CHAPTER 11

PHYSIOLOGICAL FACTORS IN DRYING AND STORING FARM CROPS

THIS CHAPTER focuses on the drying and storage of grains, oil-seeds, hay, cotton, and tobacco. However, the primary focus is on grains and oilseeds, collectively referred to as **grain**. Major causes of postharvest losses in these products are fungi, insects, and rodents. Substantial deterioration of grain can occur in storage. However, where the principles of good grain storage are applied, losses are minimal.

Preharvest invasion of grains by storage insects is usually not a problem in the midwestern United States. Field infestations can occur in grains when they are dried in the field at warm temperatures during harvest. Preharvest invasion by storage fungi is possible and does occur if appropriate weather conditions prevail when the grain is ripening. For example, preharvest invasion of corn by *Aspergillus flavus* occurs when hot weather is prevalent during grain ripening; it is, therefore, more common in the southeastern United States (McMillan et al. 1985). Invasion of wheat, soybeans, and corn by other fungi can occur when high ambient relative humidities prevail during grain ripening (Christensen and Meronuck 1986). However, the great majority of damage occurs during storage, due to improper conditions that permit storage fungi or insects to develop.

Deterioration from fungi during storage is prevented or minimized by (1) reduction of grain moisture content to below limits for growth of fungi, (2) maintenance of low grain temperatures throughout the storage period, (3) chemical treatment to prevent the development of fungi or to reduce the rate of fungal growth while the grain moisture content is being lowered to a safe level, and (4) airtight storage in which initial microbial and seed respiration reduces the oxygen level so that further activity by potentially harmful aerobic fungi is reduced.

Reduction of moisture by artificial drying is the most commonly used technique. The longer grain is stored, the lower its storage moisture should be. Some of the basic principles of grain drying and a summary of methods for predicting grain drying rate are included in the section on Drying Theory.

Reduction of grain temperature by aeration is practical in temperate climates and for grains that are harvested during cooler seasons. Fans are operated when ambient temperature is lower than grain temperature. Basic information on aeration is summarized in the section on Drying Theory. Use of refrigeration systems to reduce temperature is not generally cost-effective for feed grains but may have application for higher value food grains.

Chemical treatment of grain is becoming more common and is briefly described in the section on Prevention of Deterioration.

When grain is placed in airtight silos, the oxygen level is rapidly reduced, and carbon dioxide increases. Although many fungi will not grow under ideal hermetic conditions, some will grow initially in imperfectly sealed bins, and this growth can reduce the feeding value of the grain for some animals. Partially emptied bins may support harmful mold, yeast, and bacterial growth, which makes the grain unsuitable for human consumption. Airtight storage is briefly addressed in the section on Oxygen and Carbon Dioxide under Factors Determining Safe Storage.

Deterioration from insects can also be prevented by a combination of reducing moisture and lowering temperature. Lowering of temperatures is best achieved by aeration with cool ambient air during cool nights and periods of cool weather. Both the use of clean storage structures and the segregation of new crop grain from carryover grain or grain contaminated with insects are important. If insect infestation has already occurred, fumigation is often used to kill the insects. Aeration with cold air may retard the development of the insect population. Prevention and control of insect infestations are addressed in the section on Prevention of Deterioration.

For information on rodent problems, see the section on Prevention of Deterioration.

Moisture content is the most important factor determining successful storage. Although some grains are harvested at safe storage moistures, other grains (notably corn, rice, and most oilseeds) must usually be artificially dried prior to storage. During some harvest seasons, wheat and soybeans are harvested at moistures above those safe for storage and, therefore, also require drying.

Sauer (1992), Brooker et al. (1992), Hall (1980), Christensen and Meronuck (1986), and Gunasekaran (1986) summarize the basic aspects of grain storage and grain drying. Chapter 23 of the *ASHRAE Handbook—Applications* covers crop-drying equipment and aeration systems.

FACTORS DETERMINING SAFE STORAGE

Moisture Content

Grain is bought and sold on the basis of characteristics of representative samples. Probes or samplers, such as diverters, are used to obtain representative subsamples. Often representative subsamples must be taken from a large quantity (several tons) of grain. Manis (1992) summarizes sampling procedures and equipment. For safe storage, it is necessary to know the range in moisture content within a given bulk and whether any of the grain in the bulk has a moisture content high enough to permit damaging fungal growth. This range can be determined by taking probe samples from different portions of the bulk. Commonly, in large quantities of bulk-stored grain, some portions have moisture contents 2 to 3% higher than the average (Brusewitz 1987). If the moisture content anywhere in the bulk is too high, fungi will grow, regardless of the average. Therefore, the moisture content of a single representative sample is not a reliable measure of storage risk or spoilage hazard. Measurement of moisture content and the precision of various moisture-measuring methods are covered in the section on Moisture Measurement.

Table 1 summarizes recommended safe storage moistures for several common grains. Note that for long-term storage, lower

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moistures are recommended. Most storage fungi will not grow in environments where the relative humidity of the air between kernels is lower than 60%. The relationship between grain moisture and the relative humidity of air between kernels is addressed in the section on Equilibrium Moisture. Table 2 summarizes the relative humidities and temperatures that permit the growth of common storage fungi. Table 3 summarizes the relative humidities and temperatures that permit growth of common storage insects.

Moisture Transfer

If temperatures vary within bulk-stored grain, moisture migrates from warmer to cooler portions. The rate of movement depends on the gradients in moisture content and temperature. Sellam and Christensen (1976) studied moisture transfer in a sample of one cubic foot of shelled corn initially at 15.5% moisture. They used heat lamps to produce a temperature differential of 18°F along the length of a sealed plastic container 1.22 ft long. After 2 days, this gradient (approximately 15°F/ft) caused the moisture content at the cool end to increase by 1.2% and the moisture content at the warm end to decrease by 1.1%.

Table 1 Safe Storage Moisture for Aerated Good-Quality Grain

Grain	Maximum Safe Moisture Content, % wet basis
Shelled corn and sorghum	
To be sold as #2 grain or equivalent by spring	15
To be stored up to 1 year	14
To be stored more than 1 year	13
Soybeans	
To be sold by spring	14
To be stored up to 1 year	12
Wheat	13
Small grain (oats, barley, etc.)	13
Sunflower	
To be stored up to 6 months	10
To be stored up to 1 year	8

Source: McKenzie (1980).

Thorpe (1982) developed an equation to describe moisture transfer caused by a temperature gradient. The equation was solved numerically, and laboratory experiments of moisture transfer in wheat were successfully modeled initially at 12% moisture content. In the experiments, an 18°F temperature gradient was developed across a column of wheat 0.66 ft thick (equivalent to a gradient of 27°F/ft). After one month, the moisture content of the warmest grain dropped to 10.6%, while the moisture content of the coolest grain increased to 14%.

Smith and Sokhansanj (1990a) provided a method of approximate analysis of the energy and velocity equations of the natural convection in grain bins. They showed that for small cereals such as wheat, the influence of convection on temperature gradients may not be significant, whereas for larger cereals such as corn, the effect of convection is more noticeable. Smith and Sokhansanj (1990b) also showed that convection flows in a grain bin are significant if the radius of the storage bin is approximately equal to the height of the bin.

Christensen and Meronuck (1986) cite an example of heating that developed in wheat initially at 13.2% in a nonaerated bin. Specially prepared samples were placed at various positions in the bin at the time the bin was filled. After 3 months, the grain began to heat from fungal activity. Moisture content in some of the samples had increased to 18%, while in others it had decreased to 10%.

These examples illustrate the importance of aeration in long-term storage. Aeration is generally required for storage structures with capacities exceeding 2000 bu or 50 tons. Moisture migration can initiate fungal and insect growth, and the heat of respiration generated by these organisms accelerates their growth and leads to spoilage. Studies suggest that temperature gradients could promote spoilage of grain loaded into a ship or barge—even if the grain is initially at a uniform moisture. Most shipments do not spoil because they remain in the ship or barge for a short time and because large temperature gradients do not develop. Christensen and Meronuck (1986) report studies of grain quality in barges and ships.

Table 2 Approximate Temperature and Relative Humidity Requirements for Spore Germination and Growth of Fungi Common on Corn Kernels

Fungus	Minimum Relative Humidity for Spore Germination,[b] %	Grain Moisture,[a] % w.b.	Growth Temperature, °F		
			Lower Limit	Optimum	Upper Limit
Alternaria	91	19	25	68	97 to 104
Aspergillus glaucus	70 to 72	13.5 to 14	46	75	100
Aspergillus flavus	82	16 to 17	42 to 43	97 to 100	111 to 115
Aspergillus fumigatus	82	16 to 17	54	104 to 108	131
Cephalosporium acremonium[c]	97	22	46	75	104
Cladosporium	88	18	23	75 to 77	86 to 90
Epicoccum	91	19	25	75	82
Fusarium moniliforme	91	19	39	82	97
Fusarium graminearum, *Fusarium roseum (Gibberella zeae)*	94	20 to 21	39	75	90
Mucor	91	19	25	82	97
Nigrospora oryzae[c]	91	19	39	82	90
Penicillium funiculosum[c] *(field)*	91	19	46	86	97
Penicillium oxalicum[c] *(field)*	86	17 to 18	46	86	97
Penicillium brevicompactum (storage)	81[b]	16	28	73	86
Penicillium cyclopium (storage)	81[b]	16	28	73	86
Penicillium viridicatum (storage)	81[b]	16	28	73	97

Source: Stroshine et al. (1984).

[a] Approximate corn moisture content at 77°F, which gives an interseed relative humidity equal to the minimum at which fungus can germinate. It is probably *below* the moisture content at which the fungus would be able to compete with other fungi on grain, except for *Aspergillus glaucus*. The latter has no real competitor at 72% rh, except occasionally *Aspergillus restrictus.*

[b] Approximately 5% or more of the population can germinate at this relative humidity.

[c] Rarely found growing in stored grain, regardless of moisture and temperature.

Temperature

Most processes that cause spoilage in stored grains are accompanied by a temperature rise. Therefore, temperatures should be monitored throughout the bulk. Temperature monitoring is commonly done by attaching thermocouples to cables that extend through the bulk from the top to the bottom, with thermocouples about 3 to 6 ft apart on each cable. Single cables are used in the center of circular bins up to 25 ft in diameter. In large bins or flat storage structures, cables are spaced 20 to 25 ft apart. Relatively dry grain is a good insulator, so a **hot spot** can develop without being detected immediately (Foster and Mayes 1962). However, when these thermocouple spacings are used, extensive spoilage can usually be detected by a temperature rise at a nearby thermocouple. A temperature rise of even a few degrees is evidence that grain has spoiled or is spoiling. Forced aeration maintains a uniform and preferably low temperature throughout the bulk.

Table 2 summarizes minimum, optimum, and maximum temperatures for the growth of some common storage fungi. Storage molds grow slowly at 32 to 40°F. However, at higher moisture contents, some species of *Penicillium* will grow when the temperature is slightly below freezing. Grains with a moisture content high enough for invasion by *Aspergillus glaucus* will deteriorate rapidly at temperatures of 75 to 85°F but can be kept for months without damage at 40 to 50°F. Most grain-infesting insects become inactive below about 50°F. Mites remain active but cannot develop rapidly below about 40°F. Control of fungi and insects is described further in the section on Prevention of Deterioration.

Oxygen and Carbon Dioxide

Only a few fungi that cause stored grain deterioration can grow in an atmosphere containing only 0.1 to 0.2% oxygen or more than 60% carbon dioxide. Some yeasts can grow in grain stored in airtight storage at moisture contents above 18 to 19% and temperatures above 40°F, producing flavors that make the grain unsuitable as food. However, the grain remains suitable feed for cattle and swine (Bell and Armitage 1992), and its nutritional value may be enhanced (Beeson and Perry 1958).

Dry grain is stored in airtight underground or earth-sheltered structures in many parts of the world (Dunkel 1985, Bell and Armitage 1992). Janardhana et al. (1998) reported that while storing shelled corn at 15 to 20% moisture in a warm, high-humidity environment, visible molding and the loss of food reserves can be postponed up to 45 days by using high carbon dioxide in the storage. Alagusundarum et al. (1996) studied the diffusion of carbon dioxide introduced into bulk stored grain. Bell and Armitage (1992) and Shejbal (1980) cover controlled atmosphere storage in more detail.

Insects present when dry grain is put into storage usually die when oxygen has been depleted, and do not usually reproduce if grain is sufficiently dry and in good condition. Insects can also be controlled in conventional storage structures by forcing carbon dioxide or other gases such as nitrogen through the grain (Jay 1980, Ripp 1984, White and Jayas 1991). Generally, carbon dioxide environments are effective for insect control only when concentrations are greater than 40% for long periods. Paster et al. (1990, 1991) investigated biogenerated modified atmospheres for insect control. Athie et al. (1998) reported that using the toxic chemical phosphine with a high carbon dioxide environment increased the effectiveness of the phosphine, particularly in resistant populations. However, the costs of controlled-atmosphere storage may be uneconomic unless the structure can be inexpensively sealed or the gases can be inexpensively generated or purchased.

Grain Condition

Grain that has been stored for several months may already be invaded by storage fungi and partly deteriorated, whether or not this is evident to the naked eye. Molding occurs more rapidly in partially deteriorated grain than in sound grain when the grain is exposed to conditions favorable to mold growth. Microscopic examination and plating techniques can often reveal the fungal infection of grain in its early stages (Sauer et al. 1992, Christensen and Meronuck 1986, Stroshine et al. 1984). Accelerated storage tests, in which samples of grain are stored at a moisture content in equilibrium with air at 80% rh and 85°F and examined periodically, are useful in evaluating storability. These tests enable a manager to estimate the risk of spoilage during storage and to take appropriate action.

Equilibrium Moisture

If air remains in contact with a product for sufficient time, the partial pressure of the water vapor in the air reaches equilibrium

Table 3 Estimates of Optimum and Minimum Temperatures and Relative Humidity Conditions for Population Increase of Grain-Infesting Insects

Insect Type			Temperature, °F		Minimum Relative Humidity, %
In Regard to Temperature	In Regard to Relative Humidity	Species	Minimum	Optimum	
		Species Needing High Temperatures			
Cold hardy	Tolerant of low	*Trogoderma granarium*	75	91 to 99	1
		Cryptolestes ferrugineus	73	90 to 95	10
		Oryzaephilus surinamensis	70	88 to 93	10
	Need moderate	*Plodia interpunctella*	64	82 to 90	40
	Need high	*Cryptolestes turcicus*	70	86 to 91	50
Moderately cold hardy	Tolerant of low	*Tribolium confusum*	70	86 to 91	1
	Need moderate	*Rhyzopertha dominica*	73	90 to 95	30
		Lasioderma serricorne	72	90 to 95	30
Cold susceptible	Tolerant of low	*Tribolium castaneum*	72	90 to 95	1
		Oryzaephilus mercator	70	88 to 93	10
	Need high	*Cryptolestes pusillus*	72	82 to 91	60
		Species Thriving at Moderate Temperatures			
Cold hardy	Need moderate	*Sitotroga cerealella*	61	79 to 86	30
	Need high	*Sitophilus granarius*	59	79 to 86	50
		Stegobium paniceum	63	77 to 82	60
		Acarus siro	45	70 to 81	65
Moderately cold hardy	Need high	*Sitophilus oryzae*	63	81 to 88	60

Source: Pederson (1992). Reprinted with permission.

with the partial pressure of the water vapor in the material. The relative humidity of the air at equilibrium with a material of a given moisture is the **equilibrium relative humidity**. The moisture content of a hygroscopic material in equilibrium with air of a given relative humidity is the **equilibrium moisture content** M_e.

Several theoretical, semitheoretical, and empirical models have been proposed for calculating the M_e of grains. Morey et al. (1978) report that the modified Henderson equation is among the best equations available:

$$M_e = \frac{1}{100}\left[\frac{\ln(1.0-\phi)}{-K(t+C)}\right]^{1/N} \tag{1}$$

where

M_e = equilibrium moisture content, decimal, dry basis
t = temperature, °C = (°F – 32)/1.8
ϕ = relative humidity, decimal equivalent
K, N, C = empirical constants

Table 4 lists values for K, N, and C for various crops. ASAE *Standard* D245.5 also gives the Chung-Pfost equation, another equation used to predict M_e. Figure 1, based on the Chung-Pfost equation, shows equilibrium moisture content curves for shelled corn, wheat, soybeans, and rice. Note that equilibrium moisture depends strongly on temperature. ASAE *Standard* D245.5 gives additional curves drawn from the Chung-Pfost equation and tabulated experimental data. Pfost et al. (1976) summarize variations in reported values of M_e for several grains. Locklair et al. (1957) give data for tobacco.

The modified Henderson and the Chung-Pfost equations give only approximate values of M_e and are for desorption. When grain is rewetted after it has been dried to a low moisture, the value of M_e is generally lower for a given relative humidity. Sun and Woods (1993) reviewed the equilibrium relationship between wheat moisture content and air relative humidity. They reported that the hysteresis effect was greatest at 20 to 40% rh. They also observed that the modified Henderson equation was least effective for wheat.

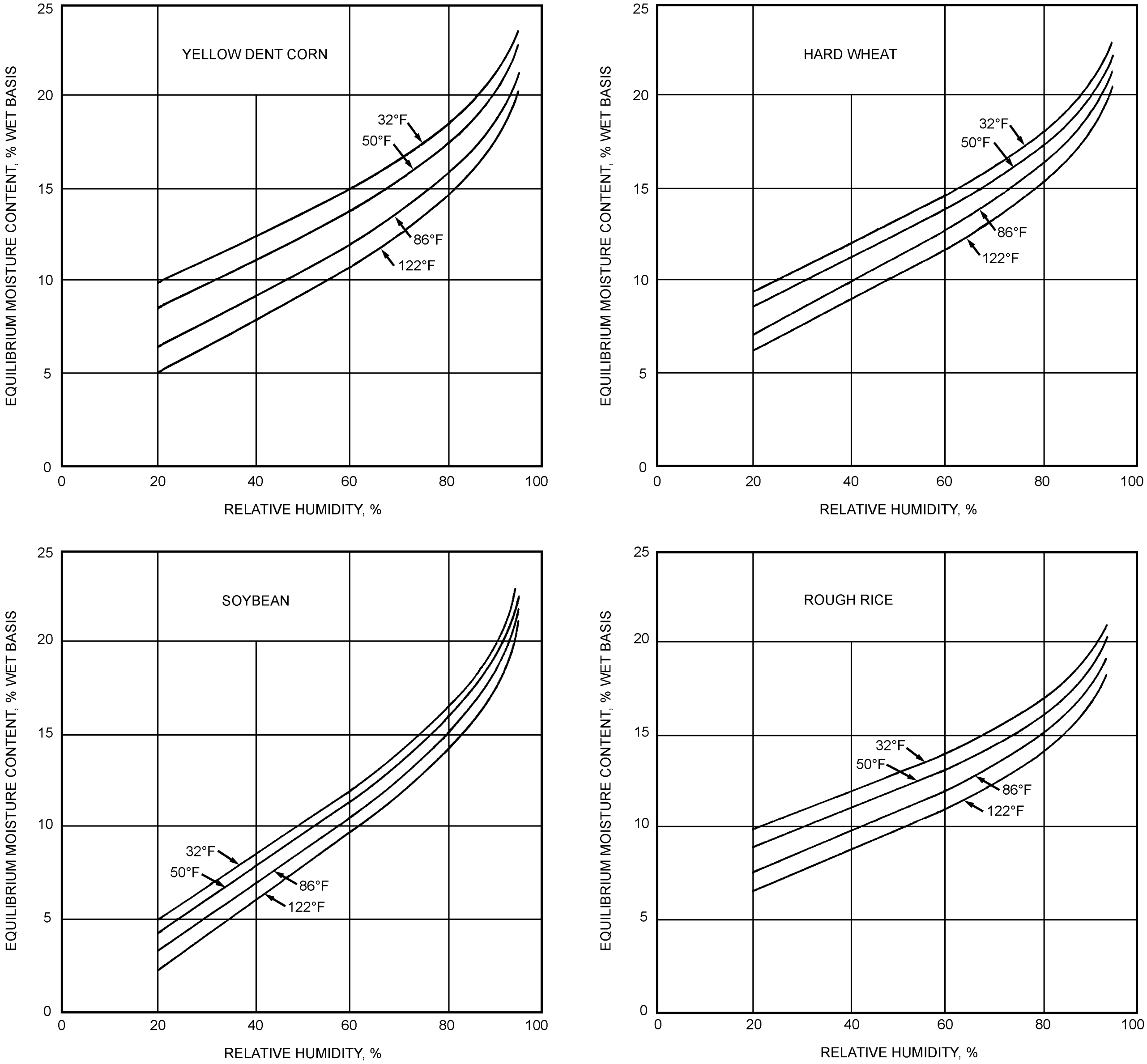

Fig. 1 Equilibrium Moisture Relationships for Certain Crops
(ASAE *Standard* D245.5)

Table 4 Desorption Equilibrium Moisture Constants for Modified Henderson Equation [Equation (1)] for Various Crops

Product	*K*	*N*	*C*
Barley	0.000022919	2.0123	195.267
Beans, edible	0.000020899	1.8812	254.230
Canola (rapeseed)	0.000505600	1.5702	40.1205
Corn, yellow dent	0.000086541	1.8634	49.810
Peanut, kernel	0.000650413	1.4984	50.561
Peanut, pod	0.000066587	2.5362	23.318
Rice, rough	0.000019187	2.4451	51.161
Sorghum	0.000085320	2.4757	113.725
Soybean	0.000305327	1.2164	134.136
Wheat, durum	0.000025738	2.2110	70.318
Wheat, hard	0.000023007	2.2857	55.815
Wheat, soft	0.000012299	2.5558	64.346

Source: ASAE *Standard* D245.5.

Variations of as much as 0.5 to 1.0% can result from differences in variety; maturity; and relative starch, protein, and oil content. Shivhare et al. (1992) reported that, under a microwave drying regime, M_e increased with drying air velocity and decreased with microwave power.

High-temperature drying can decrease the M_e of shelled corn by 0.5 to 1.0% for a given relative humidity (Tuite and Foster 1963). Sun and Woods (1994) reported that the equilibrium moisture content for wheat dried at low temperatures was generally higher than the data reported in the literature. Chung and Verma (1991) studied the M_e of rice during drying and storage.

MOISTURE MEASUREMENT

Rapid and accurate measurement of moisture of grains, seeds, and other farm crops determines whether they can be safely stored. Allowable upper limits for moisture are set by the market, and discounts and/or drying charges are usually imposed for higher moistures. Drying the grain to moistures below the accepted market limit or the limit for safe storage moisture results in additional drying expense and may actually decrease the value of the grain.

If shelled corn is dried to 12% moisture, it becomes brittle and breaks more easily during handling. The moisture removal also reduces the total weight of grain. After drying 1 bu (56.0 lb) of shelled corn at 18% moisture to 15%, only 0.965 bu (54.0 lb) remains. However, at high moistures, seed respiration and fungal growth can cause greater loss in value.

Moisture content can be expressed on a wet or dry basis. The wet basis is used by farmers and the grain trade, while dry-basis moistures are often used by engineers and scientists to describe drying rates. Unless otherwise noted, moisture contents in this chapter are on a **wet basis** and are calculated by dividing the weight of water in the material by the total weight. The **dry basis** is calculated by dividing the weight of water by the weight of dry matter.

$$\text{\% Moisture (wet basis): } M_w = \frac{100W_w}{W_w + W_d} \tag{2}$$

$$\text{\% Moisture (dry basis): } M_d = \frac{100W_w}{W_d} \tag{3}$$

where

W_w = weight of water
W_d = weight of dry matter

Percent moisture on a wet basis M_w can be converted to percent moisture on a dry basis M_d and vice versa by the following formulas:

$$M_d = \frac{100M_w}{100 - M_w} \tag{4}$$

$$M_w = \frac{100M_d}{100 + M_d} \tag{5}$$

The weight change resulting from a change in moisture can be determined by assuming that the weight of dry matter is constant. The dry matter is calculated by multiplying the weight of grain by the quantity $(1 - M_w/100)$. For example, 1000 lb of wheat at 15% moisture has 1000 (1 − 15/100) = 850 lb of dry matter and 150 lb water. As grain dries, the dry matter remains constant and the mass of water is reduced. If the dry matter is constant, the mass or moisture content of the dried grain is

$$W_w\left(1 - \frac{M_w}{100}\right) = W_d\left(1 - \frac{M_d}{100}\right) \tag{6}$$

The weight W_d of the dried grain after it reaches a moisture content of M_d is

$$W_d = W_w\left(\frac{100 - M_w}{100 - M_d}\right) \tag{7}$$

For example, if 1000 lb of grain is dried from 15% to 13% moisture, the dried weight is

$$W_d = 1000\left(\frac{100 - 15}{100 - 13}\right) = 977 \text{ lb}$$

Similarly, to find the moisture content M_d of grain after it reaches a dried weight of W_d

$$M_d = 100 - \frac{W_w}{W_d}(100 - M_w) \tag{8}$$

For example, 100 lb of grain at 15% is dried to a weight of 950 lb. The dried moisture content is

$$M_d = 100 - \frac{1000}{950}(100 - 15) = 10.5\%$$

If two quantities of grain at differing moistures are mixed, the final moisture of the mixture can be determined by calculating the weight of water in each, adding these together, and dividing by the total weight. The weight of water is the product of the decimal equivalent of M_w and the total weight. For example, if 500 lb of grain at 16% moisture is mixed with 1000 lb of grain at 14% moisture, the weight of water in each sample is

$$(500 \text{ lb})(0.16) = 80 \text{ lb}$$

$$(1000 \text{ lb})(0.14) = 140 \text{ lb}$$

The moisture content after mixing will be

$$\left[\frac{80 + 140}{500 + 1000}\right] \times 100 = 14.7\%$$

Either a **direct method** or an **indirect method** is used to determine moisture content. Direct methods involving the use of an oven determine moisture content based on the loss in product weight caused by evaporation of the water. The Karl Fischer method, a basic reference method involving a chemical reaction of water and a reagent, is classified as a direct method.

Indirect methods such as moisture meters measure the properties of the material that are functions of moisture content. Indirect moisture measurement methods are used in commercial practice. Direct methods are used in research and to calibrate indirect methods. Christensen et al. (1992) summarize approved methods used in Europe and the United States.

Direct Methods

Christensen et al. (1992) describe the fundamental or basic methods of moisture determination as (1) drying in a vacuum with a desiccant and (2) titration with a Karl Fischer reagent. It is assumed that these methods measure the true water content and can be used to verify measurements obtained with routine reference methods, including oven drying and the Brown-Duval distillation method. The Brown-Duval method, not commonly used, involves heating the grain in a special apparatus and condensing and collecting the vaporized water.

Oven techniques use either forced-convection air ovens or vacuum ovens and either ground or whole kernels. Drying times and temperatures vary considerably, and the different techniques can give significantly different results. Oven techniques are used to calibrate moisture meters (see the section on Indirect Methods). As a result, during the export of grain, the meter moisture measurements can vary between arrival and destination if the importing country uses a different standard oven technique than the exporting country.

ASAE *Standard* S352.2 is a widely used standard that recommends heating temperatures and times for various grains. The temperatures may be either 217°F (shelled corn, soybeans, sunflower) or 266°F (wheat, barley, onion). Heating times vary between 50 min (onion seeds) and 72 h (soybeans, shelled corn).

Grinding samples and using a vacuum oven reduce heating time. When initial moistures are high, a two-stage method may be used (USDA 1971). A weighed sample of whole grain is partially dried to a moisture content of 13% or below, weighed, and then ground and completely dried as in the one-stage method. The mass lost in both stages is used to calculate moisture content.

Indirect Methods

Electronic moisture meters are simple to operate and give readings within minutes. Direct methods of moisture measurement are used to calibrate the meters for each type of grain. Meters are sensitive to grain temperature, and calibration must include a temperature correction factor. The newer automatic meters or **moisture computers** sense and correct for sample temperature and print or display the corrected moisture.

Near infrared reflectance (NIR) instruments have been developed that measure moisture, protein, starch, and oil content of ground samples (Butler 1983, Cooper 1983, Watson 1977). **Near infrared transmittance (NIT) instruments** measure the properties of whole seeds.

Conductance meters measure resistance, which varies with grain moisture. The practical range of moisture content measurable by conductance meters is approximately 7 to 23%. For up to 72 h after moisture addition or removal, the moisture at the surface of the kernels differs from the moisture in the interior. Therefore, recently dried grain reads low and recently wetted grain reads high. Mixing wet and dry grain and mixing good grain with partially deteriorated grain also result in erroneous readings. Martin et al. (1986) measured the signal from the conductance Tag-Heppenstall meter and related this to individual kernel moisture variations in mixtures of wet and dry corn.

The dielectric properties of products depend largely on moisture content. The **capacitance meter** uses this relationship by using grain as the dielectric in a capacitor in a high-frequency electrical circuit. Although the capacitive reactance is the primary portion of the overall impedance measured, the resistive component is also significant in many capacitance meters. At higher frequencies and in instruments with insulated electrodes, the relative effect of the resistance is reduced, which is important in reducing errors introduced by unusual product surface conditions. Capacitance meters are affected less than conductance meters by uneven moisture distribution within kernels. Sokhansanj and Nelson (1988a) showed that the capacitance meters give low and high readings, respectively, on recently dried or rewetted grain. The range of measurable moisture content is slightly wider than that for conductance meters.

Moisture measurement by capacitance meters is sensitive to temperature, product weight, and product density (Sokhansanj and Nelson 1988b). To reduce these sources of error, a weighed sample is introduced into the measuring cell by reproducible mechanical means. Calibration, including temperature correction, is required. At least one commercially available unit measures bulk density and corrects for this factor as well as temperature. Tests of moisture meter accuracy have been reported by Hurburgh et al. (1985, 1986). Accuracy of moisture readings can be improved by taking multiple samples from a grain lot and averaging the meter measurements. Equipment for continuous measurement of moisture in flowing grain is available commercially but is not widely used in the grain trade.

Equilibrium relative humidity (described in the section on Equilibrium Moisture) can be used to indicate moisture content. It also indicates storability independent of the actual moisture content because the equilibrium relative humidity of the air surrounding the grain, to a large extent, determines whether mold growth can occur (see Table 2). Measurement of equilibrium relative humidity at specific points within a grain mass requires specialized sampling equipment and has been used primarily for research.

Hay moisture content does not receive the consideration devoted to grains. Oven methods (ASAE *Standard* S358.2) are used extensively, as well as some commercial hay and forage moisture meters. Several conductance moisture meters are available for both hay and forages, but the extreme variability of the moisture and density of the material tested lead to great variability in the readings obtained. A reasonable indication of the average moisture content of a mass of hay can be obtained if many (25 or more) measurements are taken and averaged.

Microwave radiation can be used to sense properties of grains. Kraszewski and Nelson (1992) reviewed the use of resonant microwave cavities to determine simultaneously both mass and moisture content in grain kernels.

PREVENTION OF DETERIORATION

Fungal Growth and Mycotoxins

Fungal growth is the most important limitation to successful drying and storage of grain. Sauer et al. (1992) provide a good review of microflora in grains. Early detection of mold growth would provide the storage manager with a management tool. Magan (1993) reviews early detection methods, including enzyme and biochemical tests, fungal volatiles, and respiration activity.

Mycotoxins (fungal metabolites) may affect the marketability and use of moldy grains. Wicklow (1988) reported that climate and other natural processes influenced the distribution of aflatoxigenic strains of microflora. Choudhary and Sinha (1993) reported that aflatoxigenic *Aspergillus* species were positively correlated with grain moisture content in the field and afternoon relative humidity.

In the United States, corn is one of the major crops that must be harvested above safe storage moistures. Shelled corn can be held at these higher moistures for a limited time before it must be dried. Mold growth produces carbon dioxide (CO_2). Allowable storage time at moistures above those for safe storage can be estimated by measuring CO_2 production of samples. By assuming that a simple sugar is being oxidized by microbial respiration, CO_2 production can be expressed in terms of dry matter loss in percent by weight.

Saul and Steele (1966) and Steele et al. (1969) studied the production of CO_2 in shelled corn, mostly on samples above 18%. Based on changes in the official grade of shelled corn, Saul and Steele (1966) established a criterion for acceptable deterioration of quality as 0.5% dry matter loss. This is equivalent to the production of 0.00735 lb of CO_2 per pound of dry matter. Thompson (1972) expressed Saul's data on dry matter loss per pound of dry matter as a function of moisture, time, and temperature using the following mathematical expression:

$$\mathrm{DML} = 1.3\left[\exp\left(\frac{0.006\theta}{K_m K_t}\right) - 1.0\right] + \frac{0.015\theta}{K_m K_t} \tag{9}$$

with

$$K_m = 0.103\left[\exp\left(\frac{455}{M_d^{1.53}}\right) - 0.00845 M_d + 1.558\right] \tag{10}$$

$$K_t = A \exp B(0.03t + 0.533) + C \exp[0.0183t - 0.285)] \tag{11}$$

where

DML = dry matter loss per pound of dry matter, lb/lb
θ = time in storage, h
t = grain temperature, °F
M_d = moisture content, % dry basis

Table 5 lists values for A, B, and C. According to Steele (1967), the damage level effect can be determined for dry matter losses of 0.1, 0.5, and 1.0% by multiplying θ from Equation (9) by K_d, where K_d is calculated as follows:

$$0.1\%\ \mathrm{DML}:\ K_d = 1.82\exp(-0.0143d) \tag{12a}$$

$$0.5\%\ \mathrm{DML}:\ K_d = 2.08\exp(-0.0239d) \tag{12b}$$

$$1.0\%\ \mathrm{DML}:\ K_d = 2.17\exp(-0.0254d) \tag{12c}$$

where d = mechanical damage, % by weight.

Seitz et al. (1982a, 1982b) found unacceptable levels of aflatoxin production prior to the time when 0.5% dry matter loss occurred. Nevertheless, Equations (9) through (12) give approximate predictions of mold activity, and they have been used in several computer simulation studies (Thompson 1972, Pierce and Thompson 1979, Brooker and Duggal 1982). Based on a simulation, Thompson (1972) concluded that for airflow rates between 0.5 and 2.0 cfm/bu, grain deterioration in the top layer during low-temperature drying is doubled when the airflow rate is halved. Thompson also concluded that weather variations during harvest and storage seasons can cause up to a twofold difference in deterioration. Pierce and Thompson (1979) recommend airflow rates for several common low-temperature drying systems and for various locations in the midwestern United States.

Table 5 Constants for Dry Matter Loss of Shelled Corn [Equation (11)]

Temperature Range, °F	Moisture Range, % Wet Bulb	*A*	*B*	*C*
$t < 60$	All moistures	128.76	−4.68	0
$t \geq 60$	$M_w \leq 19$	32.3	−3.48	0
$t \geq 60$	$19 < M_w \leq 28$	32.3	−3.48	$(M_w - 19)/100$
$t \geq 60$	$M_w > 28$	32.3	−3.48	0.09

Acceptable dry matter losses for wheat and barley are much lower than those for shelled corn—0.085% and 0.10%, respectively (Brook 1987). Hamer et al. (1992) reported visible mold growth at 0.15% dry matter loss. Brook reported reasonable agreement with published experimental data for the following equation (Frazer and Muir 1981) for allowable storage time as a function of percent wet basis moisture and temperature based on the development of visible mold:

$$\log\theta_D = A + BM_w + Ct + G \tag{13}$$

where

θ_D = allowable storage time, days
t = temperature, °F
A,B,C,G = empirical constants, defined as follows:

Moisture Range, % w.b.	*A*	*B*	*C*	*G*
$12.0 < M_w \leq 19.0$	6.234	−0.2118	−0.0293	0.937
$19.0 < M_w < 24.0$	4.129	−0.0997	−0.0315	1.008

Brook (1987) also reported that an adaptation of Equation (9) by Morey et al. (1981) gave reasonable results for storage time of wheat. Morey's method predicts dry matter loss by adjusting M_d for differences between corn and wheat equilibrium relative humidities.

Table 2 can be used to gain insight into the deterioration of stored grain. *Aspergillus* and *Penicillium* sp. are primarily responsible for deterioration because some of their species can grow at storage moistures and temperatures frequently encountered in commercial storage. In temperate climates, shelled corn is often harvested at relatively high moistures; during the harvest and storage season, ambient temperatures can be relatively low. Aeration of the grain during cold weather and cool nights can reduce the temperature of the grain to 40 to 60°F. This is below the optimum temperature for growth of *Aspergillus* sp. (Table 2). However, *Penicillium* sp. can still grow if grain moisture is above 16 to 17%; therefore, its growth is a persistent problem in temperate climates. If hot weather prevails prior to harvest, *Aspergillus flavus*, which competes effectively at warmer temperatures and higher moistures, can begin to grow in the field and continue to grow in stored shelled corn. In growing seasons when shelled corn must be harvested at moistures above 22%, *Fusarium*, *Alternaria*, *Epicoccum* and *Mucor* can compete with *Penicillium* sp.

Chemical Treatment. Application of chemicals slows deterioration until grain can be either dried or fed to animals. Preservatives include propionic acid, acetic acid, isobutyric acid, butyric acid (Sauer and Burroughs 1974), a combination of sorbic acid and carbon dioxide (Danziger et al. 1973), ammonia (Peplinski et al. 1978), and sulfur dioxide (Eckhoff et al. 1984). Propionic acid (Hall et al. 1974) or propionic-acetic acid mixtures, although not extensively used, are perhaps the most popular in the United States with high-moisture corn. Acetic acid and formic acid are popular in Europe. Grain treated with propionic acid can be used only as animal feed.

Hertung and Drury (1974) summarize fungicidal levels needed to preserve grain at various moistures. Both ammonia (Nofsinger et al. 1979, Nofsinger 1982) and sulfur dioxide (Eckhoff et al. 1984, Tuite et al. 1986) treatments require considerable management. Attention must be given to uniform application of the chemicals to the entire quantity of stored grain.

Antimicrobial properties occurring naturally in plants have been studied (Beuchar and Golden 1989, Shelef 1984). Some of these also inhibit mycotoxin formation (Bullerman et al. 1984, Rusal and Marth 1988). The essential oils of oregano and thyme were tested as fumigants against *Aspergillus* species and natural microflora of wheat (Paster et al. 1995). Oregano oil provided complete control at 2.0 mL/m^3; thyme oil was not completely effective at 4.0 mL/m^3 and affected seed germination at 5.0 mL/m^3.

Insect Infestation

Insects cause major losses of stored grain. Grain containing live insects or insect fragments in sufficient numbers is unsuitable for human food. When grain is stored for long periods (a year or more), insects can infest the grain and cause significant amounts of deterioration. Traps and chemical attractants have been developed that monitor insects in storage facilities (Barak and Harein 1982, Barak and Burkholder 1985, Burkholder and Ma 1985). Detection in samples of grain taken for grading and inspection is often difficult. Many of the insects are relatively small and can be seen easily only with a magnifying lens. Many of the insect larvae develop within the kernels and cannot be detected without staining techniques or grinding of the grain sample. Infested grain mixed with good grain in marketing channels compounds the infestation problem.

Sanitation is one of the most effective methods of insect control. Cleaning of bins after removal of old-crop grain and prior to filling with new-crop grain is essential. In bins containing perforated floors, fine material that collects beneath the floors can harbor insects, which infest new-crop grain when it is added. Control by aeration is feasible in temperate climates because insect activity is reduced greatly at temperatures below 50°F. The effectiveness of temperature control has been documented by Bloome and Cuperus (1984) and Epperly et al. (1987). Chemicals have frequently been used to control live insects in grain, and methods are described by Harein and Davis (1982). Thermal treatments have also been investigated (Lapp et al. 1986). Pederson (1992) summarizes the types of grain insects, the ecology of insect growth, and the methods of detecting insects in samples of grain. Athie et al. (1998) reviewed the status and future of chemical grain protectants. Armitage et al. (1994) proposed an integrated pest management strategy combining surface insecticide treatment and aeration. Control of insects in farm-stored grain is detailed by Storey et al. (1979), Quinlan (1982), and Harein and Davis (1992).

Rodents

The shift from ear corn harvesting and storage to field shelling and the introduction of metal bins have helped to reduce rodent problems. However, significant problems can arise when rodents consume grain and contaminate it with their hair and droppings. Storage structures should be made rodent-proof whenever possible. Rats can reach 13 in. up a wall, so storage structures should have concrete foundations and metal sides that resist gnawing.

In some countries, smaller on-farm storage structures are often elevated 18 in. to give protection from rodents. Double-wall construction and false ceilings should be avoided, and vents and holes should be covered with wire grates. Proper sanitation can help prevent rodent problems by eliminating areas where rodents can nest and hide. Rodents need water to survive, so elimination of available water is also effective. Techniques for killing rodents include trapping, poisoning with bait, and fumigation. Harris and Bauer (1992) address rodent problems and control in more detail.

DRYING THEORY

In ordinary applications, drying is a heat and mass transfer process that vaporizes liquid water, mixes the vapor with the drying air, and removes the vapor by carrying away the mixture mechanically. In forced-convection drying, sufficient heat for vaporization of product moisture (about 1100 Btu/lb of water) comes from the sensible heat in the drying air.

The most common mode of drying uses the sensible heat content of the air. The method can be diagrammed on the psychrometric chart by locating the state points for the air as it is heated from ambient temperature to plenum temperature and then exhausted from the grain. The process is assumed to be adiabatic (i.e., all the sensible heat lost by the air is used for moisture vaporization and converted to latent heat of the water vapor in the drying air). Therefore, the state point of the air can be considered to move along adiabatic saturation lines on the psychrometric chart. In the simplified psychrometric chart in Figure 2, the ambient air at dry-bulb temperature t_a and dew-point temperature t_{dp} is heated to drying air temperature t_d, where it has a relative humidity ϕ_1. As the air passes through the grain, its sensible heat provides the latent heat of vaporization of the water. When the air exits from the grain, its temperature has dropped to t_e, and its relative humidity has increased to ϕ_2. The moisture gained by each pound of drying air is the difference $W_2 - W_1$ in humidity ratio. If the air has sufficient contact time with the grain, the value for ϕ_2 will be the equilibrium relative humidity of the grain at that moisture and temperature t_e.

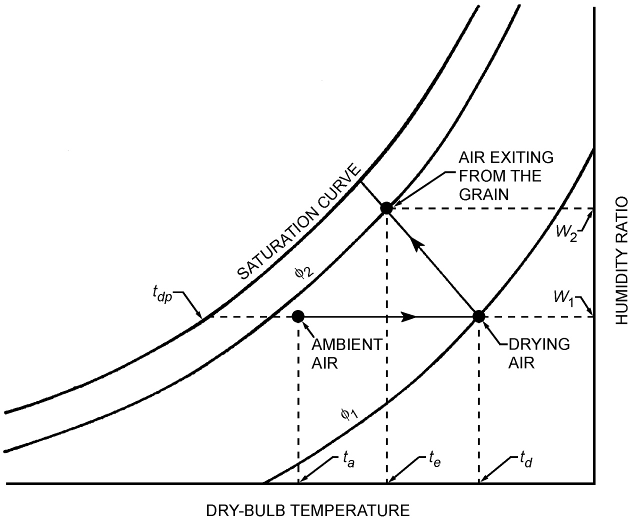

Fig. 2 Drying Process Diagrammed on Psychrometric Chart Showing Adiabatic Evaporation of Moisture from Grain

Example 1. Shelled corn at 20% moisture content is dried with air heated to 160°F. The air has an ambient temperature of 68°F with a dew point of 50°F. The air is observed to exhaust from the shelled corn at 86°F. Find the amount of energy needed to heat the air and the amount of water removed per pound of dry air.

Solution: Estimate the psychrometric air conditions, using information contained in Chapter 6 and assuming a standard atmospheric pressure of 14.696 psi.

At 68°F, the enthalpy of the dry air is $h_a = 16.337$ Btu/lb (Table 2 in Chapter 6) and the saturation vapor pressure $p_{ws} = 0.33921$ psi (Table 3 in Chapter 6). At 50°F dew point, the vapor pressure $p_w = 0.17811$ psi, and the enthalpy of the water vapor $h_g = 1083.03$ Btu/lb (Table 3 in Chapter 6). The relative humidity is then $\phi = 53\%$ [Equation (24) in Chapter 6]; humidity ratio $W = 0.0076$ lb/lb [Equation (22) in Chapter 6]; and enthalpy $h = 24.6$ Btu/lb [Equation (29) in Chapter 6]. As the air is heated, the humidity ratio is assumed to remain constant. At 160°F, the enthalpy of the dry air is $h_a = 38.474$ Btu/lb (Table 2 in Chapter 6) and the saturation vapor pressure $p_{ws} = 4.7468$ psi (Table 3 in Chapter 6). The relative humidity has been reduced to $\phi = 4\%$ [Equation (24) in Chapter 6]; enthalpy increased to $h = 46.8$ Btu/lb [Equation (29) in Chapter 6]; and the wet-bulb temperature of the drying air is $t^* = 84$°F [iterative solution to Equation (35) in Chapter 6]. The amount of energy needed to heat each pound of dry air is then 46.8 – 24.6 = 22.2 Btu.

As the heated air passes through the grain, it increases in moisture and decreases in temperature until it comes into equilibrium with the corn at the point of air exhaust (initially 20%). The exhaust air relative humidity can be estimated by reading the equilibrium relative humidity from the curve for shelled corn shown in Figure 1. Enter the curve for shelled corn at 20% equilibrium moisture content and a temperature of 86°F. The equilibrium relative humidity is approximately 92%. At 86°F, the saturation vapor pressure of the air $p_{ws} = 0.61584$ psi (Table 3 in Chapter 6); the vapor pressure $p_w = 0.5666$ psi [Equation (24) in Chapter 6]; and the humidity ratio $W = 0.0249$ lb/lb [Equation (22) in

Chapter 6]. Each pound of dry air carries with it 0.0249 – 0.0076 = 0.0173 lb of water from the grain.

After the grain at the air exhaust has dried to 15%, the equilibrium moisture content curve from Figure 1 can be used to estimate the exhaust air relative humidity. If the temperature of the air were 86°F, then the equilibrium relative humidity would be approximately 76%; if the temperature of the air were 122°F, then the equilibrium relative humidity would be approximately 81%. From Equation (35) in Chapter 6, the wet-bulb temperatures associated with these two points are 80°F and 115°F, respectively. A linear interpolation between these two points results in an air temperature of 90°F and an equilibrium relative humidity of 77%. At 90°F, the saturation vapor pressure of the air p_{ws} = 0.69889 psi (Table 3 in Chapter 6); the vapor pressure p_w = 0.5381 psi [Equation (24) in Chapter 6]; and the humidity ratio W = 0.0236 lb/lb [Equation (22) in Chapter 6]. Each pound of dry air carries with it 0.0236 – 0.0076 = 0.016 lb of water from the grain.

Thin Layer Drying

A *thin layer* of grain is a layer of grain no more than several kernels deep. The ratio of grain to air is such that there is only a small change in temperature and relative humidity of the drying air when it exits the grain. The maximum rate ($dM/d\theta$) at which a thin layer of a granular hygroscopic material (such as grain) transfers moisture to or from air can be approximated by the following equation (Hukill 1947):

$$\frac{dM}{d\theta} = -C(p_g - p_a) \tag{14}$$

where

C = constant representing vapor conductivity of kernel and surrounding air film
p_g = partial pressure of water vapor in grain
p_a = partial pressure of water vapor in drying air

If $p_g > p_a$, drying takes place. If $p_g = p_a$, moisture equilibrium exists and no moisture transfer occurs. If $p_g < p_a$, wetting occurs. The assumption of a linear relationship between (1) water vapor pressure and equilibrium relative humidity and (2) equilibrium relative humidity and moisture content over the range in which drying occurs lead to the following equation:

$$\frac{dM}{d\theta} = -k(M - M_e) \tag{15}$$

where

M = moisture content (dry basis) of material at time θ
M_e = equilibrium moisture content (dry basis) of material in reference to drying air
k = constant dependent on material

The solution to this differential equation is

$$\frac{M - M_e}{M_o - M_e} = \exp(-k\theta) \tag{16}$$

where M_o = moisture content, dry basis, when $\theta = 0$.

In later work (Hukill and Schmidt 1960, Troeger and Hukill 1971), Hukill recognized that Equation (16) did not describe the drying rate of grain adequately. Misra and Brooker (1980) identified the following model as more promising for shelled corn:

$$\frac{M - M_e}{M_o - M_e} = \exp(-K\theta^N) \tag{17}$$

They give an equation for K, which is a function of drying air temperature and velocity, and another equation for N as a function of drying air relative humidity and initial grain moisture. Their equations are valid for drying air temperatures of 36 to 160°F, drying air relative humidities of 3 to 83%, drying air velocities of 5 to 459 fpm, and initial moistures of 18 to 60% (dry basis).

Li and Morey (1984) also fit their data to Equation (17) and found that within the limits of drying airflow rates and air relative humidities used, K and N can be expressed as functions of air temperature and initial grain moisture only. Their equations for K and N apply to air temperatures ranging from 80 to 240°F, initial grain moistures of 23 to 36% dry basis, airflows of 20 to 100 cfm/bu, and air relative humidities of 5 to 40%.

Other forms of the thin layer drying equation have also been proposed. Thompson et al. (1968) fitted data for shelled corn to the following equation, which is applicable in the range of 140 to 300°F:

$$\theta = A \ln MR + B(\ln MR)^2 \tag{18}$$

where

A = –1.86178 + 0.00488t
B = 427.3740 exp (–0.03301t)
MR = $(M - M_e)/(M_o - M_e)$
θ = time, h
t = temperature, °F

Martins and Stroshine (1987) describe the effects of hybrid and damage on the thin layer drying rate and give values for constants A and B in Equation (18) for several hybrids and damage levels.

Results of thin layer drying tests for other grains have also been reported. Data are available for the following grains:

- Wheat (Watson and Bhargava 1974, Sokhansanj et al. 1984, Bruce and Sykes 1983)
- Soybeans (Hukill and Schmidt 1960, Overhults et al. 1973, Sabbah et al. 1976)
- Barley (O'Callaghan et al. 1971, Sokhansanj et al. 1984, Bruce 1985)
- Sorghum (Hukill and Schmidt 1960, Paulsen and Thompson 1973)
- Rice (Agrawal and Singh 1977, Noomhorm and Verma 1986, Banaszek and Siebenmorgen 1990)
- Sunflower (Syarief et al. 1984, Li et al. 1987)
- Canola (Sokhansanj et al. 1984, Pathak et al. 1991)
- Oats (Hukill and Schmidt 1960)
- Lentil seeds (Tang et al. 1989)

Sokhansanj and Bruce (1987) developed more rigorous thin layer drying equations based on simultaneous heat and mass transfer through a single kernel and demonstrated that such a model accurately predicts the temperature and moisture content of the grain throughout the drying process. Jayas et al. (1991) reviewed thin-layer drying models, and Parti (1993) presented comparisons of models under different conditions.

Equations (16) through (18) do not describe the usual drying process, where grain is in a deep bed and where drying air changes condition but does not necessarily reach moisture equilibrium with the grain. Those models, which are formulated using thin layer drying equations such as these, are summarized in the section on Deep Bed Drying.

Airflow Resistance

Data on resistance of grain to airflow are used for a variety of design calculations such as selecting fans, determining optimum depths for drying bins, predicting airflow paths in bins with aeration ducts, and determining the practical limitations on airflow caused by fan power requirements. For a given fan and dryer or bin, airflow resistance can change with the type of grain being dried, the depth of grain, and the amount of fine material in the grain. In many grain-drying applications, such as when air is forced through a grain bin that has a uniform grain depth and a full perforated floor, airflow is one-dimensional and the pressure drop per unit depth of grain can be assumed to be constant. Shedd (1953) determined pressure drop per unit depth versus airflow for a number of grains and seeds and summarized by plotting them on logarithmic axes. These curves (commonly called **Shedd's curves**) are included in ASAE *Standard* D272.3. They can also be calculated from the following equation (ASAE 1996, Sokhansanj and Yand 1996):

$$\frac{\Delta p}{L} = \frac{aQ^2}{\ln(1 + bQ)} \tag{19}$$

where

Δp = pressure, in. of water
L = bed depth, ft
Q = airflow rate, cfm/ft^2
a, b = empirical constants

Table 6 summarizes the constants for Equation (19) for some of the more common grains. Constants for grass seeds and some vegetables are included in ASAE *Standard* D272.3. Jayas and Mann (1994) reviewed the presentation of airflow resistance data for 22 different seeds, including grains. They reported that the mean relative percent error for each grain could be significantly reduced if the airflow range were divided into two subranges: 0.8 to 10 cfm/ft^2 and 10 to 70 cfm/ft^2.

Equation (19) gives the airflow resistance for clean, dry grain when the bin is loaded by allowing the grain to flow into the bin through a chute from a relatively low height. Kumar and Muir (1986) reported on the effect of filling method on the airflow resistance of wheat and barley. Jayas et al. (1987) showed that the resistance of canola to airflow in a horizontal direction was 0.5 to 0.7 times the resistance to airflow for the vertical direction.

The presence of fine material in grain can significantly alter the airflow resistance. Fine material is generally defined as broken kernels and other matter that can pass through a round hole sieve with a hole size slightly less than the kernel size. For shelled corn, a 0.1875 in. (3/16 in.) round hole sieve is used to measure fines.

The pressure drop per foot is routinely increased by multiplying the value from Equation (19) by a packing factor. A factor of 1.5 is used for shelled corn; 1.2 for other grains. Haque et al. (1978) developed a correction factor for airflow resistance in shelled corn with fine material fractions from 0 to 20%.

Table 6 Constants for Airflow Resistance [Equation (19)]

Material	Value of a, in. of water·min^2/ft^2	Value of b, ft^2/cfm	Range of Q, cfm/ft^2
Barley	6.76×10^{-4}	6.71×10^{-2}	1.1 to 40
Canola (rapeseed)	1.65×10^{-3}	3.69×10^{-2}	4.77 to 52
Ear corn	3.29×10^{-4}	1.65	10 to 69
Lentils	1.72×10^{-3}	1.87×10^{-1}	0.55 to 116
Oats	7.62×10^{-4}	7.06×10^{-2}	1.1 to 40
Peanuts	1.20×10^{-4}	5.64×10^{-1}	6 to 60
Popcorn, white	6.92×10^{-4}	5.99×10^{-2}	1.1 to 40
Popcorn, yellow	5.63×10^{-4}	8.94×10^{-2}	1.1 to 40
Rice, rough	8.12×10^{-4}	6.71×10^{-2}	1.1 to 30
Rice, long brown	6.48×10^{-4}	3.93×10^{-2}	1.1 to 32
Rice, long milled	6.89×10^{-4}	4.24×10^{-2}	1.1 to 32
Rice, medium brown	1.10×10^{-3}	5.53×10^{-2}	1.1 to 32
Rice, medium milled	9.16×10^{-4}	5.38×10^{-2}	1.1 to 32
Shelled corn	6.54×10^{-4}	1.54×10^{-1}	1.1 to 60
Shelled corn, low airflow	3.09×10^{-4}	4.34×10^{-2}	0.05 to 4
Sorghum	6.70×10^{-4}	4.09×10^{-2}	1.1 to 40
Soybeans	3.22×10^{-4}	8.13×10^{-2}	1.1 to 60
Sunflower, confectionery	3.48×10^{-4}	9.19×10^{-2}	1.1 to 35
Sunflower, oil	7.87×10^{-4}	1.20×10^{-1}	5 to 112
Wheat	8.53×10^{-4}	4.45×10^{-2}	1.1 to 40
Wheat, low airflow	2.66×10^{-4}	1.38×10^{-2}	0.05 to 4

Source: ASAE *Standard* D272.3.

Grama et al. (1984) reported the effect of fine material particle size distribution on resistance in shelled corn. They also reported the effect of the increased resistance from fines on fan power requirements. Kumar and Muir (1986) reported the effects of fines in wheat. Bern and Hurburgh (1992) reviewed the characteristics of fines in shelled corn, including their composition, size distribution, density, airflow resistance, and nutritive and economic value. They concluded that fines can increase airflow resistance up to 200%.

Bulk density can have a significant effect on airflow resistance. For moderate heights of 14 to 24 ft, drop height does not affect bulk density in bins filled with a spout (Chang et al. 1986). Bern et al. (1982) reported that auger stirring can decrease the bulk density of bins filled with a grain spreader but has no effect on or increases bulk density in bins filled by gravity. Magnitudes of the increase in bulk density caused by grain spreaders have been reported by Stephens and Foster (1976b, 1978) and Chang et al. (1983).

Moisture content also affects airflow resistance. Its effect may, in part, be caused by its influence on bulk density. Shedd's curves include a footnote recommending that for loose fill of clean grain, airflow resistance should be multiplied by 0.80 if the grain is in equilibrium with air at relative humidities greater than 85% (ASAE *Standard* D272.2). At 70°F, this corresponds to a moisture of 18% or more for shelled corn (Figure 1). Haque et al. (1982) give equations that correct for the effects of moisture content of shelled corn, sorghum, and wheat.

Li and Sokhansanj (1994) argued that a generalized equation for airflow resistance, a modification of Leva's equation (Leva 1959), could account for airflow resistance differences due to variations in grain density, moisture content, and fines. Supporting constants for nine seeds are presented. Giner and Denisienia (1996) proposed a modified Ergun equation for the quadratic moisture effects and linear fines effects in wheat.

When the flow lines are parallel and airflow is linear (as is the case in a drying bin with a full perforated floor), calculation of the airflow is a straightforward application of Equation (16). For a given fan attached to a particular bin filled to a uniform depth with grain, the operating point of the fan can be determined as follows. A curve is plotted showing the total static pressure in the bin plenum versus airflow to the bin. Airflow rate is calculated by dividing the total air volume supplied to the plenum by the cross-sectional area of the bin. Using Equation (16), the pressure drop per unit depth can be calculated and multiplied by the total depth of grain in the bin to give total static pressure in the plenum. The fan curve showing air delivery volume versus static pressure can be plotted on the same axes. The intersection of the curves is the operating point for the fan. These calculations can also be done on a computer, and the point of intersection of the curves can be determined using appropriate numerical methods. McKenzie et al. (1980) and Hellevang (1983) summarize airflow resistances for various bin and fan combinations in tabular and graphical form. Sokhansanj and Woodward (1991) developed a design procedure for use on personal computers to select fans for near-ambient drying of grain.

In cases where airflow is nonlinear, as in conical piles or systems with air ducts, computation is complex (Miketinac and Sokhansanj 1985). Numerical methods for predicting airflow patterns have been developed and applied to bins aerated with ducts (Brooker 1969, Segerlind 1982, Khompos et al. 1984), conical-shaped piles (Jindal and Thompson 1972), and bins in which porosity varies within the bed (Lai 1980). Lai's study applies to bins in which filling methods have created differences in bulk density within the bin or where fine material is unevenly distributed. Alagusundaram et al. (1994) studied airflow patterns through wheat, barley, and canola in bins with different patterns of partially perforated floors.

Analysis of Deep Bed Drying

The ability to predict the rate at which grain dries in a given type of dryer operating in specific weather conditions with a specified airflow and air temperature can assist designers in developing dryers for maximum efficiency. It can also guide operators in finding the optimum way to operate their particular dryers for given weather conditions. Computer simulations have helped researchers understand the mechanisms and processes involved in drying.

Two relatively simple prediction equations can be solved on a hand calculator. Hukill (1947) developed a widely known and used method that predicts the moisture distribution in a bed of grain during drying. A graphical presentation of one of the equations, which further simplifies calculations, is available. Hukill's method is summarized by Brooker et al. (1992), who give an example calculation for shelled corn drying. Barre et al. (1971) made further adaptations of Hukill's method, and Foster (1986) gives a historical perspective on the development and utility of the method. Brooker et al. (1992) also present a technique called the *heat balance equation*, which equates the heat available in the air for drying with the amount of heat needed to evaporate the desired amount of water from the grain. Both of the above methods take into account airflow, drying air temperature and relative humidity, exit air conditions, grain moisture, and the amount of grain to be dried.

Thompson et al. (1968) considered a deep bed of grain as a series of thin layers of grain stacked one on top of another. Algebraic heat and mass balances were applied to each layer, with the exit air conditions of one layer becoming the input conditions of the next layer. Thompson et al. (1969) used the model to predict concurrent-flow, crossflow, and counterflow drying of shelled corn. Paulsen and Thompson (1973) used it to evaluate crossflow drying of sorghum. Stephens and Thompson (1976) and Pierce and Thompson (1981) used the model to make recommendations about optimum design of high-temperature grain dryers.

Bakker-Arkema et al. (1978) used simultaneous heat and mass transfer equations in a series of coupled partial differential equations to describe deep bed drying. The equations, solved using a finite difference technique, predict grain temperature, grain moisture content, and air temperature and humidity ratio. Bakker-Arkema et al. (1979, 1984) give solutions for in-bin, batch, continuous crossflow, and continuous concurrent-flow dryers. Morey et al. (1976) used the model to evaluate energy requirements for drying. Morey and Li (1984) and Bakker-Arkema et al. (1983) demonstrated the effect of thin layer drying rate on the model predictions. Bridges et al. (1980) used the Thompson model for simulation of batch-in-bin drying. Morey et al. (1978) and Parry (1985) review many of the mathematical models used for high-temperature grain drying.

Computer simulations have also been developed for low-temperature and solar drying. Some of these models have been referenced in the section on Fungal Growth and Mycotoxins under Prevention of Deterioration. Thompson (1972) developed a model that was later used by Pierce and Thompson (1979) to make recommendations on airflow in solar grain drying and by Pierce (1986) to evaluate natural air drying. Sabbah et al. (1979) used the logarithmic model of Barre et al. (1971) for simulation of solar grain drying. Bridges et al. (1984) used a model to evaluate the economics of stirring devices in in-bin drying systems. Morey et al. (1979), Frazer and Muir (1981), Bowden et al. (1983), and Smith and Bailey (1983) have also modeled low-temperature drying. Sharp (1982) reviewed low-temperature drying simulation models.

Aeration of Grain

Aeration involves forcing small amounts of air through the stored grain to maintain a uniform temperature. Prior to the development of this concept, grain was turned by moving it from one storage bin to another. Foster (1986) credits Hukill (1953) with developing the concept of aeration. As mentioned in the sections on Fungal Growth and Mycotoxins and Insect Infestation, lowering of the grain temperature during winter in temperate climates can reduce the rate of deterioration from molds and insects. Aeration can also prevent temperature gradients from developing within the grain mass. Such gradients can cause moisture migration, which results in unacceptably high moistures in certain portions of the bin.

Aeration is used to cool stored grain in the fall. A typical practice is to aerate the grain when the difference between grain temperature and the average daily outside temperature exceeds 10°F. In the United States, grain is usually not warmed in the spring unless it is to be stored past early June. Foster and McKenzie (1979) and McKenzie (1980) give practical recommendations for aeration of grain. Airflow rates of 0.025 to 0.5 cfm per bushel are normally used. Air is usually distributed through the bottom of the bin using ducts. Duct spacing and fan selection are related to bin size and shape and to the airflow rate. Foster and Tuite (1992) give an overview of the topic and include information and charts used for design of such systems. Peterson (1982) gives recommendations for duct spacing in flat storages.

Several computer simulations have been developed to study the effects of heat buildup from microbial activity with and without aeration (Thompson 1972, Brooker and Duggal 1982, Metzger and Muir 1983, Lissik 1986). Aldis and Foster (1977) and Schultz et al. (1984) studied the effect of aeration on grain moisture changes.

DRYING SPECIFIC CROPS

Hay

Forage crops can be either harvested, dried, and stored as hay or harvested and stored under anaerobic conditions as silage. Hay quality can be judged by its color, leafiness, and appearance. Laboratory tests and feeding trials give a more detailed picture of hay quality. The traditional method of making hay is to mow the forage and allow it to field cure or dry in the swath and windrow. Harvesting at higher moistures with subsequent artificial drying may be economically feasible, depending on the local weather conditions.

Basic principles of hay drying and storage are covered by Hall (1980), FEC (1985), and Schuler et al. (1986). Forage must be harvested in the proper stage of maturity to attain maximum feeding value. Leaf loss from alfalfa is high when it is handled at moistures below 39%. Therefore, if it is baled at 40% moisture and dried artificially to the recommended storage moisture of 20% (Schuler et al. (1986), a significantly higher feeding value can be achieved. Both Schuler et al. (1986) and Hall (1980) give sketches for batch and in-storage hay dryers. They recommend airflows of 15 to 20 cfm per square foot of mow floor area or 200 to 500 cfm per ton.

Dehydrated alfalfa meal supplies provitamin A (carotene), vitamin E, xanthophylls (poultry pigmenting factors), vitamin K, vitamin C, and B vitamins. Figure 3 shows losses from field drying of hay found in tests conducted by Shepherd (1954). The rapid loss of carotene immediately after the forage is cut indicates the need for

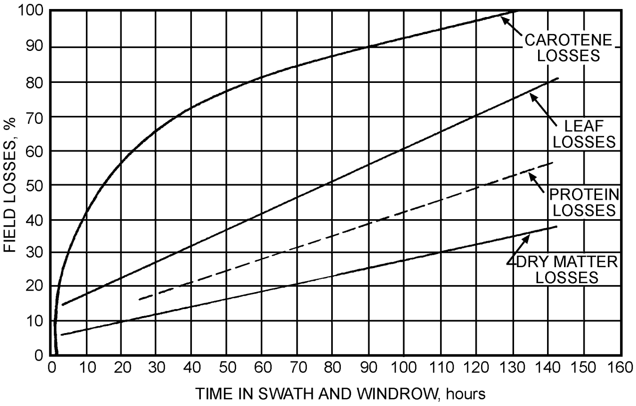

Fig. 3 Time in Swath and Windrow Versus Field Losses of Leaves, Dry Matter, Protein, and Carotene for Hay Drying

Table 7 Effect of Heating Chopped Alfalfa on Carotene Loss During Subsequent Storage of Meal

Hours in Oven at 212°F	Initial Carotene, ppm	Carotene Retained 7 Days at 149°F, %
0.75	229	37
1	228	37
2	197	37
3	176	28
4	149	21
5.5	112	18
7.5	86	15

Source: Thompson et al. (1960).
Note: Alfalfa is fresh frozen from Ryer Island, CA.

rapid transport to the dehydrator when alfalfa meal with high vitamin content is desired.

Several factors influence retention of vitamins during storage, including the starting plant material, dehydration conditions, addition of stabilizers, and storage conditions. Lowering the temperature reduces the loss rate. Inert gas atmosphere in storage also reduces losses (Hoffman et al. 1945). According to Shepherd (1954), blanching of fresh alfalfa before drying does not alter the storage stability of carotene. Table 7 shows Shepherd's results on the effect of prolonged heating at 212°F. The alfalfa was dried after 45 min; heating beyond this time represented excessive exposure to this temperature. Carotene retention in the intact meal at 149°F storage temperature was considered a measure of storage stability. Normal storage moisture is 8 to 9%. Thompson et al. (1960) summarize the effects of over- and underdrying on carotene stability.

Drying and handling of large round bales has been researched. These bales may weigh from 850 to 1500 lb and are handled individually with forklifts. Verma and Nelson (1983) studied storage of large round bales and found that dry matter loss was the primary component of the total storage losses. Bales stored so that they were protected from the weather had lower losses of dry matter than bales exposed to the weather. They were also higher in total protein. Jones et al. (1985) found significant dry matter loss in large round bales of mature fescue hay. Harrison (1985) found that addition of sulfur dioxide at the rate of 1% of dry matter had little effect on dry matter loss and nutrient contents for a mixture of alfalfa and bromegrass. However, bales protected with plastic bags did have significantly lower dry matter loss. Jones et al. (1985) found that bales of mature fescue hay stored inside and bales treated with ammonia had less dry matter loss and higher in vitro dry matter digestibility. Henry et al. (1977) and Frisby et al. (1985) developed and tested solar dryers for large round bales.

Grain

The physiological factors involved in drying and storing grain are different from those of forages. Grain is the end product of plant growth, and most physiological activity within the grain or seed is approaching a low level when harvested. With forage, the biological activity within the plant is at or near its peak at the time of harvest.

Both the deterioration of grain harvested at moistures above those safe for storage and the chemical preservation of grain are addressed in the section on Fungal Growth and Mycotoxins. Preservation by ensiling or airtight storage is addressed in the section on Oxygen and Carbon Dioxide.

For more information on grain drying, see Chapter 23 of the *ASHRAE Handbook—Applications* and Brook (1992).

Corn

Shelled field corn is used primarily as livestock feed, but some is used by milling or processing industries for manufacturing starch, corn oil, and other products. Little information is available on the relationship between the drying method and the feed value of corn. Market grade, as established by the Agricultural Marketing Service of the United States Department of Agriculture (USDA), is the primary criterion for determining corn value. Tests by Cabell et al. (1958) indicated that shelled corn with a moisture content of 29 to 32% can be dried without loss of protein nutritive value by air with temperatures as high as 240°F, provided the airflow rate is approximately 110 cfm/bu.

Breakage Susceptibility. The market grade of dry corn is affected more by the amount of fine material than by other grading factors. Fine material is defined as the broken grain and other material that passes through a 12/64 in. round-hole sieve. The physical damage done to wet corn or the brittleness imparted to the corn during drying causes it to break each time it is handled. The propensity of corn to break during subsequent handling, called **breakage susceptibility**, can be measured with a multiple-impact device called the *Stein breakage tester*. Stephens and Foster (1976a) demonstrated that corn breakage in the tester was correlated with damage during handling. Watson et al. (1986) give a standardized procedure for using the Stein breakage tester, and Watson and Herum (1986) describe and compare other devices developed for measurement of breakage susceptibility. They concluded that a device developed by Singh and Finner (1983) offers great potential for testing of grain for breakage susceptibility in commercial situations.

Paulsen et al. (1983) found significant variations in breakage susceptibility among hybrids. Corn dried with air at high temperatures (140°F) was two to six times more susceptible to breakage than corn dried at near-ambient temperatures. Gustafson and Morey (1979) found that delayed cooling (maintaining the corn at or near its temperature at the end of drying for 6 to 12 h) reduced breakage susceptibility and improved the test weight.

In a study of combination drying, Gustafson et al. (1978) found that combination drying (high-temperature drying to 18% followed by low-temperature drying to 16.6% moisture or below) significantly reduced the increase in breakage susceptibility normally caused by high-temperature drying.

Quality. Both drying temperature and corn hybrid can affect the quality of shelled corn for specific end uses. Brekke et al. (1973) found that drying at temperatures above 140°F reduced the quality of the corn for dry milling. Peplinski et al. (1982) found that optimum dry milling quality could be achieved by harvesting corn at moistures below 25%, minimizing machinery-induced damage to the kernels, and drying at air temperatures below 180°F. Paulsen and Hill (1985) found that the yield of flaking grits from dry milling of corn was significantly greater for corn that had a high test weight and relatively low breakage susceptibility. Weller et al. (1987) found that corn variety affected wet milling quality. At drying temperatures between 120 and 160°F, protein conformational changes occurred and decreased the ethanol soluble protein. Hybrids differ in resistance to storage mold (Tuite and Foster 1979), thin layer drying rate, and dry milling quality (Stroshine et al. 1986). Watson (1987) gives an extensive summary of measurement and maintenance of quality of corn, and Foster (1975) summarizes approaches to reducing damage during harvesting, handling, and drying.

Cotton

The lint moisture content for best results in ginning cotton appears to be 5 to 7%, with an optimum moisture content of 6% (Franks and Shaw 1962). Cotton, like grain, is hygroscopic and should be dried just prior to ginning. The wide variation in incoming moisture content usually requires different amounts of drying for each load. Rapid changes in the amount of drying required can best be handled by using a multipath drying tower in which the cotton is exposed for various lengths of time (2 to 10 s) at temperatures not exceeding 350°F. The air-to-cotton ratio can range from 40 to 100 cfm/lb of cotton (Franks and Shaw 1962). Laird and Baker (1983) found that substantial amounts of heat could be reclaimed and used for drying in commercial cotton gin plants. Equilibrium moisture content data for newly harvested cotton fibers are given by Griffin (1974). Anthony (1982) studied moisture gain of cotton bales during storage.

Cottonseed removed from the fibers is also dried. The germination of cottonseed is unimpaired by drying if the internal cottonseed temperatures do not exceed 140°F (Shaw and Franks 1962). This temperature is not exceeded in the tower dryer described previously. However, the moisture content of the seed can be above the recommended level of 12% following the multipath tower drying. Drying seed in a triple-pass drum at 250 to 300°F with an exposure time of 4 min, followed by cooling, reduces moisture content, inhibits the formation of free fatty acids, and improves germination compared to undried seed. Anthony (1983) dried cottonseed in a vacuum microwave dryer. The cottonseed would not germinate, but its oil properties were not harmed as long as lower temperatures were used. The drying rate was increased by reducing pressure below atmospheric. Rayburn et al. (1978) studied preservation of high-moisture cottonseed with propionic acid.

Peanuts

Peanuts in the shell normally have a moisture content of about 50% at the time of digging. Allowing peanuts to dry on the vines in the windrows for a few days removes much of this water. However, peanuts normally contain 20 to 30% moisture when removed from the vines, and some artificial drying in the shell is necessary. Drying should begin within 6 h after harvesting in order to prevent peanuts from self-heating. The maximum temperature and rate of drying must be controlled to maintain quality. High temperatures result in off-flavor or bitterness. Overly rapid drying without high temperatures results in blandness or inability to develop flavor when roasted (Bailey et al. 1954). High temperatures and rapid or excessive drying also cause the skin to slip easily and the kernels to become brittle. These conditions result in damage in the shelling operation and can be avoided if the moisture removal rate does not exceed 0.5% per hour. Because of these limitations, continuous-flow drying is not usually recommended.

Young (1984) found energy savings up to 26% when comparing recirculating dryers with conventional peanut dryers. Smith and Davidson (1982) and Smith et al. (1985) address the aeration of peanuts during warehouse storage.

Rice

Of all grains, rice is possibly the most difficult to process without quality loss. Rice containing more than 12.5% moisture cannot be stored safely for long periods, yet the recommended harvest moisture content for best milling and germination ranges from 20 to 26% (Kramer 1951). If the rice is harvested at this moisture content, drying must begin promptly to prevent heat-related damage, which can result in “stack-burn,” a yellowing of the kernel. To prevent excessive internal fissuring, which results in broken kernels during milling, multiple-pass drying is usually necessary (Calderwood and Webb 1971). Kunze and Calderwood (1980) summarize rice-drying techniques.

Because the market demands polished whole kernels of rice, it is necessary to prevent damage in the form of fissures. Rapid moisture removal or addition can create moisture gradients within kernels. According to Kunze (1984), gradients can develop in the field on a humid night before harvest, in a hopper containing a mixture of rice kernels at varying moistures, and in certain types of dryers. Banaszek and Siebenmorgen (1990) quantified the rate at which moisture absorption reduces head rice yields. Velupillai and Verma (1986) report that drying at 200°F followed by tempering in a sealed container for 24 h gave good kernel strength and head rice yields. They also found that storing the rice after drying for 3 weeks gave optimum grain quality. Bakker-Arkema et al. (1984) achieved good rice quality with concurrent-flow drying of rice.

Soybean, Sunflower, and Edible Beans

Prolonged periods of extremely wet weather during the harvest season can make artificial drying of soybeans necessary. Like peanuts and other oilseeds, soybeans cannot be dried satisfactorily with the high-temperature, high-speed methods used for cereal grains. Because of the different seed structure, rapid drying splits the seed coat and reduces quality and storage life. Overhults et al. (1975) reported a significant decrease in the quality of oil extracted from soybeans dried at temperatures above 160°F. Soybeans have one of the slowest thin layer drying rates of commonly grown cereals and oilseeds (Bakker-Arkema et al. 1983). Therefore, they dry more slowly and require more energy when dried in continuous-flow dryers.

Sunflower is a major crop in some areas of the United States. Hellevang (1987) recommends maximum drying temperatures of 200°F for continuous-flow drying of oil sunflower and 180°F for nonoil sunflower to prevent scorching of the seed meat. Schuler (1974) gives data on equilibrium moisture, airflow resistance, and specific heat of sunflower seeds. Because sunflower is about half the density of shelled corn, moisture can be removed more rapidly, and there is a tendency to overdry. This factor, along with accumulation of foreign material when drying, causes an increased fire hazard (Hellevang 1982). Schmidt and Backer (1980) attribute most of the problems encountered with storage of sunflower seed to improper drying and/or aeration.

Edible beans, a major crop in several states, should be dried with air at relative humidities above 40% to prevent stress cracking. Natural air or low-temperature drying is best (Hellevang 1987). If dried at high rates, seed coats may crack, and beans may split during subsequent handling (Otten et al. 1984, Radajewski et al. 1992). Broken beans can develop a bitter or undesirable flavor and spoil more easily during storage (Uebersax and Bedford 1980).

Wheat and Barley

In northern regions of the United States, wheat and barley may be harvested above safe storage moistures to prevent excessive field losses. Bruce (1992) modeled the effect of heated-air drying on the bread baking quality of wheat. The quality indicator was loaf volume. Moilanen et al. (1973) recommended that hard red spring wheat be dried at temperatures below 160, 140, and 120°F, respectively, for harvest moistures of 16, 20, and 24% wet basis. These data assumed airflow of 100 to 150 cfm/ft^2. For airflow of 50 cfm/ft^2, the authors recommended that the drying air temperature be reduced by 10 to 15°F. In the case of barley used for malting, the seed must be able to germinate. Therefore, the maximum recommended drying air temperature is 110 to 120°F (Hellevang 1987, Jilak 1993). Watson et al. (1962) studied the effects of harvest moisture and drying temperature on barley malting quality and recommended harvesting below 20% moisture. If wheat or barley is used for seed, the maximum recommended drying air temperature is 110°F.

In regions where soft wheat is grown, it may be economical to harvest at 20 to 24% moisture to allow double cropping with soybeans; this allows wheat harvest to begin 5 to 7 days earlier than normal and increases the yield of the soybeans (Swearingen 1979). In areas where double cropping is feasible, soft wheat can be dried using low-temperature solar drying or ambient drying with intermittent fan operation (Barrett et al. 1981). High-speed and continuous-flow systems with reduced drying air temperatures can also be used (Parsons et al. 1979). Kirleis et al. (1982) harvested soft red winter wheat at moistures of 25% or below and dried with air temperatures of 150°F or below without adverse effects on milling or cookie baking quality.

In high-temperature continuous-flow dryers, wheat and barley reduce airflow because they have a high airflow resistance. Bakker-Arkema et al. (1983) report that thin layer drying rates for barley and wheat are much faster than for corn. Barley dries more slowly than wheat, presumably because the kernels are larger. In their computer simulations of a concurrent-flow dryer, wet bushel capacity for wheat was about 80% of the capacity for shelled corn when moisture content was reduced by 4.7%. The drying capacity difference was probably caused by a decrease in airflow.

Tobacco (Curing)

Tobacco leaves normally have a moisture content of about 85% at harvest. The major methods of tobacco drying are air curing and flue curing (Johnson et al. 1960).

For **air curing**, whole plants are cut and allowed to wilt in the field until the leaves reach about 70% moisture (Walton et al. 1994). The plants are then hung in open barns, where temperatures range from 60 to 90°F and humidities from 65 to 70%. The curing period is 28 to 56 days (Jefries 1940). The desired end product for air curing is a tan leaf. Overdrying at low temperatures results in green color and low sugar content; overdrying at high temperatures results in yellow color (Walton and Henson 1971). Both conditions are undesirable because the normal chemical changes are arrested prematurely. Subsequent drying at optimum rates can reverse some damage. Underdrying at all temperatures results in undesirable dark color and damage from mold and bacterial growth (Walton et al. 1973).

Flue curing uses artificial heat. The leaves are harvested and hung in closed barns where temperatures are increased gradually during the curing period. Normally, 3 days of drying at temperatures of 90 to 120°F brings about yellowing. For the next 2 days, temperatures of 120 to 140°F are used for leaf drying; then, stems are dried at 170°F for 1 to 2 days. A bright yellow to orange color is desirable in flue-cured or bright-leaf tobacco.

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