Table 1 .... Maximum Moisture Content for Safe Storage for One Year

Crop	Moisture Content, %
Corn	13
Wheat (hard red winter)	12½
Wheat (soft red winter)	13½
Oats	13
Grain Sorghum	13
Soy Beans	11
Rough Rice	13½
Flaxseed	8
Hay	20

characteristic fermented odor. Ensiled crops are not generally considered marketable through the usual channels, nor are they useful for human food; however, ensiled products make excellent livestock feed.

Grain Condition

The condition of grain as a result of its previous history is an important, though not easily defined, factor in its storability. Grain in its original state apparently possesses some natural resistance to deteriorative changes, perhaps due in part to the seed coat. Mechanical or heat damage, mold invasion, and insect invasion tend to decrease this natural resistance.

MOISTURE MEASUREMENT

Moisture content can be expressed on either the wet or dry basis; however, the wet basis is used exclusively by farmers and in the grain trade. Unless otherwise noted, moisture contents indicated in this chapter are calculated on a wet basis. The dry basis moisture content is used by research workers and in mathematical expressions dealing with moisture content and drying. The moisture content on a wet basis is calculated by dividing the weight of water in the material by the total weight. The percent moisture on a dry basis is calculated by dividing the weight of water by the weight of dry matter.

$$\text{Percent moisture (wet basis)} = M_w = \frac{100W_w}{W_w + W_D} \quad (1)$$

$$\text{Percent moisture (dry basis)} = M_D = \frac{100W_w}{W_D} \quad (2)$$

where W_w = weight of water, pounds.
W_D = weight of dry matter, pounds.

Percent moisture on a wet basis (M_w) may be converted to percent moisture on a dry basis and vice versa by use of the following equations:

$$M_D = \frac{100(M_w)}{(100 - M_w)} \quad (3)$$

$$M_w = \frac{100(M_D)}{(100 + M_D)} \quad (4)$$

Methods used for determining moisture content can be classified as either direct or indirect. In the direct methods the water is driven from the product and the loss in product weight or the amount of vapor evolved is used to determine the moisture content. Indirect methods involve the measurement of properties of the material which are a function of the moisture content.

Direct Methods

Three oven methods are commonly used for the determination of moisture content.

Air Oven. Duplicate samples of finely ground grains (2-3 grams each) are dried for one hour at 130 C. If the initial moisture exceeds 13 percent, a two-stage method is used. A weighed sample of whole grain is partially dried to a moisture content of 13 percent or below and then ground and completely dried as in the one-stage method. The moisture lost in both stages is considered in determining the initial moisture content. The air-oven is the basic method specified for determining the moisture content of grains in the official grain standards of the United States.[1]

Another commonly used air-oven method for the determination of moisture in grain and stock feeds is presented as an official method by the Association of Official Agricultural Chemists. This method, which gives slightly higher results, uses a ground sample dried at 135 C for 2 hr.

One of the most widely accepted direct methods is based on the use of a vacuum to increase the rate of drying. Duplicate two to three gram samples of finely ground grain are dried at 90-100 C for approximately five hours at a pressure of 25 mm or less of mercury. This method is also one of the official methods of AOAC[3] and gives reasonably good agreement with the one hour air-oven method.

The Brown-Duval method is the most common distillation procedure for determining moisture content. A weighed sample of whole grain is heated in a special apparatus and the vapor evolved is condensed and collected in a cylinder calibrated directly in moisture content. The Brown-Duval method, as with the oven methods, is somewhat empirical. Proper operating procedure and accurate calibration are essential.

Indirect Methods

The simplicity and speed of measuring moisture content by electrical methods have made these the most commonly used for measuring moisture in practical applications. All electrical meters must be calibrated for each product by one of the direct methods. They are also sensitive to temperature changes and the calibration must include a temperature correction factor.

A practical limit on the range of moisture content that can be measured by conductive meters is approximately 7-23 percent. Recently dried grain will give low readings and recently wetted grain will give high readings as a result of the unrepresentative surface conditions. Mixed wet and dry grain and grain out of condition will also result in erroneous readings with the conductance type meters.

The dielectric properties of products depend to a large degree on the moisture content. The capacitance meter utilizes this relationship by introducing 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 of the capacitance meters. At higher frequencies and in instruments with insulated electrodes the relative effect of the resistance is reduced. The reduction in the resistive effect is important in reducing errors introduced by unusual product surface conditions.

Meters of the capacitance type are generally less subject to errors resulting from uneven moisture distribution. The range of moisture content that can be measured is wider than for the conductance meters.

Moisture measurement by capacitance meters is sensitive to temperature, product weight and product density. To reduce these sources of error a weighed sample is introduced into the measuring cell by some reproducible mechanical means. Calibration including temperature correction is required. Recent developments have been aimed at overcoming the need for a given sample size and density. However, no instruments are commonly available which incorporate these improvements.

The humidity of the air surrounding a product in a closed container will come to equilibrium with the product. This is achieved when the vapor pressure of the moisture in the product is equal to the vapor pressure of the air. This equilibrium relative humidity may be used as an indication of the moisture content. It has been proposed that this method could indicate the storability of grain independent of the actual moisture content since the equilibrium relative humidity of the air in grain, to a large extent, controls mold growth.

Hay Moisture Determination. The determination of hay moisture content has not received the consideration that has been devoted to grains. The oven methods have been used rather extensively. A rapid oven method of drying samples has been developed by Dexter[4] using the exhaust from a tractor. A weighed sample is placed in a cylinder and attached to the exhaust. An improved version of this exhaust oven was developed by Isaacs and Wiant[5] in which outside air was mixed with the exhaust air. This reduced the drying temperature and increased the airflow rate to prevent burning of the sample.

Electrical meters have been applied to some extent on forage crops; however, the extreme variability of the moisture and density of the material tested leads to great variability in the readings obtained. A reasonable indication of the average moisture content of a mass of hay can be obtained if a large number (25 or more) measurements are taken and averaged. An electrical scanning device for making and averaging a large number of readings automatically was developed by Isaacs and Wiant.[6]

DRYING THEORY

Drying in its ordinary applications is a heat and a mass transfer process involving the vaporization of water in the liquid state, mixing the vapor with the drying air, and removal of the vapor by mechanically carrying away the mixture. Sufficient heat for vaporization of the moisture in the product must be supplied, about 1000 Btu per pound of water. This amount must be supplied by reducing the sensible heat of the drying air or by applying heat directly to the product by conduction, radiation, dielectric heating or some other means.

Utilizing the sensible heat content of the air is by far the most common mode of drying. Drying by this method can be described from the standpoint of the drying air on the psychrometric chart. The drying process is generally assumed to be adiabatic, i.e., all of the sensible heat lost by the air is utilized for moisture vaporization and is converted to the latent heat of water vapor in drying air. The total heat content of the air does not change during its participation in the drying process. Therefore, the state point of the air may be considered to move up the adiabatic saturation lines on the psychrometric chart. (See Fig. 1.)

If in contact with the product long enough, the air will exhaust at equilibrium with the moisture in the material. That is to say that the partial pressure of the water vapor in the air is equal to the partial pressure of the water vapor in the material. There being no longer any potential for moisture transfer, no more drying takes place. The relative humidity of the air at equilibrium with material of a given moisture content is known as the *equilibrium relative humidity*. The moisture content of hygroscopic material in contact with air of a given

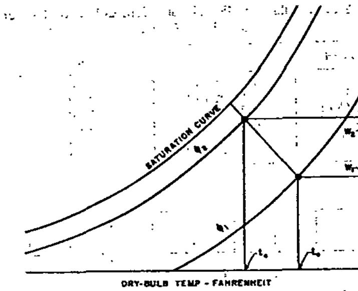

Fig. 1 .... Adiabatic Wetting of Air in a Drying Process

relative humidity for an indefinite period of time is known as the *equilibrium moisture content.*

The relationship between relative humidity and moisture content at equilibrium may be presented graphically as in Fig. 2, for different materials and at various temperatures.[7] Henderson[8] expresses the equilibrium relationship mathematically with the following equation:

$$1 - \phi = e^{-cTM_e^n} \quad (5)$$

where

ϕ = relative humidity, expressed as a decimal.
e = natural (Naperian) base of logarithms.
T = absolute temperature, Rankine degrees.
M_e = equilibrium moisture content in percent dry basis.
c = empirical constant.
n = empirical constant.

Some values of the constants c and n for various materials are given in Table 2.

Referring to Fig. 1, if drying air at temperature T_e and relative humidity ϕ_1 reaches equilibrium with material at relative humidity ϕ_2, the exhaust air temperature will be T_e. The moisture gained by each pound of drying air is the difference in the humidity ratio ($W_2 - W_1$). This does not reveal what the condition of the exhaust air is if the air is not in contact with the product long enough to reach equilibrium, nor does it say what the drying rate of the product will be under such conditions.

Several methods of analyses are available for predicting drying rates of porous materials such as grain under stated conditions of air temperature, humidity, original moisture content, and grain depth.[9,10,11] An analysis of grain drying by Hukill[9] will be presented here.

The maximum rate (dM/dt) at which a granular hygroscopic material such as grain will transfer moisture to or from air may be described by the following differential equation:

$$\frac{dM}{dt} = -C(P_g - P_a) \quad (6)$$

where

C = constant, representing the vapor conductivity of the kernel and air film around it.
P_g = partial pressure of the water vapor in the grain.
P_a = water vapor pressure in the 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.