vertical axis. Slicing knives must be kept sharp to avoid crushing the onion tissue, with resulting undesirable enzyme changes such as loss of pungency.

All onions dehydrated in the United States are now dried on multistage continuous-belt conveyors. After the onion slices are automatically spread on a continuous stainless-steel perforated belt, hot air is blown through the bed, alternately flowing upward in one section of the drier and downward in one or more following sections. The temperature of the air is gradually reduced from about 82°C to about 54°C as the product moves through the stages of the drier. The product leaves the belt drier at about 6% moisture in approximately 6 hr (Stark 1962).

The loading depth of the onion bed may vary from 4 in. (10 cm), as the freshly sliced onions are mechanically deposited on the belt, to 6 ft (1.8 m), in the final stage. This last, slowly moving stage is essentially a moving finishing bin with air at about 43°C blowing vertically through the onion mass. The air for this final drying stage is dehumidified by passing it through a bed of silica gel.

Slices may be finish-dried in stationary bins, where some additional moisture is removed and "wet spots" and "dry spots" are equilibrated until the mean moisture content is less than 4% in the final product.

Certain onion cultivars (e.g., 'W-45' and 'Creole') that make excellent dehydrated onions do not make satisfactory toasted dehydrated onions. Prater and Lukes (1963) overcame this by partially rehydrating the onions with raw onion juice from cultivars with a higher reducing sugar content and uniform sugar distribution. These onion fragments are then toasted for a few minutes to 30 hr between 70 and 176°C. Best results are obtained in a continuous toaster in a few minutes at 149–160°C. This procedure gives a uniform quality and appearance to the fragments.

Packaging. After drying, slices are separated according to size and shape by screening and air classification. Dehydrated onions are commercially sold in many size classifications, the most common being sliced, chopped, minced, granulated, and powdered. As much as one-third of the final dehydrated material may end as onion powder, although much care is exercised during all the handling to minimize the formation of this relatively lower-valued product. As dried onion is very hygroscopic, screening, grinding, and packaging must be performed in special dry rooms where the air is kept below 30% RH. Aspirators in the processing and packaging lines remove any remaining paper-shell skin fragments.

For institutional and military use, most dehydrated onion is packed in hermetically sealed No. 10 cans; for shipment to remanufacturers using larger quantities, 5-gal. (18.9-liter) triple-friction-top cans and 26-gal. (98-liter) or 55-gal. (208-liter) fiberboard drums with plastic or aluminum foil moisture barriers are used. Containers such as plastic or aluminum bags, glass or plastic jars, and chipboard boxes are used for the growing retail market.

A review of quality specifications, standards, laboratory methods, etc., for dehydrated onion and garlic has been published by the American Dehydrated Onion and Garlic Association (1969).

Effect of Drying Method on Rehydration. Shimazu *et al.* (1965) determined rehydration volumes of diced onions dehydrated by conventional methods at different temperatures or by freeze drying. Water-vapor sorption properties and X-ray assessments of crystallinity also were obtained for cellulose extracted from the dehydrated diced onions and for cellulose extracted from fresh onions and then dehydrated. Rehydration was fastest in the freeze-dried onion, and the volume of the original product was approximated. The final volume of the other rehydrated products was considerably smaller than that of the fresh product. Cellulose crystallinity was greatest in the freeze-dried samples, probably as a result of freezing, which produced large internal voids. Cellulose crystallinity was not appreciably affected by the dehydration temperature during conventional dehydration.

Parsley

Parsley (*Petroselinum crispum*) is a bright green biennial herb whose characteristic flavor and odor are due to volatile oils in the stems and leaves. The bright green sprigs are frequently used for garnishing and for flavoring soups, stews, gravy, poultry stuffing, and meat dishes. Parsley is very high in vitamin C, containing four times as much as an equal weight of fresh oranges.

The largest acreages of parsley are planted in Texas, California, and New Jersey. Three types of parsley are grown in this country: curled, plain-leaved, and turnip-rooted. The curly-leaved type is used for dehydration. Two prominent cultivars of curly-leaved parsley are 'Evergreen' and 'Moss-Curled'.

Normally, 5 months after planting, starting in January, parsley can first be harvested, and thereafter every 60–90 days depending upon growing conditions. Three cuttings from one planting is the usual practice. After machine harvesting and collection in field trailers, parsley is quickly hauled to the plant. Here it is unloaded, cleaned, and fed at a uniform rate onto a wide conveyor belt where it is inspected; yellow leaves or other defects are sorted out.

Dehydration is accomplished in a three-stage continuous-belt drier with a drying time of only 30 min. Parsley is neither blanched nor sulfited before drying. Final moisture content of the finished product is about 4%. The whole dried parsley emerges into a mechanical and air separating system where the stems are removed from the leaves. The leaves are sold as flakes or granules; leaves and stems are ground for powder. The entire parsley dehydration process described above, from field to final package, takes less than 2 hr.

Parsley may also be washed, dried, and chopped, and the stems discarded by screening and air-separation. The leaves are then fed into an air-lift drier where they are rapidly dehydrated as they are lifted by a rising column of heated, dehumidified air.

Peas

In the past, drying green peas (*Pisum sativum* L.) was regarded as a difficult process. Cruess and MacKinney (1943) noted that, because of the

hardening of the outer tissues, peas dry very slowly toward the end of the process. Hand *et al.* (1955) concluded that low moisture levels are essential for storage stability of dehydrated peas and that "conventional air drying under a variety of conditions failed to produce dehydrated peas of satisfactory low moisture content without causing damage to the product." In the late 1950s, Moyer *et al.* (1959A,B) developed a mechanical technique for slitting the seed coat of the pea prior to dehydration. This procedure revived the use of air drying for peas. As a result of the slitting operation, the rate of drying was increased, lower final moistures were obtainable, the rehydration ratio and rehydration rate were increased, and the quality of the rehydrated product was improved.

Pea cultivars can be classified as tall or dwarf, early or late, small pod or large pod, and smooth-seeded or wrinkle-seeded. There is also a distinct, edible-pod type (sugar peas). Most cultivars that make an acceptable frozen or canned pea appear to be satisfactory for dehydration. Good-quality dried products have been made from 'Thomas Laxton' and 'Dark Skinned Perfection' cultivars.

The optimal maturity of peas for dehydration occurs when alcohol-insoluble solids are 9 to 11% which corresponds to tenderometer readings ranging from 85 to 95 (Moyer *et al.* 1959A). At this stage of growth, the yield per acre is relatively low, and accordingly the cost of raw material may be high.

Peas are harvested, vined, dry-cleaned, and size-graded. Sizes 3, 4, and 5, which will pass through a 13/32-in. (1.0-cm) mesh screen but not through a 10/32-in. (0.8-cm) screen, are recommended for good-quality dried products. Smaller sizes usually do not rehydrate well, and larger sizes may be too high in starch content. The peas are thoroughly washed in cold water and are sorted to eliminate pods, stems, off-color peas, and other defects. Blanching may be accomplished in hot water at 99°C or in atmospheric steam for 1-2 min. The drying rate tends to decrease with increasing maturity of the peas, but this effect can be overcome in part by increasing the severity of the blanching treatment (Moyer *et al.* 1959B).

After blanching, peas are run through a slitting machine. Commercial machines are available that handle about 6000 lb (2724 kg)/hr; they make about a 1/8-in. (0.3-cm) slit in each pea. The slit peas are dipped into, or sprayed with, a sulfite–bisulfite solution of sufficient concentration to produce a dried product containing 300–500 ppm SO_2.

Slitted peas may be dried successfully in tray-tunnel driers, cabinet driers, continuous-belt driers, or belt-trough driers. It is advisable to remove peas from any of these drying systems when they have been reduced to about 8% moisture and to continue drying to 4% moisture in bin driers, using desiccated air at 49°C. In two-stage tunnel driers, temperatures of 82°C for the initial stage and 71°C for the second stage are recommended. With through-circulation continuous-belt driers, temperatures from 88 to 93° may be used during the early part of the drying cycle.

A combination of air-drying and freeze-drying techniques has been successfully applied to green peas (Loeffler *et al.* 1970). In this process, peas are first air-dried to about 50% moisture, then frozen and stored in freezers; later they are freeze-dried to 2–3% moisture. Quick rehydration qualities and greater rehydrated volume of freeze-dried peas are achieved with this combination process at a significantly lower cost, because the initial air drying results in greater utilization of the freeze-drying equipment.

Shah (1972) demonstrated the potential of partial dehydration of peas by saturated salt solution. The salt treatment reduced the drying time from 360 to 240 min, and the salt-treated peas had better chlorophyll retention during storage.

Shah and Edwards (1976) studied the influence of pea size and maturity on drying rates. They reported that smaller, less mature peas showed higher drying rates than larger and comparatively more mature peas, and that smaller peas rehydrated more completely. Shah and Sufi (1979) also suggested that pricking peas prior to dehydration can accelerate dehydration and improve the rehydration characteristics of green peas.

Peppers

The name *pepper* refers to both *Piper nigrum*, the plant that yields black or white pepper, and the capsicums, or garden peppers. The capsicums bear a remarkable range of sizes, shapes, and colors of fruits; plant sizes and growth habits are also variable (Boswell *et al.* 1959). Heiser and Smith (1953) classify chili peppers, base for the well-known and widely used Tabasco sauce, under *Capsicum frutescens*, and all other cultivated peppers grown in the United States—bell peppers, pimientos, paprika—as varieties of *C. annuum*.

Many of the capsicums are used primarily as spices. These can be divided into three broad types: those grown and processed for their flavor, such as chili peppers, with color as a secondary characteristic; those grown and processed primarily for their color, such as paprika; and those grown and processed for their heat, such as Cayenne pepper and hot red pepper. All these groups are frequently lumped together in an all-inclusive nomenclature as chilies or chili peppers.

Chili Peppers. Very "hot" capsicums are imported into the United States in large quantities from Mexico and Africa. Substantial quantities of dried chili pepper are produced in California. Some are dried whole and sold in bulk. Mature chili peppers are sun-dried in the Southwest. In recent years, the use of sun drying has been confined to small home projects. Modern dehydration techniques are used by practically all commercial dehydrators of chili peppers in the United States.

In California, the two important chili cultivars grown and dried for spices are the 'Ancho' (or Mexican) and the 'Anaheim' (or California). The 'Ancho,' while sometimes possessing less color than the 'Anaheim,' is preferred for its typical chili flavor.

Only fully mature pods should be harvested. A second picking is made a few weeks later to gather the remaining peppers that were not ripe at the first picking. The peppers are brought into the plant in bulk or burlap bags. The pods are washed and spread on trays either as whole pods or in 1-in. (2.54-cm) slices. Sliced pods not only dry faster but give a superior initial color. A temperature of 79°C has been used for drying chili peppers, but Lease and Lease (1962) stated that a drying temperature of 65°C results in improved initial color, color retention, and pungency. At 65°C, the drying time for whole pods may average about 12 hr; for slices, 6 hr. Chili peppers are usually dried to a final moisture content of 7–8%. They may be ground immediately after drying or held as whole pods and ground as needed.

In California, some dehydrators dry whole or cut pods only to 12–15% moisture and store them at 0°C. When the peppers are to be ground, they are spread on trays again and dried to 7–8%. This method is reported to give maximum color and pungency retention. Some processors use a two-stage tunnel-drying system, drying to 20% moisture in the first-stage tunnel and down to 3% in the second stage. Some chili pepper packers grind the dried chili and hold the powder under cold storage until it is shipped, in order to retain maximum pungency and color. Experimental use of the antioxidant BHA, sprayed on peppers as a 0.2% solution, resulted in markedly improved color retention in the ground pepper (Lease and Lease 1962).

Bell Peppers. In the United States more than 50% of the bell peppers are grown in California, Florida, and New Jersey. For dehydration, bell peppers with thick walls, large size, and high solids are desirable. A strain of 'Yolo Wonder', a cultivar used by dehydrators in California, yields pods that weigh 8–10 oz (226–284 g) each, are 3½–5 in. (8.9–12.7 cm) in diameter, and have walls ¼–½ in. (0.64–1.27 cm) thick.

Dehydrated bell peppers are sold primarily in the form of dice to manufacturers of canned stewed tomatoes and dry soup mixes. Since manufacturers frequently require all green or all red dice ingredient, harvesting of bell peppers must be so scheduled as to produce a minimum of peppers that are partly red and partly green. A blend of red and green dice sells for a lower price than either all red or all green.

Bell peppers are harvested by hand and brought to the plant in 1000-lb (454-kg) bins or bulk trailers. They are washed, inspected, graded for color

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