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COMMERCIAL FRUIT PROCESSING

Second Edition

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Dehydration of Fruits

L. P. Somogyi and B. S. Luh

Drying of fruit is one of the oldest techniques of food preservation known to man—and one of the newest. Its essential feature is that the moisture content of food is reduced to a level below that at which microorganisms can grow.

Early American colonists used sun-dried fruit as a regular part of their diet in winter months, and in rural areas of the United States drying of fruit was a part of the family farming enterprise.

During the past century the volume of dehydrated fruit produced has fluctuated widely in response to needs of large-scale military conflicts. During the Franco-Prussian War, Boer War, and World War I, there was a tremendous increase in demand for dried food products. World War II focused even more attention on the industry, as transportation and deployment of men and supplies involved much greater areas than ever before. But during the intervening years of peaceful commerce little progress was achieved in gaining domestic consumer acceptance of dehydrated fruits. The value of dehydrated foods under wartime conditions was undeniable, but the technology was not sufficiently advanced to make any impact on the public in general. Sun drying still accounts for the major part of the dried fruits consumed in the world today; mechanically dehydrated fruits are produced in relatively small amounts but the quantities of these are rising rapidly. This may be partially attributed to the high degree of sophistication attained by dehydration technology during the past 25 years, resulting in products that are winning consumer acceptance in retail markets.

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Today the potential for dehydration is greater than ever. Much has been done to improve the quality of dehydrated foods. Among the things that have led to improvement are the use of raw materials better adapted to the requirements of dehydration, new processing technology, more careful application of known processing procedures as well as sophisticated quality control procedures, improved equipment, lower moisture content in finished products, better control of sulfur application, and improved packaging (Van Arsdel *et al.* 1973; Potter 1978; McBean 1971).

Although preservation is usually the principal reason for dehydration, other considerations often are important. Significant reductions in the weight and bulk of foods are particularly attractive to backpackers and campers. Production of convenience items, such as dehydrated fruit snack and fruit drinks, instant applesauce, pie filling and mixes, and "natural" foods (i.e., fruit products processed without the use of chemical additives), and their retail marketing are rapidly expanding (Kitson and Britton 1978; Salunkhe *et al.* 1974). The accent today is increasingly on convenience foods in almost every field and the word "instant" has a new connotation in our vocabulary. Development of new forms of dried fruit and successful preparation of intermediate moisture food has led to products that are stable to storage and pleasant to eat directly (Silge 1981).

Fruits that are properly dehydrated, particularly to a moisture level below 5%, have the following advantages:

- They have an almost unlimited shelf life under proper storage conditions, because a high degree of inhibition of bacteria, enzymatic, and mold actions is achieved.
- They have substantially lower transportation, handling, and storage costs and do not require costly refrigeration during transport and storage. Their average weight is 1/7 to 1/9 of the raw, canned, or frozen counterparts. Shipping and handling weight is therefore reduced by approximately 90%.
- Dehydration hardly affects the main calorie-providing constituents of fruits. It leaves the mineral content virtually unchanged. Therefore, the process is helpful in preserving the nutritive content of the final product. Vitamin losses are no greater with dehydration than with other preservation methods, and low-moisture fruits can be conveniently fortified with vitamins.
- They provide a consistent product, an important modern marketing requirement. Seasonal variation in product quality is either absent or at a minimum with low-moisture fruits.
- They provide opportunities for maximum convenience, flexibility, and economics as industrial or foodservice ingredients, because they can be sized, shaped, formed, etc., to fit almost any requirement. With

Table 8.1. U.S. Dried Fruit Production in Tons (Dry Basis), 1970–1980

Year	Apples	Apricots	Dates	Figs	Peaches	Pears	Prunes	Raisins	Total
1970	11,862	5,600	18,200	12,280	2,275	585	158,360	193,450	402,612
1971	6,012	4,000	19,500	10,370	1,880	750	91,850	194,830	329,172
1972	9,288	3,000	15,700	8,950	1,500	980	41,750	105,350	186,496
1973	15,481	3,280	23,100	11,220	1,500	790	161,760	224,550	441,651
1974	12,325	2,640	22,700	11,430	1,750	700	106,221	242,150	386,916
1975	14,344	4,500	24,800	8,840	2,375	980	102,695	283,650	442,184
1976	14,331	4,650	22,400	7,000	2,500	1,270	106,322	218,400	376,873
1977	14,094	5,100	25,400	11,000	2,500	1,130	116,414	248,900	424,538
1978	13,813	3,600	21,550	6,930	2,000	855	94,966	172,500	316,214
1979	15,982	5,300	22,350	10,240	1,800	1,530	95,451	303,400	456,063
1980	12,357	3,600	22,500	9,900	3,100	1,310	131,626	311,200	496,553

Source: Clampet (1981).

Table 8.2. Commercial Production of Dried Fruits in Specified Countries, in Metric Tons, 1978–1980

Commodity and country	1978	1979	1980
Apples			
South Africa	247	118	251
Total	247	118	251
Apricots			
Australia	2,051	2,380	1,500
Iran	5,000	4,000	3,500
South Africa	1,139	1,505	1,704
Spain	680	900	700
Turkey	8,000	12,000	7,000
Total	16,870	20,785	14,404
Currants			
Australia	4,375	6,124	6,450
Greece	66,800	57,000	64,500
South Africa	894	691	973
Total	72,069	63,815	71,923
Figs			
Greece	18,350	18,230	17,000
Portugal	4,250	5,000	3,500
Spain	4,250	6,000	5,000
Turkey	50,000	52,000	57,000
Total	76,850	81,230	82,500
Peaches			
Australia	233	180	200
Chile	1,300	1,300	1,300
South Africa	1,931	2,354	2,707
Total	3,464	3,834	4,207
Pears			
Australia	291	153	200
South Africa	570	636	888
Total	861	789	1,088
Prunes			
Argentina	9,500	10,000	10,000
Autralia	2,214	4,000	2,400
Chile	5,200	5,400	5,500
France	22,190	24,308	16,500
South Africa	2,081	1,583	1,673
Yugoslavia	14,350	10,798	15,000
Total	55,535	56,089	51,073
Raisins			
Australia	64,518	54,077	90,307
Greece	81,000	79,000	61,350
Iran	70,000	60,000	60,000
South Africa	12,881	17,520	25,396
Spain	2,500	3,500	3,300
Turkey	82,000	83,000	100,000
Total	312,899	297,097	340,353

Source: Clampet (1981).

low-moisture fruits, the purchaser uses all that he buys thus eliminating waste disposal and pollution problems. Further, they go a long way towards attaining price stability throughout the year.

- They utilize the most economical and disposable form of packaging. The two major considerations in packaging dried fruits are the exclusion of moisture and oxygen. Metal cans, plastic bags, and laminated bags and boxes effectively limit the passage of moisture and oxygen.
- They offer many distinctive conveniences as snack products.

INDUSTRY LOCATION AND PRODUCTION STATISTICS

There were 184 fruit and vegetable dehydrating plants in 1977. Of these plants, 63% were located in the western region, and about 90% (446,000 tons) of the dried fruit output was produced in California in 1980. Apples, apricots, figs, peaches, pears, prunes, and raisins are the important dried fruits, with raisins accounting for the greatest volume. Dried fruits, particularly apples, are also produced in Washington and Oregon, and some fruit drying is practiced in Arizona, Idaho, New York, and Virginia.

As shown in Table 8.1, total production of dried fruits increased by approximately 10% in the United States during the 1970's (Clampet 1981). In recent years, however, increasing interest has arisen in the use of dehydrated products, particularly in convenience foods, foodservice systems, and cereal and bakery products.

The following countries are important dried fruit producers: Australia, Argentina, Algeria, Chile, France, Greece, Iran, Portugal, Spain, South Africa, Turkey, and Yugoslavia. Dried fruit production of the more important fruits in these countries is shown in Table 8.2. The data shown represent mainly sun-dried fruits; only a few mechanical driers are used in these countries to produce low-moisture fruits.

DEFINITION OF DEHYDRATION TERMS

Dehydration terms are often misused or applied indiscriminately.

Dried is the term applied to all dried products, regardless of the method of drying.

Evaporation refers to the use of sun and forced-air driers to evaporate moisture away from fruit to a fairly stable product. Usually, drying conditions, such as humidity, temperature, and air flow, are now carefully controlled during the processing of evaporated fruit. The moisture level of evaporated fruit is approximately 25%. In general, sun drying will not lower the moisture content of fruit below 15%; therefore, the shelf life of such fruit products does not exceed 1 year, unless they are held in cold storage.

Dehydration refers to the use of mechanical equipment and artificial heating methods under carefully controlled conditions of temperature, humidity, and air flow. Although the term "dehydrated" does not refer to any specific moisture in the finished product, it is usually considered to imply virtually complete water removal to a range of 1–5% moisture. Products with such low water content can be stored at room temperature for periods well in excess of 2 years with no detectable change in quality, and indications are that most low-moisture fruits will remain acceptable for periods of 5 years or more when stored under temperate conditions (about 65°F) in moisture-proof containers.

Freeze drying is a method of drying in which the fruit is frozen and than dried under high vacuum to around 2% moisture. The ice sublimes off as water vapor without melting. Controlled heat is usually applied to the process without melting the frozen material; this is called *accelerated freeze drying* (Hanson 1961).

Intermediate-moisture or *semimoisture, fruits* (IMFs) are defined on the basis of water activity level rather than on the percentage of moisture. Restraint of the water molecules to a degree that prohibits spoilage by microorganisms occurs at different moisture contents depending on the amount and nature of the dissolved material present and to some degree on the insoluble components. Food may be classified as an IMF if it has an a_w greater than that of common low-moisture food (0.2) and less than that of most fresh food (0.85). In practice most IMFs have an a_w in the range of 0.65–0.85 and contain 15–30% moisture.

"Water activity" (a_w) is defined as the ratio of the water vapor pressure in equilibrium with a food to the vapor pressure of water at the same temperature. Bacteria will not grow if a_w is below 0.9, and yeasts and molds are inhibited below a_w of 0.7 (Heidelboug and Karel 1975).

Vacuum drying is a method of drying in a vacuum chamber under reduced atmospheric pressure to remove water from the food at less than the boiling point under ambient conditions.

PREDRYING TREATMENTS

Preparation of raw fruit for drying is similar to that for canning and freezing except sulfur is applied to preserve the color of dried fruits. The steps involved in the common predrying treatments applied to the important fruits are (1) selection and sorting for size, maturity, and soundness; (2) washing; (3) peeling by hand, lye solution, or abrasion; (4) cutting into halves, wedges, slices, cubes, nuggets, etc.; (5) alkali dipping, used for raisins, grapes, and prunes; (6) blanching, used for some fruits; and (7) sulfuring.

The general procedures and equipment used for fruit preparation prior to various types of processing are discussed in detail in Chapter 3 of this volume. Only preparation practices used specifically for dried fruits are discussed here.

Sulfuring

For many years sulfur dioxide (SO_2) has been used to help preserve the color of dried fruits. It is the only chemical additive widely added to dried fruits for its antioxidant and preservative effects. Several sulfite salts and SO_2 gas are generally recognized as safe (GRAS) for use in foods by the FDA. Recently the confirmation of sulfites as a GRAS ingredient has been opposed by various consumer groups because of allergic reactions by certain individuals resulting from consumption of sulfite-treated food (Pintuaro *et al.* 1983). The FDA has ordered that consumers in restaurants or in retail stores must be informed if sulfites are applied to preserve fruits or vegetables.

The presence of SO_2 very effectively retards the browning of fruits in which the enzymes have not been inactivated by sufficiently high heat normally used for drying. Sun-dried fruits, (e.g., apricots, peaches, and pears) are usually exposed to the fumes of burning elemental sulfur before being put out to dry in the sun. Apples often are treated with solutions of sulfite before dehydration. Solutions used range from 0.2 to 0.5% (as SO_2) made up of sodium sulfite and sodium bisulfite in about equal proportion. Sulfite solutions are less suitable than burning sulfur because the solutions penetrate the fruit poorly and leach its natural sugar, acid, and flavor components. In addition to preventing enzymatic browning, SO_2 treatment reduces destruction of carotene and ascorbic acid, which are the important nutrients of fruits.

Sulfuring dried fruits to preserve their natural color must be closely controlled so that enough sulfur is present to maintain the physical and nutritional properties of the product throughout its expected shelf life, but the amount should not be so large that it adversely affects flavor. Control of the level of SO_2, which is usually set in the finished product specification, often presents some problems. In a typical product, such as low-moisture apples, the rate and the amount of sulfite absorption by the fruit depend on piece size, type and maturity of fruit, drying method and conditions used, and the method of sulfite application. In particular, the gas concentration in the sulfuring chamber greatly affects the content of SO_2 in the finished product. Bolin and Boyle (1972) studied SO_2 absorption during drying for several cultivars of apples at various maturities.

They found the final SO_2 content increased directly with the soluble solids level of the fresh fruit. The average increase was found to be 200 ppm SO_2 per degree Brix.

The usual levels of SO_2 that are desirable in dried fruit products are shown in Table 8.3. Fruits high in carotene, such as apricots and peaches, require higher SO_2 levels to retain natural color.

Ahlborg *et al.* (1977) reported a survey of SO_2 and sulfite levels in various commercial dried fruits. They found the highest concentration in dried apricots (5.4 g/kg) and in dried pears (7.0 g/kg). Bolin *et al.* (1976) demonstrated that packaging material and packaging atmosphere are important to control SO_2 loss from dried peaches during extended storage and in preserving the light color of the fruit. Nitrogen packing reduced the loss of SO_2 from fruit.

To control the SO_2 content of dehydrated apples under commercial practice, usually three independent applications of sulfite during the process are required. Peeled and cored apple pieces are exposed to 2–3% bisulfite solution for a few minutes while in the flume water, after the cutting operation. This is followed by exposure to SO_2 fumes in the "kiln" during the first 3–5 hr of drying, which is designed to yield a product containing approximately 24% moisture. In order to control the content of SO_2 in the finished product, it is common practice today to dry apples in the kiln below the 24% moisture level to about 16–18% moisture, then determine the SO_2 content and remoisturize the apple to 24% moisture with a solution containing a sufficient amount of sulfite to achieve the desired SO_2 content in the finished product.

During processing of low-moisture fruit from SO_2-treated, evaporated material, substantial loss of SO_2 is expected. The volatilization of SO_2 can be as high as 50% during the vacuum drying process.

Marked reduction of SO_2 in fruit before consumption can be induced by immersing the fruits in hot water (Bolin and Boyle 1972). Sulfured apricots, peaches, and pears held in boiling water lost SO_2 rapidly and continuously while being hydrated (Table 8.4). When the boiling water was replaced by 20° Brix sugar syrup, the SO_2 loss was increased by about 15%. These treatments produced the most rapid reduction of SO_2 from dried fruit, with a 50% decrease observed in about ½ hr. Although a moderate increase in storage temperature over a long time can induce accelerated SO_2 loss, dry heat at high temperature for up to 1 hr does not induce rapid loss of SO_2. On the contrary, due to a decrease in moisture content, a slight increase in the percentage of SO_2 was observed then evaporated apricots containing 3645 ppm SO_2 were exposed to dry heat for 1 hr.

Table 8.3. Usual Levels of Sulfur Dioxide in Processed Dried Fruits

Fruit	SO_2 (ppm)
Apples	1000–2000
Apricots	2000–4000
Peaches	2000–4000
Pears	1000–2000
Raisins (sulfur-bleached)	1000–1500

Table 8.4. Sulfur Dioxide Loss (MFB[1]) and Moisture Gain During Boiling in Water

	Apricots		Peaches		Pears	
Boiling time (min)	SO_2 loss (ppm)	Moisture gain (%)	SO_2 loss (ppm)	Moisture gain (%)	SO_2 loss (ppm)	Moisture gain (%)
0	6430	28.6	970	35.3	830	38.0
10	5440	58.6	560	58.6	650	47.5
20	4900	63.7	570	61.3	620	54.6
30	3750	68.0	523	62.7	480	56.2
90	3350	76.5	240	70.1	380	63.8

Source: Bolin and Boyle (1972).
[1]Moisture-free basis.

Stafford and Bolin (1972) showed that a 30-sec dip treatment of dried apricots, peaches, and pears in a 7% solution of potassium metabisulfite substituted for the time-consuming and difficult control process of resulfuring dried apricots by the conventional method involving burning sulfur in a sulfur house for 8–12 hr over the fruit spread on trays.

To achieve comparable levels of retained SO_2 in fruits such as mangos, nectarines, and peaches prepared for solar drying, higher levels of sodium bisulfite were required for solar drying, higher levels of sodium bisulfite were required for predrying treatments than for fruit prepared for hot-air drying (Wagner *et al.* 1978). For solar-dried nectarines and peaches 1.25% SO_2 concentration in the soaking solution was sufficient to attain a concentration of at least 2000 ppm SO_2 in the dried product. When hot-air drying was used, 2.00 to 2.25% SO_2 was required in the soak solution to achieve the same SO_2 level in the finished product. Retention of SO_2 was higher in peeled nectarines than in unpeeled fruit.

A combination of ascorbic acid with SO_2 has also been recommended (Voirol 1972). Such an approach has the advantage of replacing some of the SO_2 with a natural constituent of fruits, while still retaining the enzyme-inhibiting property of SO_2.

Replacement of Sulfur

Although SO_2 is the most widely used compound to prevent browning of dehydrated fruit, it (1) causes corrosion of equipment, (2) induces off-flavors, (3) destroys some important nutrients such as vitamin B_1, and (4) is not approved for use in some countries.

Important marketing countries such as Germany and Japan have regulations that substantially limit the use of SO_2 in low-moisture fruits, and within the United States there are increasing demands for SO_2-free dried fruits. Therefore, alternative treatments and the use of more acceptable food additives that retard enzymatic browning of fruits have been considered (Roberts and McWeeny 1972).

Several additives or special treatments to retard enzymatic browning and other oxidative reactions during drying have been investigated. These include lowering pH (using citric or other organic acids), rapid dehydration to very low water contents, use of other antioxidants (ascorbic acid, tocopherols, cysteine, glutathione, etc.), heat inactivation (Individual Quick Blanching), and reduction of the water activity (osmotic treatment).

Miller and Winter (1972) reported that when peaches were dehydrated or sun-dried after a 3-min dip in a 1.0% ascorbic acid and 0.25% malic acid solution, the dehydrated fruits had very good color and were far superior to nontreated fruits. Panelists judged the flavor of the dipped peaches superior to that of commercially dried fruit treated with SO_2.

Ponting *et al.* (1972) found that when 'Golden Delicious' and 'Newton Pippin' apple slices were dipped into solutions of ascorbic acid, calcium sulphate, and sulfur dioxide, the color of the fruit was protected better when both ascorbic acid and a low concentration of SO_2 were combined with calcium, but combinations of ascorbic acid with SO_2 did not improve the results more than an increase of one ingredient by itself. Likewise, three-way combinations of ascorbic acid, SO_2, and calcium were no more effective than two-way combinations of either ascorbic acid or SO_2 with calcium.

Dipping apples and pears into solutions containing 200 g NaCl in 100 liters of water was recommended by Voirol (1972) to preserve color. Even better results were obtained when the fruits were dipped into solutions of 200 g ascorbic acid in 100 liters of water, or in a solution of both substances (100 g NaCl and 10 g ascorbic acid in 100 liters of water). Good results were obtained with cherries, peaches, and plums by treating them at room temperature in solutions containing either 5% ascorbic acid, or 0.1% ascorbic acid and 2% citric acid, or 0.5% ascorbic acid and 0.5% NaCl.

The revival of home dehydration for fruit preservation stimulated development of oven dehydrators operating at low temperature (between 120°–150°F or 50–65°C) with air velocities of about 750 fpm (228 mpm). Peaches, apricots, bananas, mangos, pineapples, nectarines, apples, pears, papayas, and plums cut into ¼–⅜ in. (6–9.5 mm) were placed one layer deep into a forced-draft oven with cross-flow air and dried at 120°F (50°C) without sulfite or blanching pretreatment (Gee *et al.* 1977). Drying required 16–24 hr to reach 0.5 a_w. The resulting dried fruit pieces had a bright natural color and were stable for many months when stored at room temperature in the absence of light.

A new blanching process, IQB or Individual Quick Blanch (Lazar *et al.* 1976), may be used prior to dehydration to inactivate enzymes and at the same time improve the nutritional value and texture of the processed product. In the IQB system, pieces of fruits or vegetables are spread in a single layer at a density of about 1 lb/ft^2 (5 kg/m^2) or on a mesh belt moving rapidly through a steam chest where maximum heating rates result from complete exposure of each piece to live steam. Before the interior of the pieces becomes very hot, the product is discharged as a deep bed onto another belt moving slowly through an insulated chamber, where the heat is already added, and the holding time is sufficient to equilibrate the product temperature at a mass average temperature high enough to stop enzyme activity.

Osmovac Drying

Ponting (1973) has described osmovac drying for dehydration of fruit pieces, slices, or chunks. Fresh fruit is exposed to concentrated sugar syrup (dry sugar) or to salt to remove water from the fruit by osmosis. Over 50% of the initial weight of the fruit can be removed as water by this means (Farkas and Lazar 1969). The partially dehydrated fruit piece is then further dried by other conventional dehydration techniques—most commonly, but not necessarily in a vacuum shelf drier–to a low moisture content. This two-stage combination of osmotic and vacuum drying is referred to as "osmovac" process.

The high concentration of sugar surrounding the fruit pieces prevents enzymatic browning of the fruit, making it possible to produce a dry product of good color with little or no SO_2 or other reducing agents. It is reported that fruits such as apples (Ponting 1973), peaches, bananas (Bongirwar and Sreenivasan 1977), mangoes and plantains (Hope and Vitale 1972; Jackson and Mohamed 1971) have been dehydrated with significantly improved flavor and excellent color; also, interesting textures were produced with the osmovac technique and the application of little or no SO_2. The following additional advantages are claimed for this technique: (1) reduced time during which the product is exposed to high temperature, (2) minimized heat damage to color and flavor, (3) the use of sugar syrup as the osmotic agent reduces the loss of fresh fruit flavor, and

(4) some fruit acid is removed by osmosis which, combined with the residual sugar from the osmotic treatment, produces a blander and sweeter product than conventionally dried fruit. However, the decrease of acidity and the addition of sugar may be disadvantageous in certain products.

Dixon and Jen (1977) identified some of the chemical changes that occur in osmovac-dried apple slices. They found that the sugar-to-acid ratio of the final product increases by as much as threefold compared with that of the initial apples. However, the osmovac-dried apples had a sweet pleasing taste, appropriate for a snack item or breakfast cereal component.

Ponting (1973) summarized other problems with the osmovac process: (1) storage stability may be changed with certain products due to rancidity development in products treated with sugar and dried to low moisture; (2) cost of the process including the unresolved problem of utilization of the excess sugar solution; and (3) sticking together of sugar-treated fruit pieces into large clusters that are difficult to separate without inducing a large amount of fines.

Farkas and Lazar (1969) studies the effects of various factors related to the osmotic dehydration of nonsulfured 'Golden Delicious' apple pieces. They correlated data for time, temperature, sugar concentration, and weight reduction. Their results are presented in Fig. 8.1. They found that under the most favorable condition of 70° Brix sugar solution at 50°C (122°F), about 8 hr were required to reduce ½-in.-thick (12.5-mm) apple slices to 50% of their untreated weight.

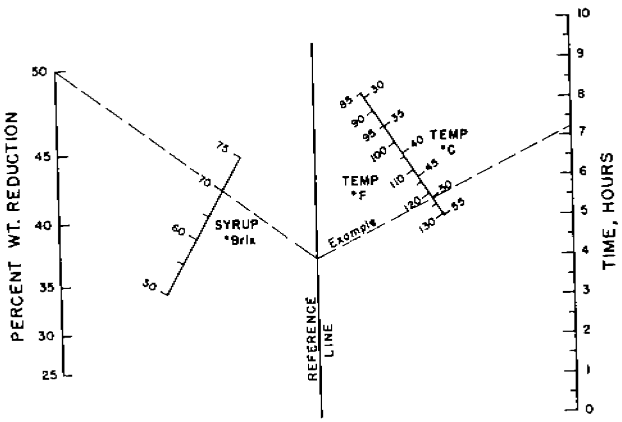

FIG. 8.1. Nomograph for determining percentage of weight reduction for ½-in. (1.27-cm) thick half-rings of 'Golden Delicious' apples during osmotic drying. [Copyright by Institute of Food Technologists and reprinted with permission from Food Technology *23* (5) 91 (1969).]

Centrifugal Fluidized Bed (CFB)

The CFB process can achieve blanching plus about 50% water reduction in less than 6 min. The treatment can be followed further by any conventional dehydration process. Brown *et al.* (1972) reported that peeled and cored 'Newton Pippin' apples diced to ⅜ × ⅜ × 5/16 in. (9.5 × 9.5 × 8 mm) were prepared successfully for air or vacuum drying without the use of SO_2 in a CFB system operated at 2400 ft/min (730 m/min) air velocity at 240°F (115°C) process temperature. This process eliminates the disadvantages associated with the introduction of sugar or salt to the product during the osmotic method. The CFB method reportedly offers the advantages of simplicity of design and an intimate gas-to-particle conduction that provides uniform particle exposure without mechanical agitation. The equipment can be designed to operate as a continuous process. However, it is limited to small particles, about ½-in. (1.25-cm) cubes or smaller pieces.

DRYING METHODS

Several drying methods are commercially used, each better suited for a particular situation. Sun drying of fruit crops is still practiced for certain fruits, such as prunes, grapes, and dates. Atmospheric dehydration processes utilizing kiln, tower, and cabinet driers are used for apples, prunes, etc. Continuous processes (e.g., tunnel, belt trough, fluidized bed and foam-mat drying) are mainly used for vegetables. Spray drying is suitable for fruit juice concentrates, and vacuum dehydration processes are useful for low-moisture fruits with high sugar content such as peaches, pears, and apricots.

The selection of drying methods depends on the following factors:

- Form of raw material—liquid; paste, slurry, pulp, thick liquid; large aggregates; small aggregates.
- Properties of raw material—very sensitive to oxidation; sensitive to temperature damage; thermoplastic residues; none of these.
- Desired product characteristics—powder; instant solubility; excellent rehydration; retention of shape (complete or partial).
- Cost—low; medium; high; very high.

There are three basic types of drying process:

- Sundrying and solar drying.
- Atmospheric dehydration including (1) stationary or batch processes (kiln, tower, and cabinet driers) and (2) continuous processes (tunnel, continuous belt, belt-trough, fluidized-bed, explosion puffing, foam-mat, spray, drum, and microwave-heated driers).

- Subatmospheric dehydration (vacuum shelf, vacuum belt, vacuum drum, and freeze driers).

The principles of these basic processes are described in this section. Various modifications are discussed in the next section under descriptions of individual types of equipment.

Sun Drying

Sun drying of fruit crops as a method of food preservation is still practiced largely unchanged from ancient times in many parts of the world including the United States. It is limited to climates with hot sun and dry atmosphere, and to certain fruits such as prunes, grapes, dates, figs, apricots, and pears. These crops are processed in substantial quantities by this primitive method without much technical aid, by simply spreading fruits on the ground, on racks, trays, or roofs, and exposing them to the sun until dry.

Only small capital investment is required with this simple procedure. Since sun drying depends on uncontrolled factors, production of uniform and high-quality products is not expected. Some overdrying and contamination by dust, dirt, and insects of the finished product are usually tolerated. The most obvious disadvantage of sun drying is its complete dependence upon the elements. It is a slow process, unsuitable for producing high-quality products. Since sun-dried products generally have moisture levels no lower than 15–20%, they have a limited shelf life.

Solar Drying

In recent years considerable interest has been focused on the use of solar energy for hot-air dehydration because of the rapid increase of fuel costs (Flink 1977). In commercial application, solar energy is used alone or may be supplemented by an auxiliary energy source, including geothermal energy, wastes, and biomass (Anon. 1982).

A simple method of accelerating the sun-drying rate of fruit on trays is to paint the trays black; this causes a greater portion of the incident solar radiation to be absorbed and transmitted to the drying fruit (Bolin *et al.* 1982). Halved apricots that were sun-dried in black trays lost 16% more moisture in 1 day of drying than fruit dried on unpainted wooden trays.

A solar trough was designed by Bolin *et al.* (1982) in which fruit is heated by direct incident radiation and indirect reflected radiation. This system requires 40% less time to dry apricots in 24% moisture than the conventional tray drying method. A solar trough could be used to reduce fruit moisture to 50% after which the fruit could be air-dried in bins to the desired moisture level.

Another type of direct solar drier employs mirrors to increase solar energy (Wagner *et al.* 1977; Bryan *et al.* 1978). In two-stage drying procedure, the first stage depends on direct and reflected solar radiation, followed by heated air blown over the fruit when solar radiation is insufficient for drying.

In indirect solar driers (Bolin and Salunkhe 1982), solar energy is collected by a solar collector that, in turn, heats the air as it blows over it before being channeled into the dehydration chamber.

Among the various collector designs, greatest interest is in flat-plate collectors. One of the largest dehydrators of this type is currently used in California for raisin drying (Anon. 1978). This solar drier unit consists of 22,000 ft^2 (2044 m^2) of single-glazed solar flat-plate collectors, a 700-ton rock heat storage system, and a heat recovery wheel. All of these are connected on one dehydration tunnel. Natural gas is used to supply supplemental heat when necessary. The heat recovery wheel scavenges heat from the exhaust, providing a heating efficiency of over 80%.

Dehydration

Dehydration includes the application of artificial heat to vaporize water and some means of removing water vapor after its separation from the fruit tissues. The removal of water involves mass transfer, and the application of heat in some manner also involves heat transfer. Energy must be supplied to vaporize the water and to remove the resultant water vapor from the drying surface. The quantity of heat energy required to vaporize water depends upon the temperature at which vaporization occurs. In practice, the efficiencies are usually between 20 and 50%.

The general equation for heat transfer is:

$$q = hsA(t_a - t_s)$$

where q is the heat transfer rate in Btu/hr, hs is the heat transfer coefficient, A is the area, t_a is the air temperature, and t_s is the temperature at the drying surface.

Typical heat transfer coefficients (hs) for certain dehydration equipment were given by Williams-Gardner (1971) as follows:

Type of drier	Heat transfer coefficient (Btu/hr/ft² °F)
Vacuum shelf	1
Agitated tray	5–60
Rotary vacuum	5–50
Indirect rotary	2–10
Jacketed through	2–15
Drum	200–300

Heat may be applied to the drying material by conduction, radiation, and convection. While all three modes of heat transfer can occur during drying, depending on the method used, one mode usually dominates to such an extent that its influence is predominant. A current of air is the most common medium for transferring heat to a drying fruit, and convection is the main principle involved. Conduction and radiation are usually associated with vacuum drying. Once heat is supplied to the drying material's surface, it is distributed throughout the material by conduction.

Two important aspects of mass transfer in dehydration are (1) the transfer of water to the surface of the material being dried and (2) the removal of water vapor from the surface. The drying curve (Fig. 8.2), which relates the amount of moisture with time, usually consists of two phases: a constant rate period and a falling rate period. During the constant rate period, water is readily available at the surface of drying foods, and therefore drying rate is determined by the temperature, the relative humidity, and the flow rate of the air. This is a rather short time period during the initial stage of the drying process, and during this period the drying rate is high. When the product has lost most of its surface water, the remaining moisture must diffuse from inside to the surface before evaporation can take place. This results in the "falling rate" period of drying, which in the later stages of the process becomes extremely slow. During this stage the relative humidity of the air will fall below 100%, and

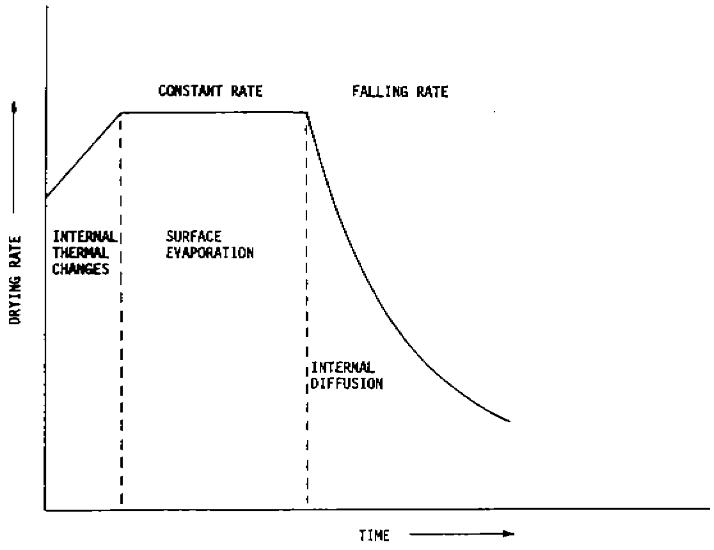

FIG. 8.2. A typical drying curve.

the dominant factor limiting drying rate is no longer heat supply, but the availability of water at the evaporation site.

To achieve dehydrated products of high quality at a reasonable cost, dehydration must occur fairly rapidly. Four main factors affect the rate and total time of drying:

1. Properties of the Food Product.—The biochemical and biophysical characteristics of individual foods define what type of dehydration procedure may be applied without causing unacceptable changes in flavor, color, texture, and nutritional qualities. The most important characteristics are the structure and composition of raw materials, which affect the migration of water toward the surface during drying; shrinkage, which is caused by the stress during dehydration and results in a retardation and limit of the rehydration of the dried product; browning reactions (both enzymatic and nonenzymatic browning reactions); and rehydration characteristics of the finished product.

2. Particle Size and Its Geometry.—The geometry of product in relation to heat transfer, surface, and medium play an important part in determining the overall drying time: the thicker the product, the longer time is required to remove moisture. Generally, fruit is cut into small pieces prior to dehydration. This provides a large surface area that can be exposed to the heating medium and from which moisture can escape. Smaller particles arranged in thinner layers also reduce the distance heat must travel to the center of the piece and, at the same time, reduce the distance moisture must move to reach the surface and evaporate.

The depth of the product in a layer (tray loading) has a great effect on drying time. The lower the tray loading and the greater the distance between the particles, the shorter the drying time and more uniform the finished product.

3. Physical Properties of the Drying Environment.—The temperature, humidity, and velocity of air and the atmospheric pressure greatly influence the rate of drying. The greater the temperature difference between the heating medium and the food, the greater will be the rate of heat transfer, which provides the force for moisture removal. The hotter the air, the more moisture it will hold; therefore, in the vicinity of the dehydrating food it will take up more moisture being given out from the food. In the later stages of drying, heat damage is more likely to occur because the temperature of the product will rise gradually as the drying rate falls and evaporative cooling decreases. Thus, in drying processes it is customary to commence with high temperature, followed by gradually falling temperatures to levels at which deterioration due to heating is reduced.

Beside air temperature, other important factors are air velocity (air in motion more effectively removes water) and the humidity of air (dry air holds more moisture). The combined effect of humidity and temperature of air is determined by the psychrometric relationship as measured by the wet bulb temperature. The drying rate has been shown to be proportional to the wet bulb depression.

Finally, the effect of atmospheric pressure vs vacuum should be considered at this point. At an atmospheric pressure of 760 mm Hg, water boils at 212°F (100° C); at pressures below 760 mm Hg, boiling of water occurs at a lower temperature. Therefore, if fruit is dehydrated in a heated vacuum chamber, its moisture can be removed at a lower temperature than if it is dehydrated at atmospheric pressure. This provides a system to dehydrate products at a lower temperature thus reducing the degradation in color, flavor, and texture of the product.

4. Characteristics of the Drying Equipment.—It is necessary to use the kind of equipment most suitable to a particular operation. A guide to drying equipment and design/selection factors that can contribute to improved operations was published by Levine (1977). In the following section the most important dehydration equipment used commercially is described.

DEHYDRATION EQUIPMENT

Atmospheric Forced-Air Driers

Several methods of artificial drying involve the passage of heated air with controlled relative humidity over the food to be dried, or the passage of food through heated air. Various devices are used to control air circulation and to recirculate air.

Kiln Drier. The kiln drier, in which the natural draft from rising heated air brings about the drying of the food is the simplest and oldest type of dehydration equipment still in commercial use. Kiln driers generally have two levels: gas burners on the lower floor provide heat, and the warm air rises through a slotted floor to the upper level. Food material such as apple slices are spread out on the slotted floor in a layer about 10 in (25 cm) deep and turned over periodically. Kiln driers are still widely used in producing evaporated apples slices. After being dipped in sulfite solution, peeled and cored apple rings or slices are dried to about 14–44% moisture in about 6–8 hr. The sulfite dip may be replaced by use of burning sulfur during the kiln-drying process. This type of drier is inefficient in the use of heat, results in slow drying, and does not permit accurate control of the process.

A number of modifications have been developed to increase the efficiency of kilns and to speed up the drying process. Fans may be set in the wall of the furnace room or in the roof vents to force the heated air more rapidly through the fruit, thereby shortening the drying time. During the initial drying period, when drying is rapid, all of the hot gases are allowed to escape through the roof vents. As drying progresses, much of the air may be recirculated by fans, thus increasing the efficiency of heat consumption.

Tower ("Stack") Drier. A tower drier consists of a furnace room containing a furnace and heating pipes and cabinets in which trays of fruit are dried. In a typical design each "stack" or cabinet holds about 12 trays, usually 3 ft^2 (0.33 m^2) in size; and a furnace room accommodates about six stacks of trays (Cruess 1958). Heated air from the furnace rises through the trays holding the fruit. As the fruits on the bottom trays of the stack become dry, they are removed and are replaced with freshly loaded trays on the top of the stack. This necessitates that each time a fresh tray enters the stack, the entire set of trays are shifted downward.

Cabinet Drier. A cabinet drier is similar in operation to a stack drier, except that the heat for drying is supplied in steam coils that are located between the trays. This type of equipment provides some control and uniformity of the temperature; thus it represents a substantial improvement over the "stack drying" system. It is suitable, however, only for small-scale operations. The equipment is inexpensive and very convenient for drying fruit and vegetable pieces. The duration of a drying cycle is 10–12 hr. A cabinet drier is particularly useful for establishing the drying characteristics of a new product, prior to a large-scale commercial run. Because of its small capacity and high operating cost, a cabinet drier is commercially economical only for high-valued raw materials.

Tunnel Drier. The most flexible and efficient dehydration system is the tunnel drier, which is widely used in drying fruits. The equipment is essentially similar to a cabinet drier, except that it allows a continuous operation along a rectangular tunnel through which move tray-loaded trucks. The tunnel is supplied with a current of heated air that is introduced at one end. A tunnel drier provides rapid drying without injury and permits a uniform drying process.

The size of tunnel driers varies greatly. A typical system for fruit (Holdsworth 1971) consists of two or three single-stage tunnels about 30 ft (9.1 m) long, each 6¼ ft (2.0 m) wide and 7 ft (2.1 m) high. The air is usually directed in a counterflow direction and reaches about 180°–200°F (82–93°C) and 90°F (32°C) wet bulb temperature at the end. The air velocity is between 600 and 1200 ft/min (183 and 366 m/min). Such a unit could dry apple slices that are 5/16–¼ in. (8–6 mm) thick from 23–24%

moisture to 2.5% moisture in 2–3 hr, at a rate of about 1000 lb/hr (454 kg/hr) of finished product.

Tunnel driers are classified by the direction in which the air traverses the product. In a "parallel-flow" unit, the fresh material encounters the direst and warmest air initially, and leaves the drier at the coolest end; in a "countercurrent-flow" unit, the air direction is opposite to the movement of the product, so the dry product leaving the drier encounters hot dry air as it enters the system.

A parallel-flow system has high initial rates of evaporation and presents little danger of overheating the product, since the surface temperature of the fruit is below the dry bulb temperature as heat is removed by the evaporation process. But since the product is in contact with progressively cooler air, which results in a decrease in drying rate, very low moisture contents cannot be achieved with this system. Parallel-flow equipment is generally used only for drying grapes, or it is used in combination with counterflow equipment.

The countercurrent-flow process is more economical and is often used in fruit dehydration equipment. Most tunnel driers, however, operate as a double-stage plant, and the two stages are often arranged as separate tunnels. A countercurrent/parallel system is so arranged that the product first encounters air flowing in a countercurrent direction, followed by air flowing in a parallel direction; this is achieved by feeding the air in at the central point. The parallel/countercurrent flow system is the most widely-used arrangement in commercial two-stage operations and takes advantage of the high rate of initial evaporation provided by parallel-flow systems. This system has been found to result in more uniform drying, increased output, and good overall quality. Often, the first stage is shorter in length than the second to compensate for the low drying rate in the second stage. A double-stage system enables independent adjustment of air temperature. In a parallel-flow system a higher air temperature is followed by a lower temperature in the finishing countercurrent position, which is very advantageous.

Multistage driers consisting of three, four, or five drier stages are also used. Such systems are very flexible and can achieve close to optimum drying conditions for a wide variety of products.

Continuous Belt (Conveyor) Drier. A continuous belt (conveyor) drier is similar in principal to a tunnel drier, except the food material is conveyed through a hot air system on a continuous moving belt without the use of trays. Therefore, the system has the obvious advantage of eliminating the costly handling of products on trays before and after drying. It also allows continuous operation and automatic feeding and collection of the dried material. A commonly used continuous belt drier is

equipped with a belt about 75 ft (23 m) long and 8 ft (2.4 m) wide, which takes 2½ hr to travel through the system. The raw fruit is loaded uniformly 4–6 in. (10–15 cm) deep onto the belt, which is made out of woven metal mesh or interlocking plates. The speed of the conveyor is variable to suit both the product and the heat conditions. Furthermore, process conditions are usually controlled by designing the system in sections, thus allowing different flow rates, humidities, and temperatures to be set in each section, and by rotating the product when it moves from one section belt to the next.

Lower initial inlet temperatures are normally used in the first heat zone of a belt drier than in a tunnel drier because the effect of passing the hot air stream through the product, rather than over it, produces a higher rate of evaporation. Temperature, therefore, must be controlled carefully to avoid scorching, case hardening, and protein denaturation because of the high rate of evaporation. The temperature in the second zone is usually kept at 10°–15°F (5°–8°C) lower than in the first, and in the third zone about 10°F (5°C) below the second zone. Some fruits with high sugar content tend to adhere to the belt at the discharge end; these require a rotating brush or other scraping device to remove them from the plate surface. Adhesion may be minimized by applying a coat of "dehydrator's wax" or food-grade mineral oil spray to the belt.

Belt-Trough Drier. In a belt-trough drier a continuous stainless steel wire mesh belt forms a trough about 10 ft (3.3 m) in length and 4 ft (1.2 m) in width. The raw material is fed onto one end of the trough and is dehydrated by forcing heated air upward across the belt and the product. The belt moves continuously, keeping the food pieces in the trough in constant motion and continuously exposing new surfaces. The movement of the belt and lateral inclination of the drier away from the input end, plus continuous feeding of fresh product into the input end, forces the product across the trough surface toward the lower discharge end. Trough driers are used in two-stage series for dehydration of product to 10–12% moisture; single-stage units are suitable for processing partially dried products such as dehydro-frozen products with about 50% weight reduction. Belt-trough driers have been successfully used for dehydrating vegetable pieces; however, they are not suitable for drying fruits because fruit pieces that exude sugar on drying tend to stick together and clump with the tumbling motion.

Fluidized-Bed Drier. In a fluidized-bed drier, a modification of the belt-trough drier, airflow from beneath is sufficient to lift particles of food and at the same time convey them toward the outlet. The moist air is exhausted at the top of the equipment. The process is continuous, and the length of time particles remain in the drier can be regulated by the depth of the bed and by other means. Fluidized-bed driers offer the advantages of simplicity of design, intimate gas-to-particle contact, and uniform particle exposure without mechanical agitation. Their use, however, is limited because if air velocity becomes too great, channeling will occur and most of the air will escape without performing its function; at even higher air velocities, particles may be ejected from the bed (Brown *et al.* 1972). Thus, the use of conventional fluidized beds is limited to the preparation of food powders. They are often installed as secondary driers to finish the drying process initiated in other types of driers.

The minimum air velocity to produce fluidization was found to be 375 ft/min (114 m/min) for ⅜-in. (9.5-mm) diced apples (Holdsworth 1971). The initial hot air treatments were 30 min at 212°, 194°, and 176°F (100°, 90°, and 80°C, respectively) and finally 3–3½ hr at 140°F (60°C). The initial temperature had a negligible effect on drying rate or overall length of drying time. The apple dice dried rapidly to 10% moisture in 1½ hr, followed by very slow drying.

Lazar and Farkas (1971) have extended the fluidized-bed technique by developing the centrifugal fluidized bed (CFB), which achieves high drying rates of 7.5–25 ft/sec (2.3–7.6 m/sec). They designed a pilot unit that employed a centrifugal force greater than the gravitational force, which has the effect of increasing the apparent density of the particles and allows smooth, homogeneous fluidization at much greater air velocities. Increased air velocity provides improved heat transfer so that moderate temperatures can be used, thus eliminating problems of scorching or surface heat damage associated with high-temperature drying. Brown *et al.* (1972) reported that ⅜ × ⅜ × 5/16 in. (9.5 × 9.5 × 8.0 mm) 'Newton Pippin' apple dice was reduced 50% in weight in less than 6 min in the CFB operated at an air velocity of 2400 ft/min (132 m/min) at 240°F (115°C).

Explosion Puffing. In explosion puffing, fruit pieces are partially dehydrated in a conventional manner and then heated in a closed vessel, known as a "gun," having a quick-opening lid. When the water contained within the pieces is heated above its atmospheric boiling point, and pressure at a predetermined value has thereby developed in the chamber, the pieces are instantly discharged to atmospheric pressure. The flashing water vapor from within each piece creates a porous structure that permits much faster dehydration and much more rapid rehydration of the dried product. The fruit particles are then dried to 4–5% moisture by conventional drying methods.

The moisture content of the fruit pieces entering the gun is critical to achieve successful puffing. For apples the acceptable range of moisture content for puffing is between 20 and 30%, for blueberries 19–30%. Below this range little puffing is achieved, and the product will become scorched. At higher moisture content the pieces tend to collapse after puffing (Eisenhardt *et al.* 1968). The process is estimated to cost more than conventional dehydration processes, but the rehydration time of the finished puffed product is much shorter. It is claimed that this is the first low-cost process that produces relatively large pieces of dehydrated fruits that will reconstitute rapidly. Explosion puffing has been particularly successful with apples and blueberries.

Eskew and Cording (1968) developed a process for greatly reducing the bulk of explosive puffed fruits without in any way impairing their rapid rehydration characteristic, appearance, flavor, or nutritional value on reconstitution. With this process, the bulk of the compressed dry product may be reduced below that of conventionally air-dried material. The process involves compressing the explosive-puffed pieces of fruit in their slightly moist plastic state after puffing, but before final processing to a stabilized form. The compression can be done in one or more stages between closely set rolls, which may or may not be heated, and the fruit pieces may be compressed while still warm from the gun or after cooling. The compression in rolls resulted in a reduction in one dimension of about 1/7–1/15 of the dimension prior to compression of puffed apple pieces.

Foam-Mat Driers. Foam-mat drying involves drying liquid or puréed materials as thin layers of stabilized foam by heated air at atmospheric pressure. The foam is prepared in a continuous mixer by the addition of gas; when required, a small amount of edible foam stabilizer is added. The prepared foam is spread on perforated trays and dired by hot air, followed by crushing into powder.

Foam-mat-dried foods are characterized by a very porous structure, which makes them capable of nearly instant rehydration even in cold water. Many liquid or puréed fruits have been successfully foamed and dehydrated. Low-moisture powders of orange, grapefruit, lemon, lime, pineapple, apple, and grape juices have been produced.

The principal advantage of this process is that products can be dried at relatively low temperatures at atmospheric pressure because the foamed material high initial rates of water removal. Typical drying requirements for ⅛-in. (3-mm) thick fruit juice concentrate is 15 min in 160°F (71°C) air to achieve 2% moisture content. Compared to ordinary air-dried fruits, foam-mat-dried powders have superior flavor and color and are nearly instantly soluble in water. The processing cost of foam-mat-dried products is expected to be less than that of vacuum- or freeze-dried products (Hertzendorf *et al.* 1970).

Foam-mat drying is limited to specific products, such as fruit powders for preparation of instant drinks. Because of their open, porous structures, these products have limited storage stability. Their structure is conducive to the adsorption of oxygen and moisture, which may promote reactions deleterious to quality. Also, because of the hygroscopicity of foam-dried fruit powders and the mild temperatures employed in the foam-mat processes in some cases, it is difficult to obtain sufficiently low moisture in single-stage drying. Several finish-drying procedures have been suggested, such as supplemental drying in a vacuum chamber or the use of an in-package desiccant.

Spray Driers. Spray drying involves the dispersion of liquid or slurry in a stream of heated air. Followed by collection of the dried particles after their separation from the air. The process, widely used to dehydrate fruit juices, has several features that favor high-quality products. The fine dispersion of the particles provides a large surface area, resulting in short drying times with high heat transfer rates. The temperature of the droplets remains below the wet bulb temperature of the drying gas until almost all the water has been removed due to the high evaporation rate. The final dried product is delivered as a free-flowing powder. Spray drying also is a continuous and simple to operate system, and because of its large throughput, its cost of operation is relatively low.

The essential components of the numerous types of spray-drying equipment available are (1) an atomizing system operating at 250–500 psi (17.6–35.2 kg/cm^2); (2) a hot-gas-producing unit; (3) a chamber for the sprayed particles to meet with hot gas; and (4) a recovery system. The specific design of these components may vary with the product being dried since each product needs its own set of drying conditions (e.g., size of atomized particles, type of air flow in the drying chamber, air temperature, separation and collection method). Three types of atomizers are used commonly: the pressure nozzle, or jet, type; the two-fluid nozzle type, in which the fluid is broken up into a spray by means of a jet of air or steam introduced into a slowly moving fluid; and the centrifugal or disk type. Spray driers are designed with three types of air flow: horizontal cocurrent driers; vertical cocurrent driers, which can be upward or downward, and simple or complex; and vertical countercurrent driers. Product collection is normally achieved by means of a cyclone and scrubber system or by a filter with the dry product being discharged from the base of the collection unit.

A recently developed spray drier is the BIRS drier (Hussman 1963), in which droplets of liquid fall from the top of a 200-ft (61-m) tower through countercurrent cool (about 86°F or 30°C), dry, and dehumidified air. Droplets descend in the tower in about 90 sec. Juice products, such as lemon and orange, that are difficult to dry in hot air can be successfully dried in this drier. Although the resulting dry products have more dense particles than conventional spray-dried products, they retain much more natural flavor because of the low-temperature process. Due to the high capital and operating costs of the BIRS drier, it has not yet been widely accepted in commercial operations.

Drum Driers. In drum drying, which is suitable for a wide range of liquid, slurried, and pureed products, a thin layer of product is applied to the surface of a slowly revolving heated drum; and in the course of about 300° of one revolution, the moisture in the product is flashed off, and the dried material is scraped off the drum by a stationary or reciprocating blade at some point on the periphery. The drum is generally heated from within by steam; the outer surface of the drum offers a drying interface with a good heat transfer. Drum driers are capable of increasing the solids content of puree from about 9–30% to 90–98% solids. The residence time of the product in the drier is on the order of 2 sec to a few minutes.

Drum driers can be divided into two broad classifications: single- and double-drum driers. The drums of a double-drier unit turn in opposite directions, and the feed material is applied to both drums. The equipment may be used either under atmospheric or vacuum conditions. Double-drum machines employ a "nip" feed with the space between the drums capable of adjustment, thus providing a means of controlling the film thickness. With a single-drum drier the feed is usually at the top, where the drum passes a shallow trough for the feed material.

Although drum drying is an inexpensive drying method, its commercial application is limited to less heat-sensitive products. Its usefulness for fruit dehydration is quite limited because the high temperatures required, usually above 250°F (121°C), impart a cooked flavor and off-color to the fruit product. Also, the high sugar content of most fruit juices makes them difficult to remove from drum driers because of the high thermoplasticity of such products. Application of chilled air directed to a narrow strip just before the removal blade cools the thin sheet of fruit and makes its removal easier.

Microwave Driers. Microwave heating has been tried experimentally for dehydration of fruits. Since microwaves selectively heat water with little direct heating of most solids, rapid and uniform drying can be achieved throughout the product at relatively low temperatures. In a process developed by Tobby (1966), fruit pieces having a dimension of ⅝ × ⅝ × ⅝ in. (16 × 16 × 16 mm) and an initial moisture content of about 85% were quickly dried to about 14% moisture; the dried pieces were sweet, unwrinkled, and stable. The process was completed in a specially designed drying cabinet using electromagnetic radiation at 100 megacycles.

The use of microwave energy for freeze drying was investigated by Gould and Kenyon (1970). Since microwave energy has the ability to selectively heat ice crystals, thus eliminating the problem of heat conduction across the dried food layer during the middle and end of the freeze-drying cycle, the final stages of the freeze-drying cycle were accelerated. The use of microwave energy reduced the drying time required in conventional freeze drying by 1/10 to 1/20. The main problems to be overcome are nonuniform heating, impedance matching, and ionization causing slow discharge.

Microwave equipment also is complicated and expensive, and no commercial installations are using it at the present for fruit dehydration. Microwave driers are more likely to be used for finish-drying than for the complete dehydration process. Synergistic effects between hot air and microwaves were demonstrated during the finish-drying of fruits by Salunkhe *et al.* (1974). Microwave energy also can be used to equilibrate food pieces that have a low moisture content on the surface layer and a high moisture content at the center. The use of microwave energy would make it unnecessary to draw down the average moisture content as much as is now being practiced prior to compression (Anon. 1982).

Vacuum Driers

The main purpose of vacuum drying is to enable the removal of moisture at less than the boiling point under ambient conditions. Vacuum drying provides important advantages for certain products in terms of final quality. Because of the high installation and operating cost of vacuum driers, they are used only for high-value raw materials or products requiring reduction to extremely low levels of moisture without damage. An important feature of vacuum drying is the virtual absence of air during dehydration; this makes the process attractive for drying material that may deteriorate as a result of oxidation or may be modified chemically as a result of exposure to air at elevated temperatures. Products that may decompose or change in structure, texture, appearance, and flavor as a result of the application of high temperature can be dried under vacuum with minimum damage.

All vacuum-drying systems have the following essential components: vacuum chamber, heat supply, vacuum-producing unit; and device to collect water vapor as it evaporates from the food. All vacuum driers also must have an efficient means of heat transfer to the product in order to provide the necessary latent heat of evaporation and a means for removal of vapor evolved from the product during drying. Such driers must be designed to establish and maintain a vacuum, and they must be vacuum tight to keep pumping requirements to a minimum. A vacuum drier and associated vessels must be of adequate strength to withstand the differential pressure of the atmosphere on the outside and the vacuum maintained

inside. The outside pressure may exceed internal pressure by as much as 2000 lb/ft^2 (90 kg/m^2).

Vacuum Shelf Drier. A vacuum shelf drier, the simplest type of vacuum drier, consists of a vacuum chamber containing a number of shelves arranged to supply heat to the product and to support the trays on which the product is loaded into the chamber. The shelves may be heated electrically, or more often by circulating a heated fluid through them. The heated shelves are called platens, and they convey heat to the food in contact with them by conduction; where several platens are placed one above another they also radiate heat to the food on the platen below. The rate of heat transfer is slow in this type of equipment compared with that in driers in which the drying material is moved or agitated by some means. The vacuum chamber is connected to suitable vacuum-producing equipment, located outside the vacuum chamber, which may be a vacuum pump or a steam ejector. Another essential part of a vacuum drier that has a vacuum pump is a cold-wall condenser, which collects water vapor. This may be located inside or outside the vacuum chamber, but must be ahead of the vacuum pump to prevent water vapor from entering the pump. A steam ejector also may be used to create the vacuum. It is a kind of aspirator in which high-velocity steam jetting past an opening draws air and water vapor from the vacuum chamber. In units with a steam ejector, a condensor is not necessary because the steam ejector can condense water vapor as it is drawn along with the air from the vacuum chamber.

A shelf drier is suitable for batch-type operation only. The equipment is easy to maintain and is very suitable for high-vacuum operation. A wide range of fruit products—liquids, pastes, powders, discrete particles, chunks, slices, and wedges—can be processed in this type of drier.

Conical Rotating Vacuum Drier. The conical rotating vacuum drier is a batch-type drier. The rotation of the vessel provides a very gentle sliding action of the product over the internal walls of the vessel, which is jacketed for the circulation of hot water, steam, or other heating medium. The sliding movement results in close contact of the product with the heat-transfer surface. The movement of the product ensures an even temperature throughout its mass. This type of drier is suitable for powders or discrete particles, providing that they do not tend to form lumps or to adhere to the walls of the vessel, thus impeding heat transfer and drying.

Rotary Vacuum Drier. The rotary vacuum drier, a very efficient dryer, has a horizontal stationary cylindrical vessel with a jacket for the heat-transfer medium. The unit is capable of batch-type operation only. It will handle a wide range of products and is suitable for high-vacuum operation.

Vacuum Belt Drier. Continuous vacuum operation can be achieved in a vacuum belt drier. This type of drier consists of a horizontal tanklike chamber in which there are one or more conveyor belts. The chamber is connected to vacuum-producing and moisture-condensing systems. Appropriate isolation locking arrangements at the charging and discharging ends permit a continuous flow of material through the drier. A series of infrared heater panels or heated platens are located above and sometimes below the conveyor to supply heat. A tumbling effect is produced at the end of each conveyor band when a multiconveyor belt system is used to ensure exposure to the heat sources on each side of the particles as they progress through the drier. The continuous vacuum belt drier is particularly suitable for the drying of fruit pieces, granules, and discrete particles at a relatively high vacuum. The capital cost of this equipment is much greater than for a batch unit of similar capacity.

Freeze Driers. In conventional vacuum drying, moisture in the foods is evaporated from the liquid to the vapor phase. In freeze drying, the moisture is removed from the product by sublimation, i.e., converting ice directly into water vapor. Therefore, no transfer of liquid occurs from the center of the mass to the surface. As drying proceeds, the ice layer gradually recedes toward the center, leaving vacant spaces formerly occupied by ice crystals. The advantages of freeze drying are high flavor retention; maximum retention of nutritional value; minimal damage to product structure and texture; little change in product shape, color, and appearance; and finished products with an open structure that permits fast and complete rehydration. The disadvantages of the process include high capital investment; high processing costs; and the need for special packaging to avoid oxidation and moisture pickup in finished products.

The freeze-drying process involves two basic steps. The raw fruit is first frozen in the conventional manner and then dried to around 2% moisture in a vacuum chamber while still frozen.

The freezing rate may affect the reconstitution property of freeze-dried foods because the porous nature of the product is controlled by this factor. The process of vapor removal is influenced by the size, shape, and tortuosity of the pores. In general, the faster the freezing rate, the smaller the voids, and the slower the freeze-drying rate (Karel 1963).

The most common type of freeze-drying equipment is a batch chamber system similar to a vacuum shelf drier but with special features to meet the needs of the freeze-drying process. The material to be dried is placed on trays arranged between the heated plates. The plates are either electrically heated or internally heated with steam, pressurized hot water, or oil. Before heat is applied, a vacuum must be drawn in the chamber. The vacuum is produced either with a mechanical pump or with steam ejec-

tors. Rapid evacuation of the chamber is essential once the product is loaded to ensure that there is no thawing before freeze drying is started. The vacuum system must maintain a pressure under 1 Torr so that the product remains frozen as long as water is present duirng the drying cycle. Figure 8.3 shows the relationship between pressure and temperature that makes freeze drying possible.

Refrigerated condensers are usually applied to condense the water vapor that is removed from the product. The surface of the refrigerated condenser must be maintained at a lower temperature than the ice within the product to ensure mass transfer. To improve storage stability of freeze-dried fruits, it is a common practice at the completion of the drying process to break the vacuum in the chamber with nitrogen gas, thereby preventing the instantaneous absorption of oxygen by the open pores of the dried product. The nitrogen-impregnated product is then packed under nitrogen in airtight, moisture-proof containers.

A great deal of research has focused on methods to improve heat transfer during freeze drying. The early technique of supplying by conduction from plates to food placed between them restricted vapor flow and also provided uneven contact. To overcome this, expanded metal inserts are used between the plates and the metals. This process, referred to as "accelerated freeze drying," is described in detail by Hanson (1961).

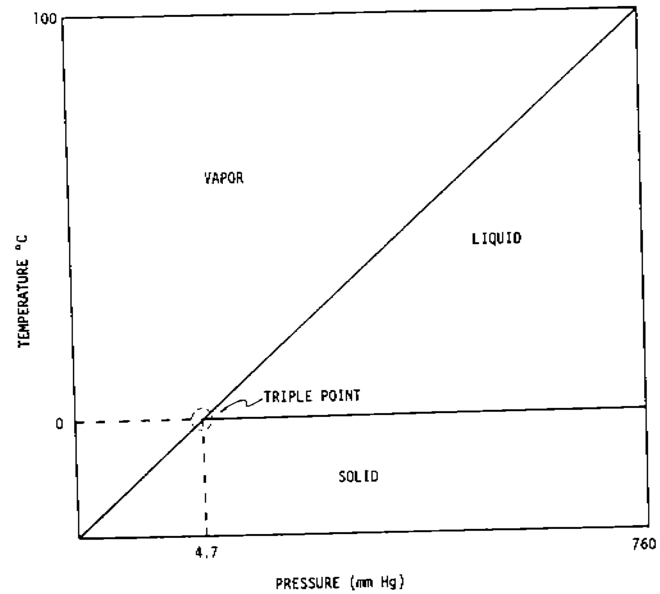

FIG. 8.3. Phase diagram of water shows relationship between temperature and pressure that makes freeze drying possible.

To improve the efficiency of the freeze-drying process, multiple batch chamber operations are employed by some plants. Continuous systems have also been designed (Togashi and Mercer 1966). Considerable attention is being given to hybrid schemes that take advantage of the positive effect of freeze drying on the cellular structure of food but reduce the cost of the process by removing some of the moisture before freezing or freeze drying (Anon. 1982).

Freeze drying is applicable to a wide range of fruit products. The major problem is its very high cost compared with the costs of canning, freezing, or other dehydration methods. Freeze drying has proved to be the superior method of dehydration for many common fruits, including blueberries, cherries, and strawberries (Anon. 1982).

In freeze drying, as in other dehydration techniques, it is difficult to dehydrate large pieces of product. As the size of product pieces increases, so does the cost of freeze drying, quality problems, and reconstitution problems.

POSTDEHYDRATION TREATMENTS

Treatments of finished dehydrated fruits vary with the kind of fruit and intended utilization of the product. Common postdehydration treatments are described in this section.

Sweating

During the sweating process dehydrated fruits are held in bins or boxes in order to equalize moisture. In the case of sun- and kiln-dried evaporated fruit, sweating involves readdition of moisture to a desired level. Bins are used for secondary drying to reduce moisture levels of particulate fruits from 10–15% to 3–5%, a range at which drying rates are limited by slow diffusion of water. Temperatures of 100°–120°F (38–49°C) and air flow, provided by a small blower fan, of about 100 ft min (33 m/min suit the nearly dry product. These conditions minimize the risk of heat damage at a stage when fruit products are most susceptible to degradation. During bin drying, which may take up to 36 hr, water contents are equalized as well as reduced. Air for the process is frequently dehumidified by condensation of water through refrigeration or by a desiccant such as silica gel. Bins used for secondary drying may vary in size and capacity. The usual size is about 4 × 4 × 4 ft (122 × 122 × 122 cm) with a perforated mesh or plate bottom, which is hinged for dropping down to a suitable angle to allow the dry material to discharge through a sliding door at the front of the bin; or a false bottom can be set permanently at an angle of about 45° to assist forward flow of the dry product.

Most continuous dehydration equipment, or bin dryers when used for final drying, usually discharge the dried product into a conveying system that brings the material to a sieving and aspirating plant to remove fines. In the course of this transfer, the product becomes well mixed. In this way, any unevenness in moisture is corrected. At this point in the process, when the low-moisture material leaves the bins or dehydrators, the area of the plant where final sieving, grading, selection, and packaging take place should be air conditioned and dehumidified to below 30% RH.

Screening

Most dehydrated fruit products have a specification for acceptable screen size distribution. During production of dehydrated fruit, fines are formed in the cutting operation and in the normal movement of product through the processing line. Screening is therefore required to remove the unwanted size portion of the dried product which can be utilized in other products. Sometimes the fines represent a loss due to operation. The removal of unwanted size pieces of fines is usually accomplished by passing the dry product over a vibrating wire cloth or perforated metal screens and collecting the fractions separately. The acceptable fraction passes onto the final inspection operation.

Inspection

The dried product is inspected to remove foreign materials, discolored pieces, or other imperfections such as skin, carpel, or stem particles. Manual and visual selection of most dehydrated fruit products is necessary and is carried out by inspectors who remove undesirable particles while the product is moving along on a continuous PVC belt at a speed of about 15–20 min (4.6–6.0 m/min). In addition to inspectors, magnetic devices are usually installed over the belt to remove metal contaminants.

Instantization Treatments

Various treaments are often used to improve the rehydration rate of low-moisture fruit products. A "flaking" treatment developed by Roberts and Faulkner (1965) involves warming fruit particles of less than 5% moisture and passing them between rollers spaced 0.001 in. (0.025 mm) apart. This process results in a shaped product having a thickness of approximately 0.01 in. (0.25 mm) because the product is resilient and partially tends to assume its initial thickness. The application of steel rollers 15 in. (40.6 cm) in diameter and 36 in. (76.2 cm) long rotating at about 300 rpm is recommended. The flakes are only compressed; because their cellular structure is unruptured, they rapidly resume their original particle size and shape during rehydration. Flaked fruit products rehydrate much more rapidly than regular products, and the rehydration rate of the flakes may be controlled by adjusting the thickness of the final product.

Another flaking treatment (Puccinelli 1968) recommended for low-moisture fruit differs from the Roberts and Faulkner method in that it tries to rupture the cells. This is achieved by passing the fruit pieces (dehydrated to 12–30% moisture) between counter-rotating rolls rotating at different speeds. Then the products having broken cellular structure are dehydrated to a moisture content of 2–10%. Products with unruptured cells will reconstitute as a piece, while those with ruptured cells tend to become mushy after rehydration.

Another instantization process involves perforating partially dried apple segments at about 16–30% moisture content, then dehydrating the perforated segments to an ultimate moisture content of less than 5% (Dorsey and Strashun 1962). The perforation treatment shortens the time required for dehydration to an ultimate moisture content. The dehydrated apple segments will rehydrate much more readily than apple segments that have not been perforated (Fig. 8.4). The punctures caused by this treatment largely disappear after rehydration. Perforation is accomplished by using a pair of rollers carried on spindles adjustably spaced;

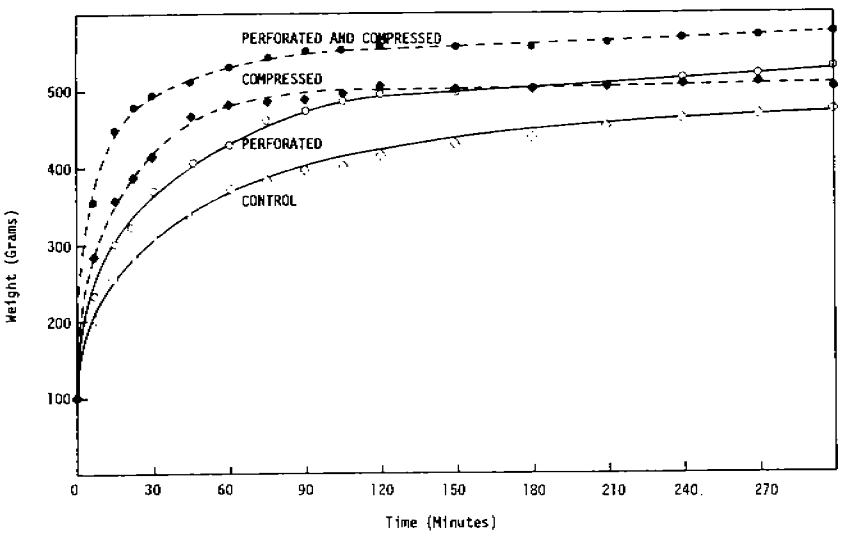

FIG. 8.4. Rehydration curves for instantized versus noninstantized low-moisture apple slices in hot (150°F or 65°C) water. (Courtesy of Vacu-Dry Co.)

one of the rollers is formed with a plurality of perforators or studs. The rollers operate in counter directions and the partially dried apple segments are passed through the rollers to perforate the segments.

For larger fruit pieces such as apple slices or wedges the improved rehydration effect resulting from compression and perforation treatments are additive; often both treatments are applied simultaneously to such products.

Packaging

The shelf life of a dehydrated fruit product is influenced to a large extent by its packaging, which must conform to certain special criteria: (a) protection of the dehydrated product against moisture, light, air, dust, microflora, foreign odor, insects and rodents; (b) strength and stability to maintain original container properties through storage, handling, and marketing; (c) size, shape, and appearance to promote salability of the product; (d) composition approved for use in contact with foods; and (e) acceptable cost.

Evaporated apples are packed tightly in fiberboard boxes lined with 2- to 4-mil polyethylene bags from which most of the air between the individual pieces has been expelled. Fruit dried to 24% moisture may be expected to retain its moisture content during considerable periods under ordinary conditions because it is in approximate equilibrium with the atmosphere at a relative humidity of about 75%.

The hygroscopic nature of low-moisture fruit tissue makes it imperative that special precautions be taken against moisture absorption. Low-moisture products must be packaged as soon as possible after removal from the dehydrator; and hermetically sealed containers are required to prevent absorption of moisture with subsequent caking and loss of quality during extended storage.

Dehydrated fruits are packed for institutional and remanufacturing use in large units such as bags, drums, bins, cartons, and cans. Heat-sealed polyethylene liners are usually required for bulk packs. For smaller retail market or catering packs, metal cans of foil-laminated, flexible pouches often are used. In case of high-value, freeze-dried products, small flexible containers prepared from three-ply laminates such as polyolefin–foil–Mylar are recommended.

Some dehydrated commodities, particularly freeze-dried products, must be packed in inert gas to ensure storage stability. Nitrogen gas is most commonly used to extend the storage stability of oxygen-sensitive products (Villota *et al.* 1980). In inert gas packing, oxygen levels of 1–2% can be routinely attained. Tin cans are used for nitrogen packing. Gas packing of cans is a well-established process. The simplest method of insert gas packing consists of piercing a hole in a filled and sealed can and placing it in a cabinet that is then evacuated. This operation removes the air from the can. When a sufficiently low pressure has been reached, nitrogen gas is admitted until atmospheric pressure is attained again. The cabinet is then opened and the holes are sealed by soldering. The more common method of gas packing is to run the filled cans through a sealing machine that applies only the first clinch. The partially sealed cans are placed in a vacuum chamber, evacuated, flushed with nitrogen, and sealed completely.

Vacuum Packing. Vacuum packing has been used to some extent with powdered or small grain and compressed dehydrated products. The container used must withstand the pressure differential without leaking. The vacuum needed to effectively extend shelf life is difficult to attain in commercial practice.

In-Package Desiccation. In-package desiccation has been used successfully for many dried fruit products, particularly for powders. The desiccant compound is placed in the container inside a small envelope made out of a moisture-permeable material that prevents contamination of the product with the desiccant. Calcium oxide (silica gel), a high-capacity adsorbent and desiccant, is usually applied. It is a granular, amorphous form of silica that can adsorb approximately 40% of its weight in moisture at 100% RH, and even when saturated remains dry and free-flowing. Package desiccation is effective if a storage period at reasonably low temperature (around 70°F or 21°C) is allowed for reduction of moisture to a suitable low level before any high temperatures are encountered.

To ensure the free-flowing property of fruit powders, particularly those high in sugar content such as prunes, figs, dates, and apple powders, an anticaking agent is mixed with the low-moisture product, usually during the milling operation. Calcium stearate is the most commonly used anticaking agent in dehydrated products. It is mixed with the fruit powder at a rate of approximately 0.25–0.50%. Silica gels and hydrated sodium silica aluminate have also been recommended as anticaking agents in dehydrated fruit powders. Fumed silicas at a rate of 1–2% have also been recommended to prevent caking of powdered fruits such as orange juice crystals (Salunkhe *et al.* 1974).

Compression

Freeze-dried fruits retain their original size, thus the space-saving advantage of conventional dehydration is lost. However, freeze-dried products can be compressed to reduce their bulkiness and packaging costs. Research at the U.S. Army Natick Laboratories resulted in significant

FIG. 8.5. Compressed freeze-dried cherry disk (center bottom). After rehydration, each disk (3 × ⅝ or 7.6 × 1.6 cm) provides sufficient filling for a 9-in (23-cm) pie. (Courtesy of U.S. Army Natick Laboratories.)

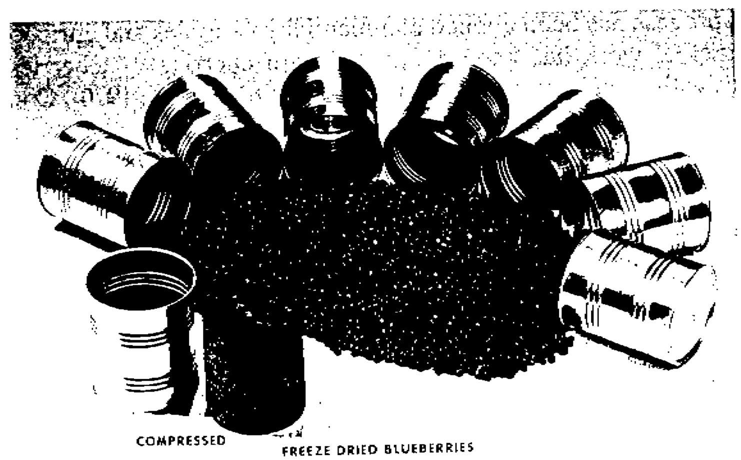

FIG. 8.6. Compressed freeze-dried blueberries. The compression process reduces the volume of freeze-dried berries 7 to 1. (Courtesy of U.S. Army Natick Laboratories.)

volume reductions of blueberries and cherries without impairing their rehydratability, appearance, flavor, or texture on reconstitution (Rahman *et al.* 1970; Do *et al.* 1975). The process involves freeze drying of sulfite-dipped IQF blueberries or red tart cherries to a moisture of less than 2%, then subjecting them to dry heat in an oven at 200°F (93°C) for approximately 10 min. The fruit becomes thermoplastic after heating and is compressed in a Carver Press with forces between 100 and 1500 lb/in.^{2} (7 and 20 kg/cm^2) and a dwell time of approximately 5 sec. The compressed, dehydrated fruits (Figs. 8.5 and 8.6) were either in the form of bars (3 × 1 × ½ in.; 7.6 × 2.5 × 1.3 cm) or disks (3 in diameter; 7.6 cm) which can fit into a No. 2½ can. Cherry disks were ½ in. thick and blueberry disks were ⅝ in. thick. The resulting reduction in volume was 1:7 for blueberries and 1:8 for cherries. This represents a reduction of 12- and 13-fold when the volume of dehydrated and compressed fruit is compared to those of loose frozen products.

Dehydrofreezing

Dehydrofreezing aims to combine the best features of both drying and freezing. The process consists of drying fruit—after peeling, coring, or pitting, and sulfiting treatments—to about 50% of its original weight and volume. Drying is usually accomplished in a tunnel drier, and then the product is frozen for preservation. The quality of dehydrofrozen fruit is equal to that of frozen products, as the drying process is discontinued at a stage where quality impairment usually does not occur. The advantages of the process are a 50% reduction in storage and freight charges and even greater savings in packaging costs in comparison with frozen products.

This process has been applied commercially to apples and apricots, and experimental work has been conducted with cherries, blueberries, and peaches with promising results (Lazar *et al.* 1961; Kitson 1970). Commercial production of dehydrofrozen apples, which are suitable for use in pies, exceeds that of any other dehydrofrozen commodity (Salunkhe *et al.* 1974). The apples are cored, trimmed, sliced, sulfured by immersion, dried to 50% weight reduction and frozen rapidly, preferably by air blast at −20 to −30°F (−29° to −34°C) and stored at 0°F (−18°C), or lower.

QUALITY CONTROL

The objective of quality control procedures is to ensure that the finished product shipped from a plant is within the specifications that have been established for that product. To ensure the acceptability of the product, the raw material must be inspected, important processing data (drying temperature, vacuum, process time, etc.) must be monitored and

recorded, and the finished product must be tested. The development of meaningful sampling procedures and enforcement of proper plant sanitation are also important functions of the quality control personnel. However, these aspects are basically the same for all food processing operations and will not be specifically discussed here.

Quality control measures that are unique for dried fruit products are moisture content, sulfur dioxide content, screen analysis, physical characteristics of dried fruit, reconstitution ratio, bacterial count, and oxygen content of gas-packed products.

Moisture Content

Several methods are available for determining moisture in fruits. The vacuum oven method involves the measurement of the weight loss due to the evaporation of water. The procedure is to granulate the sample and dry it in a vacuum oven at 70°C (158°F) for about 5 hr.

A more rapid calculation of moisture in dry products can be made by using an infrared moisture meter. The sample first must be finely ground and passed through a 10-mesh screen. A given weight is dried under an infrared lamp, and the loss in weight is recorded by a sensitive scale on the tester. This test provides results in about 7–10 min. However, this method is not as accurate as the vacuum oven method.

The Karl–Fisher titration method for moisture determination is very convenient for low-moisture fruit products. This sensitive test is based on the non-stoichiometric reaction of water with iodine and sulfur dioxide in pyridine-methanol solution. For the details of moisture determination methods, the reader should consult Joslyn (1970).

Sulfur Dioxide Content

Sulfur dioxide determinations in fruit are usually carried out by the Monier-Williams method in which SO_2 is removed from the fruit by distillation in the presence of a strong acid (HCl) and subsequently measured in the distillate gravimetrically or by titration (Joslyn 1970).

Screen Analysis.

Screen analysis and the proportion of fines are often important quality characteristics of dehydrated fruits. The number and size of the screens to be used depends on the range of particle sizes expected or defined in the product specification. If desirable, a preliminary screening will establish these parameters. The analytical procedure involves weighing the sample and transferring it quantitatively to dry sieves. The sieves are then placed in a shaker and allowed to shake for a specified time, usually 3–5 min. The slices of 'Totapuri' and 'Seeding' cultivars in India. Drying required 10 hr with 1.3 lb/ft^2 (6.5 kg/m^2) tray load, while sun drying was completed in 15 hr. Blanched slices dried quicker than unblanched ones. Soaking the mango slices in 1% potassium metabisulfite solution for 30 min improved the retention of ascorbic acid, and sulfur-treated slices were lighter in color and rated higher by an organoleptic panel after 6 months of storage. Pulverized mango powder has been used in the preparation of curry.

Slices of Florida-grown mangos, pretreated with a 5-min dip in 2% sodium bisulfite solution, were successfully dried in solar driers (Coleman *et al.* 1980).

Kiwifruit. Slices of kiwifruits too small for fresh market have been dried successfully without sulfite treatment (Simons 1978). The best color retention was obtained with 4-mm slices dried below 122°F (50°C). Dried pieces may be consumed without further treatment or after rehydration to nearly full shape or size, or they may be candied for use as a confection.

Persimmon. Testoni and Maltini (1978) reported that 5/16-in. (8-mm) thick slices of Japanese persimmon grown in Italy were dehydrated to 20% moisture in a shelf oven with hot-air circulation at 40°–50°C (104°–106°F).

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