

FUNDAMENTALS OF DRYING
AGRICULTURAL CROPS

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

George L. Gallaher

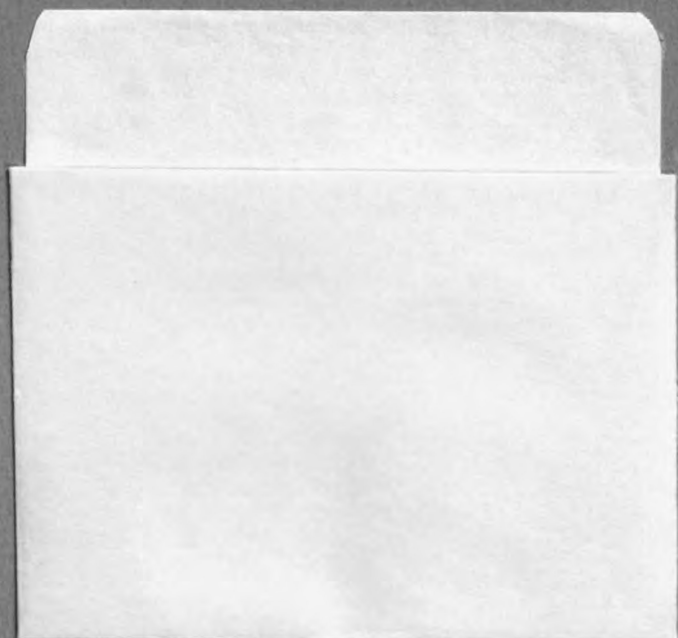
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FUNDAMENTALS OF DRYING AGRICULTURAL CROPS

By

George L. Gallaher

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FUNDAMENTALS OF DRYING AGRICULTURAL CROPS

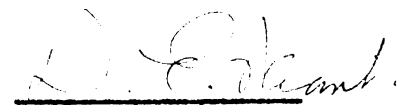
by George L. Callaher

The drying of agricultural crops is considered from the fundamental standpoint of vapor pressure difference. Vapor pressure is the primary driving force which causes the movement of moisture from a material. By showing how such factors as moisture content, temperature, and humidity influence the vapor pressures involved, a logical picture of drying is presented.

In addition, a possible method of making drying calculations is proposed. The method is based on vapor pressure difference and employs an accepted formula for calculating the evaporation rate of free surface water. By extending the formula and showing how the vapor pressure of a material varies with drying, it is possible to make drying time calculations. The information required and method of making the calculations are shown.

A series of carefully controlled experimental tests were made on alfalfa hay to provide data for comparison with the computed values. The results of the tests and the comparison with computed values are given.

Approved:


Major Professor

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TABLE OF CONTENTS

	Page
INTRODUCTION -----	1
Definition of the Problem -----	1
Importance of the Problem -----	1
Previous Investigations -----	2
Method of Attacking the Problem -----	3
EXPLANATION OF DRYING -----	5
Types of Moisture to be Removed -----	5
Law of Evaporation -----	6
Drying Rate Expression -----	7
Drying Rate Proportionality Factor -----	9
Analogy Between Flow of Moisture, Heat Flow, and Flow of Electricity -----	10
THE PSYCHROMETRIC CHART -----	13
Description -----	13
Construction of the Chart -----	13
Methods of Locating a Point on the Chart -----	19
Use of the Psychrometric Chart -----	20
MEASUREMENT OF VAPOR PRESSURE OF VARIOUS COMMODITIES -----	22
Direct Method of Measuring Vapor Pressure -----	22
Indirect Determination of Vapor Pressure -----	24
Change in Vapor Pressure as Drying Progresses -----	29
THERMODYNAMICS OF DRYING -----	32
Heat Required and Sources -----	32
Determination of Heat of Adsorption -----	32
Constant Wet Bulb Process -----	36
Efficiency of Drying -----	37
SOLUTION FOR THE DRYING TIME -----	39
EXPERIMENTAL PROCEDURE -----	47
DESCRIPTION OF THE APPARATUS -----	43
Details of the Equipment -----	43
Measuring and Control Devices -----	57
Safety Devices -----	59
METHOD OF TESTING -----	61

	Page
PRESENTATION OF THE DATA	65
DISCUSSION OF THE RESULTS	75
Agreement of Data and Theory	75
Influence of Temperature	76
Influence of Humidity	77
Effect of Depth	78
Influence of Air Flow	78
Effect of Density	79
Type of Material	80
Moisture Content	80
CONCLUSIONS	81

TABLES

	Page
Table 1 Vapor Pressure of Hard Red Winter Wheat at 80°F -----	28
Table 2 Illustrative Calculations for Vapor Pressure During Drying -----	28
Table 3 Vapor Pressure of Alfalfa -----	34
Table 4 Method of Computing Drying Time for Wheat -	42
Table 5 Computations for Leaving Vapor Pressure '---	42
Table 6 Drying Time for Second Layer -----	45
Table 7 Summary of Tests -----	67
Table 8 Data from Drying Tests -----	68
Table 9 Computations for Drying Tests -----	71

FIGURES

		Page
Figure 1	Psychrometric Chart for Barometric Pressure of 29.92 "Hg. -----	14
Figure 2	Construction of the Psychrometric Chart -	16
Figure 3	Apparatus for Measuring Vapor Pressure --	23
Figure 4	Equilibrium Moisture Content Curve for Hard Red Winter Wheat at 80°F. -----	26
Figure 5	Vapor Pressure of Hard Red Winter Wheat at 80°F. -----	26
Figure 6	Vapor Pressure of Hard Red Winter Wheat at Various Temperatures -----	30
Figure 7	Log-Log Plot of Alfalfa Vapor Pressure --	35
Figure 8	Variation of Heat of Adsorption with Moisture Content for Alfalfa -----	35
Figure 9	Illustrative Curve of Drying Rate Reciprocal vs Moisture Content -----	40
Figure 10	Typical Drying Time Curve -----	40
Figure 11	Drying Curves for Several Layers -----	46
Figure 12	Sketch of Laboratory Drying Apparatus ---	49
Figure 13	General View of Apparatus from Fan End --	49
Figure 14	General View of Apparatus from Plenum End -----	50
Figure 15	Closeup of Fan -----	51
Figure 16	Steam Inlet for Humidifying the Air -----	52
Figure 17	Electric Heater Coils -----	53
Figure 18	Control Section -----	54
Figure 19	Scales and Plenum -----	55
Figure 20	Orifice and Exit Air Assembly -----	56

	Page
Figure 21 Air Compressor and Supply -----	57
Figure 22 Manometers -----	58
Figure 23 Control Apparatus -----	59
Figure 24 Squeezing Bale into Test Section -----	61
Figure 25 Weighing the Bale -----	62
Figure 26 Bale Removed from Test Section -----	64
Figure 27 Vapor Pressure of Alfalfa for the Drying Tests -----	70
Figure 28 Comparison of Computed Curves with Test Data -----	72
Figure 29 Comparison of Computed Curves with Test Data -----	73
Figure 30 Comparison of Computed Curves with Test Data -----	74

SYMBOLS

W'	drying rate, lbs of water/hour
K'	proportionality factor, lbs of water/(hour)(ft ²)(°Hg)
p	vapor pressure of water, either free or in a commodity, °Hg
p_a	vapor pressure of water in the air, °Hg
A	water surface area, ft ²
a, b	experimental constants
V	velocity, ft/min
W	drying rate, %db/hour
K	proportionality factor, %db/(hour)(°Hg)
C	instrumental constant in psychrometry; equals approximately 3.67
B	barometric pressure, °Hg
t_d	dry bulb temperature, °F
t_w	wet bulb temperature, °F
M	moisture content, % dry basis (%db)
t	time, hours
C'	experimental factor; equals approximately 1.45 for bales of alfalfa hay
K''	proportionality factor; equals C' times lb dry air/(hr)(lb dry matter)

INTRODUCTION

Definition of the Problem

The problem undertaken in this thesis is to explain what causes drying and to show how temperature, humidity, air flow, moisture content, and density influence the drying of agricultural crops.

Importance of the Problem

The proper drying of crops such as hay and grain is an important problem in agriculture today. The method of natural field drying which has been depended upon for centuries is no longer practical. Too much food value is lost when the crop is dried in the field exposed to the elements of nature. The longer the drying time, the more losses sustained. Therefore, faster drying by artificial means is desirable. However, the current artificial drying practices are not based on well founded principles, but rather on a few miscellaneous rules-of-the-thumb. If the real benefits of artificial drying are to be achieved, a fundamental understanding of the drying process and the variables involved in drying is necessary. With such information,

artificial drying will result in high quality products and economy of operation.

Previous Investigations

There were a few meager attempts at artificial drying of grains made during the 19th century. Not until the close of the century, however, was artificial drying being used with any real success; and then it was with such commodities as prunes, raisins, and walnuts. Between 1900 and 1925 the first recorded attempts to dry forage crops were made. During this period several drying plants were constructed, one by the United States Department of Agriculture at Hayts, Missouri in 1910.

Since 1925, artificial drying of agricultural crops was undertaken in earnest. Today, the literature is full of reports on artificial drying experiences. A complete bibliography on agricultural drying for the past 25 years will contain several hundred papers. The papers are noticeably lacking, however, in that they do not supply the fundamentals of drying necessary to set up and solve the drying problems of agriculture. They do not contain complete information so that they can be correlated with the work of others. The fundamentals and design facts which are common to all drying problems have not been determined. In late years the need for this type of information has been recognized and strides in this direction are being made. Some of the more notable work along this line are

investigations by Barre¹, Fenton², and Hukill³. Their investigations have supplied some of the basic drying information as applied to agriculture.

For the truly theoretical approach to drying, the chemical engineers have made the biggest contribution. Work by Lewis⁴, Sherwood⁵, and Newman⁶ has provided the most fundamental picture of the drying process. A better understanding of their work will do much to solve the drying problems as applied to agriculture. W. H. Carrier of air conditioning and refrigeration fame also has contributed considerable basic information to the drying field. He has written several important papers^{7,8} and is an authority on the subject.

Method of Attacking the Problem

An extensive review of the important drying literature was made. The purpose was to start with the fundamentals of the drying problem and find out exactly "what causes a commodity to dry". It was felt that the theory of drying should be understood before any experimental work was started. As a result, the first part of the thesis is theoretical and explains the drying problem from the fundamental standpoint of vapor pressure difference. Vapor pressure is the primary driving force which causes movement of moisture from a substance. By showing how such factors as moisture content, temperature, and humidity influence the

vapor pressures involved, one can gain a logical picture of drying.

In addition, a possible method of making drying calculations is proposed. The method is based on vapor pressure difference and employs an accepted formula⁸ for calculating the evaporation rate of free surface water. By extending the formula and showing how the vapor pressure of a commodity varies with drying, it is possible to make drying time calculations. The information required and method of making such calculations are shown.

In order to substantiate the theoretical calculations, a series of carefully controlled experimental tests were made. These tests were conducted on alfalfa hay and the results of this work comprise the last part of this thesis.

EXPLANATION OF DRYING

Types of Moisture to be Removed

Agricultural commodities may be termed hygroscopic materials because they contain varying amount of hygroscopic water. They may also contain free moisture, especially when their moisture content is very high. These two types of moisture make up the total moisture content⁸.

Free moisture is any water that is readily evaporated and is not held in the liquid state by any forces other than those normally found for an exposed surface of water. Such moisture exerts a vapor pressure according to its temperature. A film or droplets of water on a leaf might be considered free moisture.

Hygroscopic moisture is that moisture which is held internally in a substance. In this condition it is held more firmly than is free moisture. Its vapor pressure is reduced below that of free moisture by the absorptive effect of the substance⁷.

A definite value of moisture content is the demarcation line between the two kinds of moisture. All in excess of this value is free moisture. Under natural conditions free moisture will rapidly evaporate leaving only the hygroscopic water. Some of the hygroscopic moisture will then also evaporate until the commodity reaches what is called equilibrium with the surrounding air. Generally days and

even weeks are required to reach equilibrium. The amount of hygroscopic water in a material which is in equilibrium with the surrounding air depends on the relative humidity of the air. The greater the relative humidity, the more hygroscopic moisture. (Also, the air temperature influences the equilibrium but in a slight amount. With other things constant, lower air temperature means more hygroscopic moisture.) If the relative humidity is held at zero, all the hygroscopic moisture will leave the substance (gradually) and the result will be equivalent to an oven dry substance. On the other hand if the relative humidity is raised to 100%, the substance will pick up additional water from the air and reach a maximum value of hygroscopic moisture. This value is also the previously mentioned dividing line. If any more moisture is added to the substance it will be free moisture.

Law of Evaporation

Drying is the removal of any evaporate liquid. In this work, the term drying is used to denote the evaporation of water from a farm commodity such as hay or grain. This water in the form of a vapor then dissipates into the surrounding air. All such evaporation processes when involving free water are governed by the law of evaporation:

For a given condition of atmospheric movement, the rate of evaporation is proportional to the difference in vapor pressure between the liquid and the vapor of that liquid in the immediate vicinity (see page 1694 of reference 9).

In theoretical considerations water vapor is treated as a perfect gas. This makes it amenable to mathematical computations. As a gas, it is easy to understand that the vapor will tend to flow from a region of high pressure to one of lower pressure. This is the primary factor that causes the flow of water vapor. The above law states this clearly and furthermore says that the rate of flow is proportional to the vapor pressure difference. With such a law many moisture flow problems may be understood quite simply if the vapor pressures involved are known.

Drying Rate Expression

The rate of evaporation of free moisture follows the law of evaporation and is fairly well understood. It depends on (1) the vapor pressure of the moisture which is a function of its temperature, (2) the vapor pressure of the surrounding air, and (3) the effective velocity of the surrounding air. These factors may be expressed in the following relationship which is the law of evaporation stated as a formula:

$$W' = K' A (p - p_a) \quad (1)$$

where W' equals pounds of water per hour, A is the surface area, p is the vapor pressure of the liquid water, p_a is the

vapor pressure of the moisture in the air, and K' is the proportionality factor which includes the effect of velocity. For air blowing over a free water surface K' has been found equal to $a + bV$ where V is the air velocity and a and b are experimental constants depending upon the direction of air flow⁹.

Equation (1) may be considered the maximum rate of drying attainable for any substance. In practice only the initial stages of drying of very thin materials attain this. In hygroscopic materials, as the surface free moisture is evaporated the rate of drying decreases. However, Carrier⁷ states that if the reduced vapor pressure of the material (below that of free moisture) is known, the expression will still be valid. In other words the drying rate remains the same function of the vapor pressure difference, the reduced drying rate being accounted for by the reduced value of p . Such a statement appears reasonably correct. The difference in vapor pressure has long been considered the primary function affecting drying. Whether or not the proportionality factor remains constant throughout the whole drying process, however, is a point not clear. Since use of equation 1 requires a value for K' and it is so important in moisture flow considerations, the next section discusses K' in detail.

Drying Rate Proportionality Factor

The proportionality factor K' of the drying rate expression must be determined from experimental data. Very complete information is required before it can be evaluated. Because such data are limited, values of K' are not readily available. Every material will have its own value and in addition it may vary somewhat as drying progresses. Barro indicates some variation, in his work with vapor pressures.¹ Any such variation, if found, may be due to the "velocity effect". When a substance is quite wet the drying rate varies somewhat with velocity¹⁰, while at low moisture contents the velocity has no appreciable effect.¹¹ Some apparent variation, however, may be due only to added heat by radiation or conduction¹⁰ which is difficult to account for. The chances are that if accurate vapor pressure information is available the variation in K' with drying will be found quite slight. The reduced difference in vapor pressure with drying provides a logical means of accounting for reduced drying rate. For the present, since any variation large or small is not actually known, K' will be assumed a constant. Methods of handling it as a variable can be introduced if experimental evidence warrants.

Another problem encountered with the proportionality factor is the units involved. For evaporation from a water surface, pounds of water per hour per unit vapor pressure difference per square foot of surface is reasonable. For

drying a commodity such as hay or grain, however, a surface area is rather difficult to conceive. Since the surface area is roughly proportional to the dry weight, "pounds of dry matter" in place of "square foot of surface" should be suitable. With this change, the drying rate is in lb of water/(lb dry matter)(hr). If this is multiplied by 100 the drying rate will be change in moisture content (%db) per hour. Since the moisture content is the desired value in agricultural work it is convenient to include the factor "100". The drying rate expression now becomes:

$$W = K (p - p_a) \quad (2)$$

where p and p_a are defined as before; K is change in moisture content (%db)/(hour)("Hg), and W is change in moisture content (%db) per hour.

Analogy Between Flow of Moisture, Heat Flow, and Flow of Electricity

It is interesting to note that a direct analogy exists between the flow of water vapor, heat flow, and the flow of electricity. In heat conduction problems, the flow of heat Q (in Btu/hr) equals the thermal conductivity times the cross-sectional area taken normal to the heat flow times dt/dL . Where dt/dL is the change in temperature with distance through which the heat must flow. This temperature difference is the driving force that causes the heat to flow:

$$Q = \text{thermal conductivity} \times \text{Area} \times \frac{dt}{dL} \quad (3)$$

In electrical problems, the flow of current I (in amperes or coulombs/sec) equals the electrical conductivity times the cross-sectional area taken normal to the current flow times dE/dL . Where dE/dL is the drop in voltage with distance through which the current must flow. This voltage difference is the driving force that causes current to flow:

$$I = \text{electrical conductivity} \times \text{Area} \times \frac{dE}{dL} \quad (4)$$

Likewise in vapor problems, the flow of water vapor V (in pounds/hr) equals the permeability times the cross-sectional area taken normal to the moisture flow times dp/dL .¹² Where dp/dL is the change in vapor pressure with distance through which the vapor must flow. This pressure difference is the driving force that causes the vapor to flow:

$$V = \text{permeability} \times \text{Area} \times \frac{dp}{dL} \quad (5)$$

The above flow equations are well established for heat flow and current flow. Experimental values of thermal and electrical conductivities have been obtained for many materials. Experience has shown the equations to be quite accurate and valuable. The vapor flow equation is not so well established, however. Experimental values of permeability for various materials are not too well known. The expression for vapor flow is relatively new.

In recent years, interest in permeability has increased with the demand for vapor barriers for insulation and packaging of foods. A wrapper with a low permeance is considered very good because it greatly retards the flow of

water vapor through it. The distinction between permeance and permeability is important and is similar to that between conduction and conductivity. Permeance is the rate of water vapor transmission through any specified thickness of material while permeability indicates rate per unit thickness. The permeance of an inch board is much smaller than the permeance of a shaving cut from it, yet their permeabilities are the same.

THE PSYCHROMETRIC CHART

Description

A study of moisture and its removal will involve a knowledge of air, moisture, and their mixtures. An understanding of the psychrometric chart provides most of this information. It presents the properties of air-moisture mixtures in a convenient form and is a valuable key to investigating moisture problems. One disadvantage of the chart is that it applies for only one value of barometric pressure. For air or convection drying of farm crops, however, standard barometric pressure provides sufficient accuracy.

The usual form of the psychrometric chart is shown in figure 1. The bottom scale is the dry bulb temperature of the air in question. The vertical scale on the left is the vapor pressure of the moisture in the air. The vertical scale on the right is the absolute humidity of the air in grains of moisture per pound of dry air. The curves slanting up to the right are lines of relative humidity in percent. The lines slanting down to the right are constant wet bulb temperatures. It can be seen that the important properties of air are clearly represented.

Construction of the Chart

The information on the psychrometric chart has been computed originally from algebraic formulas. In certain instances it may be desirable to compute the required

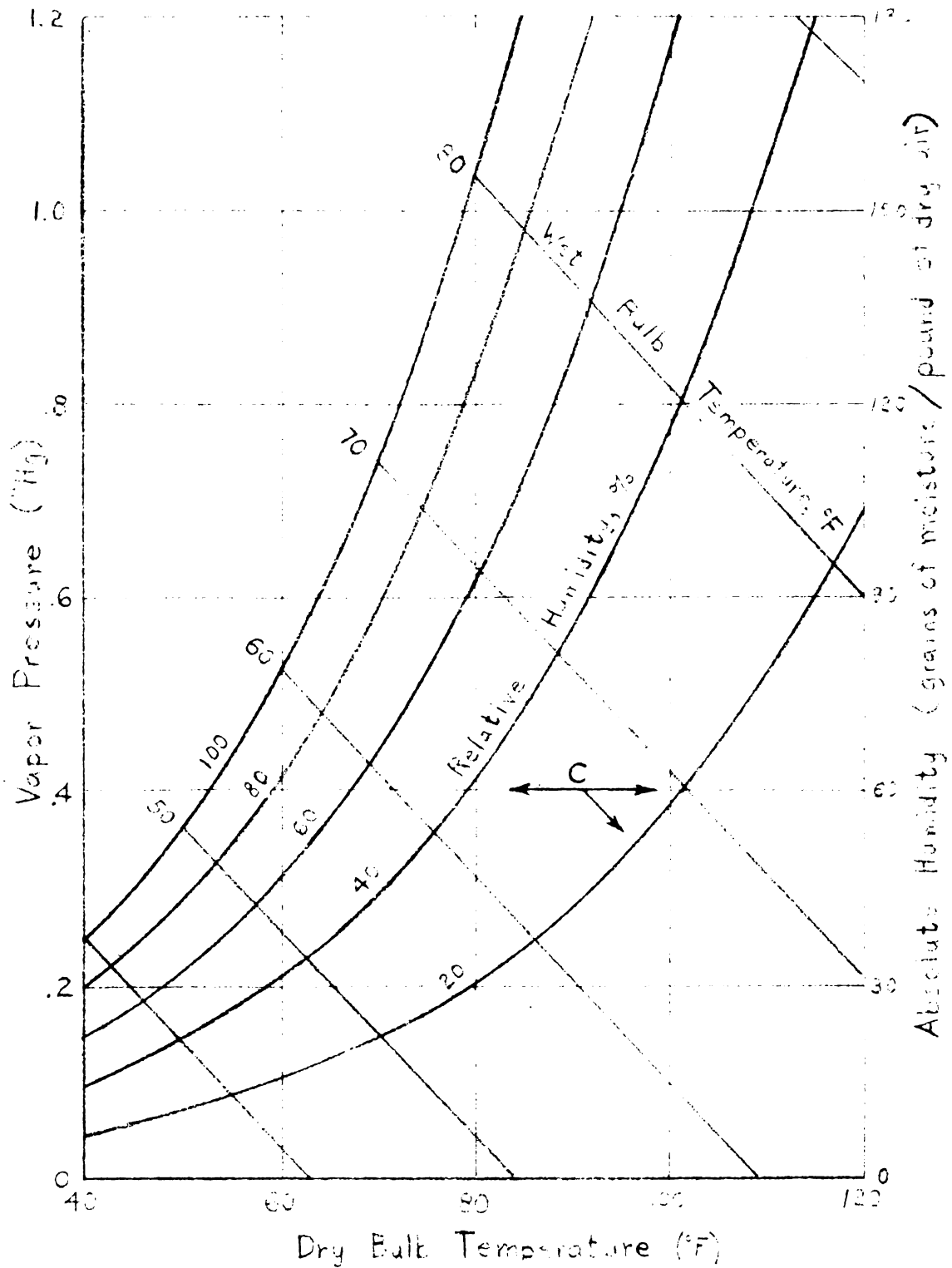
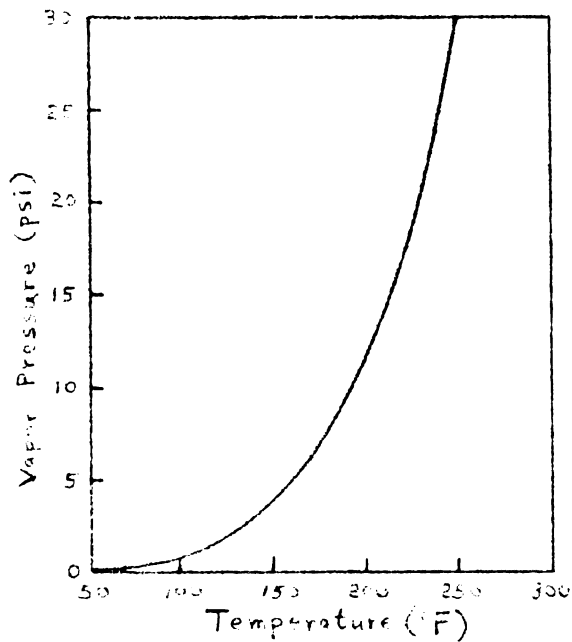


Figure 1. - Psychrometric Chart for Barometric Pressure of 29.92" Hg.

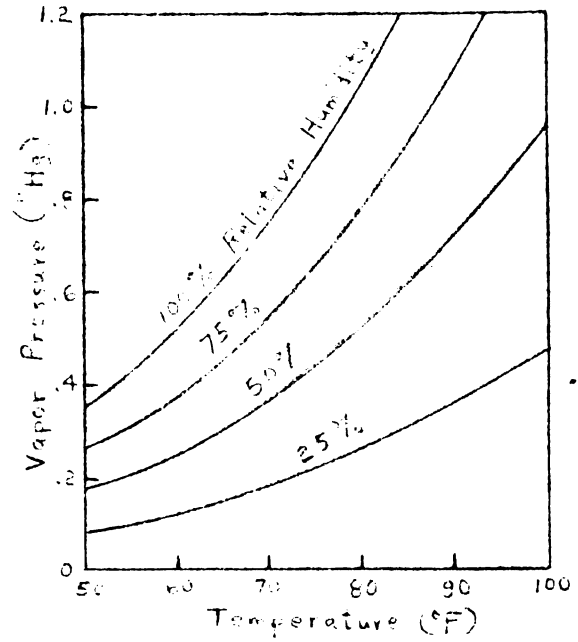
information directly. Because of this reason and the importance of the psychrometric chart in drying, the theory and construction of it are given. The theory involved in its construction is only approximate but for practical purposes the chart is very useful and satisfactory. (More accurate air-vapor properties will soon be available for extremely critical scientific work. The American Society for Heating and Ventilating Engineers is sponsoring a complete reevaluation of air-vapor properties.¹³⁾

The first step in constructing a psychrometric chart is establishment of a pressure-temperature curve for saturated water. Such values are available in any steam tables.¹⁴ Figure 2a shows this curve. Everyone is acquainted with one point on this curve which is the boiling point of water at standard pressure, 212°F at 14.7 psi. The normal psychrometric chart uses only the lower part of this curve for the air temperatures encountered are generally in the 35-110°F range. The water vapor saturation pressures in this range are quite small so that it is more convenient to give pressure in inches of mercury ("Hg). This curve is the saturation or 100% relative humidity line seen on all psychrometric charts.

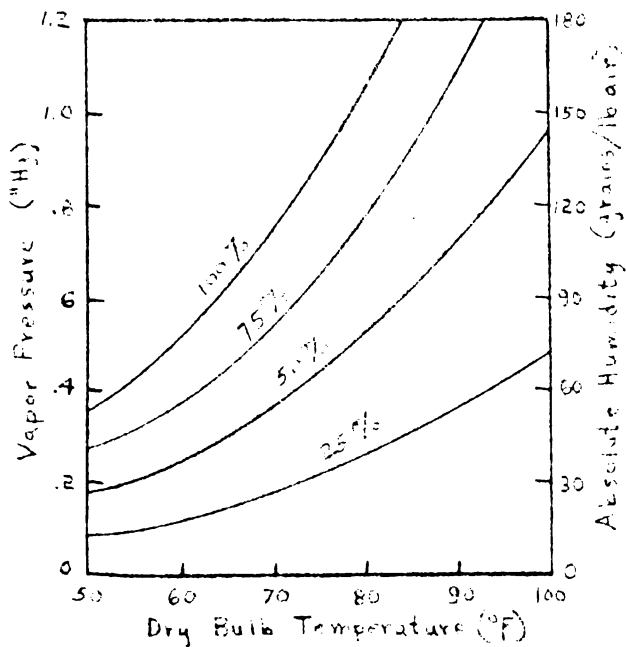
By definition, relative humidity is the ratio of the actual vapor pressure to the pressure of saturated vapor at the prevailing dry bulb temperature, t_d . Therefore, the relative humidity lines may be quickly established once the saturation curve is drawn. For example the 50% curve is a



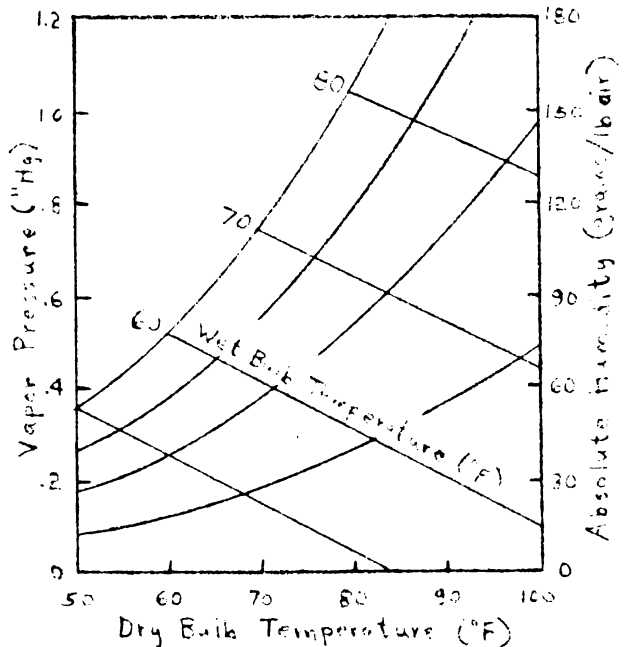
(a)



(b)



(c)



(d)

Figure 2. - Construction of the Psychrometric Chart.

line drawn through points at each value of temperature that are 50% of the vertical distance up to the saturation pressure. Figure 2b shows the relative humidity lines at increments of 25%.

In many psychrometric charts the vapor pressure ordinate scale is not given and instead the absolute humidity is shown. Absolute humidity is pounds or grains of moisture/pound of dry air. The relationship between these two scales may be determined from the perfect gas law for mixtures.

$$\frac{P}{x} \frac{V}{m} = \frac{m}{x} \frac{R}{x} \frac{T}{m} \quad (6)$$

where P is pressure in lb/ft², V is total volume in ft³, m is pounds of gas, R is the gas constant and T is absolute temperature in degrees Rankine. The subscript m is for the mixture and x for one of the gases making up the mixture. The mixture in this case is that of dry air and water vapor. Let the subscript v represent the water vapor and a the dry air. Then (6) may be written for vapor and air as:

$$\frac{P_v}{V} \frac{V}{m} = \frac{m_v}{V} \frac{R_v}{V} \frac{T}{m} \quad (7)$$

and

$$\frac{P_a}{V} \frac{V}{m} = \frac{m_a}{V} \frac{R_a}{V} \frac{T}{m} \quad (8)$$

Equation (7) may be divided by equation (8) giving:

$$\frac{P_v}{P_a} = \frac{\frac{m_v}{V} \frac{R_v}{V}}{\frac{m_a}{V} \frac{R_a}{V}} = \frac{m_v}{m_a} \quad 1.61 \quad (9)$$

According to Dalton's law of partial pressures $P_v + P_a = E$ or barometric pressure. Thus equation (9) may be written as:

$$\frac{P_v}{E - P_v} = 1.61 \frac{m_v}{m_a} \quad (10)$$

Let m_a equal one pound of dry air and solve for m_v (lb vapor/lb dry air):

$$m_v = \frac{P_v}{1.61(E - P_v)} \quad (11)$$

If E and P_v are in "Hg, and m_v is in grains of moisture the above expression will reduce to m_v equals approximately $150 P_v$ for values of P_v up to about 1"Hg. Figure 2c includes the absolute humidity scale as established from this relationship.

Another value given on most psychrometric charts is the wet bulb temperature, t_w . This is the temperature of a thermometer whose bulb is covered with an absorbent material saturated with water. For accurate readings the air must be moving past the thermometer at a velocity of 10 ft/sec or greater.

There are two theories involving the wet bulb temperature. One is the diffusional theory of Maxwell and the other is the convectional theory of August. Arnold¹⁵ claims that the true wet bulb temperature depends on both. In its simplest form, the relationship involving the wet bulb temperature¹⁶ is:

$$p - p_a = C B (t_d - t_w) 10^{-4} \quad (12)$$

where p equals the water vapor pressure at the wet bulb temperature, C is an instrumental constant, and the remaining

terms have been previously defined. The value of C is where the theories differ. The United States Weather Bureau uses a value of C which varies slightly with t_w .¹⁷ This variation was determined from a large series of experiments by Professor Ferrel. For ordinary work, when temperatures are in $^{\circ}\text{F}$ and pressures in "Hg, C may be used as 3.67. With this value, equation (12) can be used to construct constant wet bulb temperature lines. Figure 2d shows the psychrometric chart with the wet bulb temperature lines added.

Methods of Locating a Point on the Chart

Any given air sample is represented by some one point on the chart. Once the point is located, the various properties of the sample, such as humidity, vapor pressure, etc. can be read directly. There are many methods of locating a point on the psychrometric chart, but three are more common.

1- The dew point method is probably the most accurate method. By definition, the dew point is the temperature at which the air-vapor mixture becomes saturated by cooling at constant pressure. This temperature on the 100% relative humidity curve gives the vapor pressure. The intersection of the dry bulb temperature and the vapor pressure locates the point in question.

2- Use of wet and dry bulb temperatures is a very common method of entering the psychrometric chart. A sling psychrometer provides an easy method of getting these

temperatures. The intersection of these two temperature lines locates the desired point on the chart.

3- The hair hygrometer measures the relative humidity directly. It is not too accurate unless frequently calibrated but is all right for some purposes. If the air temperature is also known that air can be found on the chart.

Use of the Psychrometric Chart

All the various processes of cooling or heating and drying or humidifying the air can be followed on the psychrometric chart. Since the drying generally practiced with agricultural products is convection or air drying, the chart is very useful in solving drying problems. As mentioned in a previous section the drying rate is dependent on the vapor pressure of the air. This can be read quickly from the chart for any air. Many other things can be included on the psychrometric chart such as specific volume, sensible heat factor, total heat of the air, etc.

Some of the more common changes that occur to air can quickly be shown. For example, consider air at point C on the chart in figure 1. If this air is heated it follows a horizontal line to the right from C. Cooling of the air follows a horizontal line to the left from C. As the air is cooled its relative humidity increases. The temperature at which relative humidity reaches 100% is the dew point temperature. If it is cooled still further some of the moisture will condense out and the vapor pressure will be

lowered. Another method of removing moisture is to pass the air through an adsorber such as silica gel. Such a process follows a path downward and to the right from point C. The air is heated because the heat of vaporization is released when moisture is condensed out of the air,

The total heat content or enthalpy of the air will be mentioned because it is important in drying processes. The total heat content is the summation of the latent heat (due to change in state) and the sensible heat (due to change in temperature). The total heat content has been found to be almost constant along the wet bulb temperature lines. Because of this, many psychrometric charts have the wet bulb temperature lines labeled in Btu/lb. Actually this value is the sigma heat as defined by Carrier¹⁸ but the total heat is practically the same. The total heat value is useful in determining how many Btu are required for a certain process.

MEASUREMENT OF VAPOR PRESSURES OF VARIOUS COMMODITIES

Direct Method of Measuring Vapor Pressures

There are several methods of measuring the vapor pressure of a commodity. A direct method which is actually very simple but which requires good equipment and careful work is described herein. A rough sketch of the necessary apparatus is shown in figure 3. A is the flask which contains the material - for example, a handful of wheat - the vapor pressure of which is desired. T is a U-shaped section of glass tubing called a trap. A manometer of some form is necessary for measuring the pressure and is shown in the figure. C and D are stopcocks. Ground glass joints should be used to insure tight fits. The manometric fluid can be either mercury or an oil of low vapor pressure. The oil provides greater sensitivity but requires more care in using. A mercury manometer of the Dubrovin type is very desirable, if available. It has a sensitivity about seven times that of an ordinary U-tube mercury manometer. Reference 19 gives a complete description of some extremely accurate vapor pressure measuring apparatus.

The procedure for making a measurement is as follows: The material for which the vapor pressure is desired is placed in flask A and the flask is then surrounded by a constant temperature bath. The flask containing the sample and the rest of the apparatus are evacuated through the open stopcocks

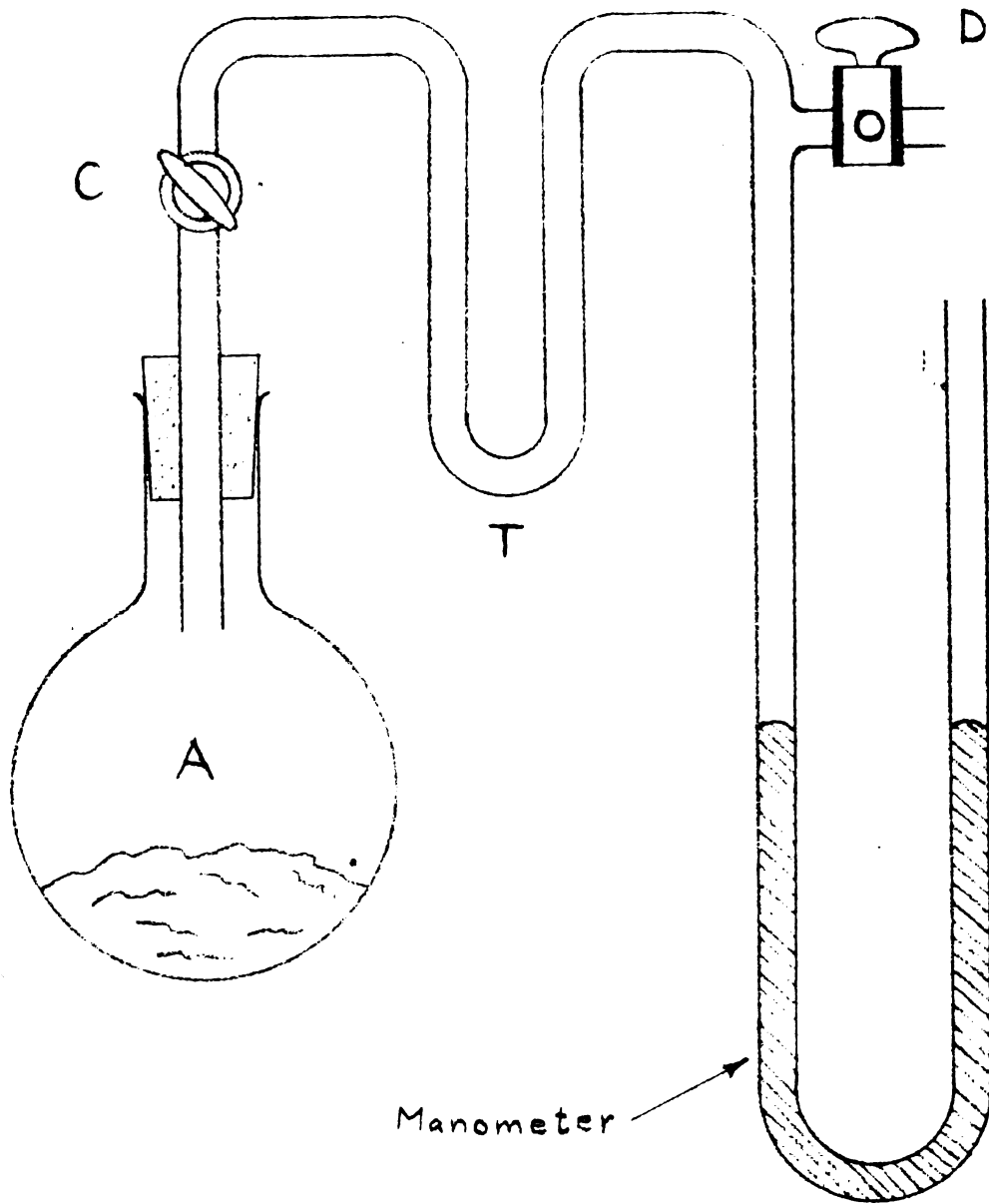


Figure 3. - Apparatus for Measuring Vapor Pressure.

C and D with an oil pump. During the evacuation trap T is kept cold by means of a solid carbon dioxide-alcohol mixture. This causes the water vapor to freeze in the trap while the noncondensable gasses (air or carbon dioxide) are exhausted. When the equipment is evacuated, stopcock D is closed and the small amount of ice in the trap is allowed to evaporate. It may require a half hour or more for the vapor pressure in the equipment to reach equilibrium with the sample. This pressure can then be read on the manometer and is the vapor pressure of the commodity. The total time per test should not take over an hour. This method can be used to determine the vapor pressure of many materials and also the vapor pressure of the air samples.

Indirect Determination of Vapor Pressure

When a hygroscopic substance is placed in an atmosphere of constant humidity, its moisture content gradually changes until it reaches and maintains a definite value depending upon the air humidity. This is called the equilibrium moisture content. Equilibrium moisture contents have been established experimentally for many materials in atmospheres of various temperatures and relative humidities.

A common method of obtaining air with a definite relative humidity is with sulfuric acid solutions.²⁰ The more concentrated the acid, the less moisture in the air above it. Samples can be suspended in jars over acid solutions of different strengths. By weighing the samples at

intervals and finding the equilibrium weights, the equilibrium moisture content can be determined. Reference 21 tells of such tests for alfalfa hay. Such tests generally take several weeks.

An illustrative equilibrium moisture content curve for hard red winter wheat²² is shown in figure 4. Such curves are generally established for a certain temperature. (Figure 4 is for 80°F.) A family of similar curves exists for other temperatures. The actual difference in the curves for 10-20°F variation, however, has generally been found to be quite slight. Such equilibrium moisture content information is quite valuable and may be used to determine the vapor pressure of the given commodity. Barre makes this suggestion as an aid in understanding moisture transfer problems. Fenton determined vapor pressures from such equilibrium information and plotted the results directly on the psychrometric chart.²

Another method of handling the vapor pressure is to plot it against the moisture content, making separate curves for each temperature. The mechanics of this operation are quite simple. Consider the curve of figure 4 which gives the equilibrium moisture content for wheat in air at various relative humidities and 80°F. Since the moisture content of the wheat is in equilibrium with the moisture in the air, the vapor pressure of the moisture in the wheat must equal the vapor pressure of the air. (If the vapor pressures are unequal, moisture will be transferred and the wheat will not be in equilibrium.) The vapor pressure of the air is readily

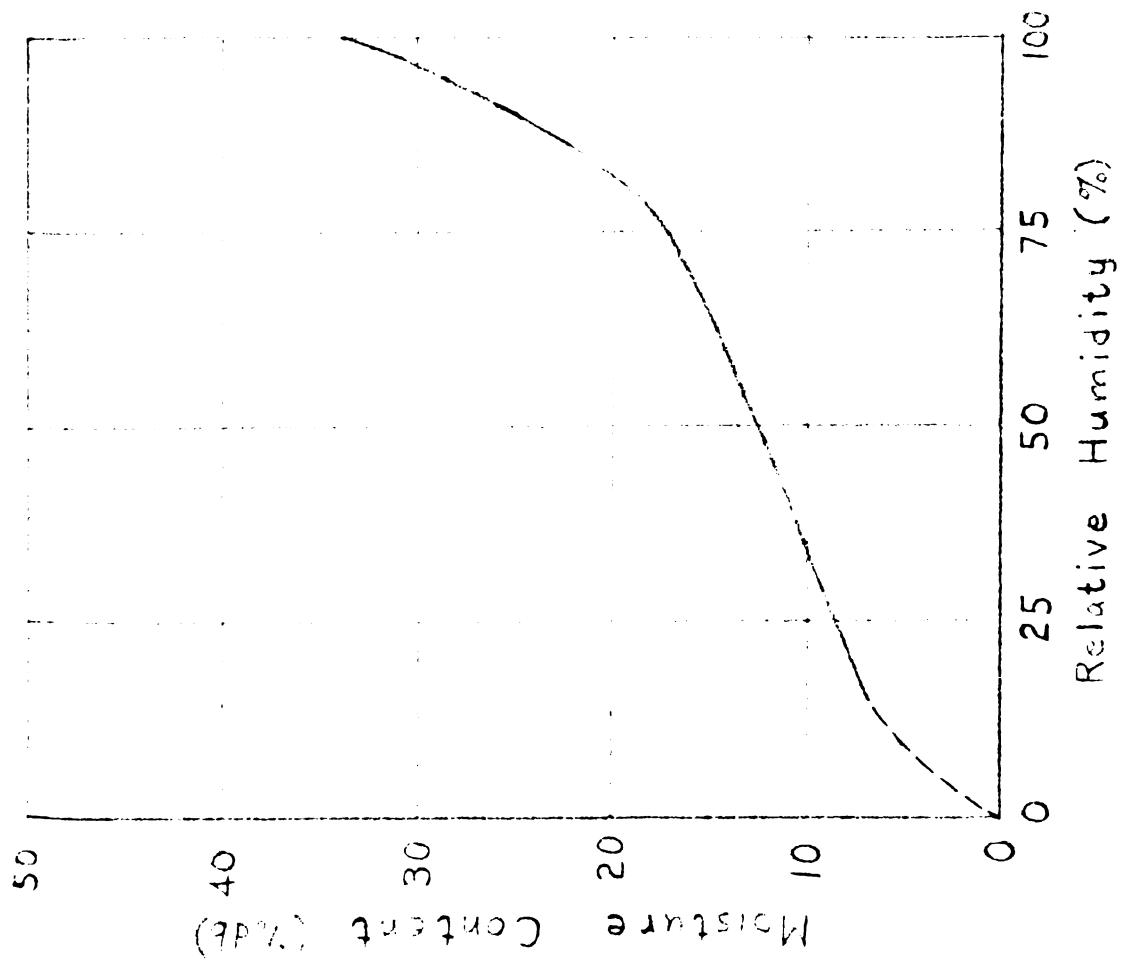


Figure 4. - Equilibrium Moisture Content Curve for Hard Red Winter Wheat, at 80°F.

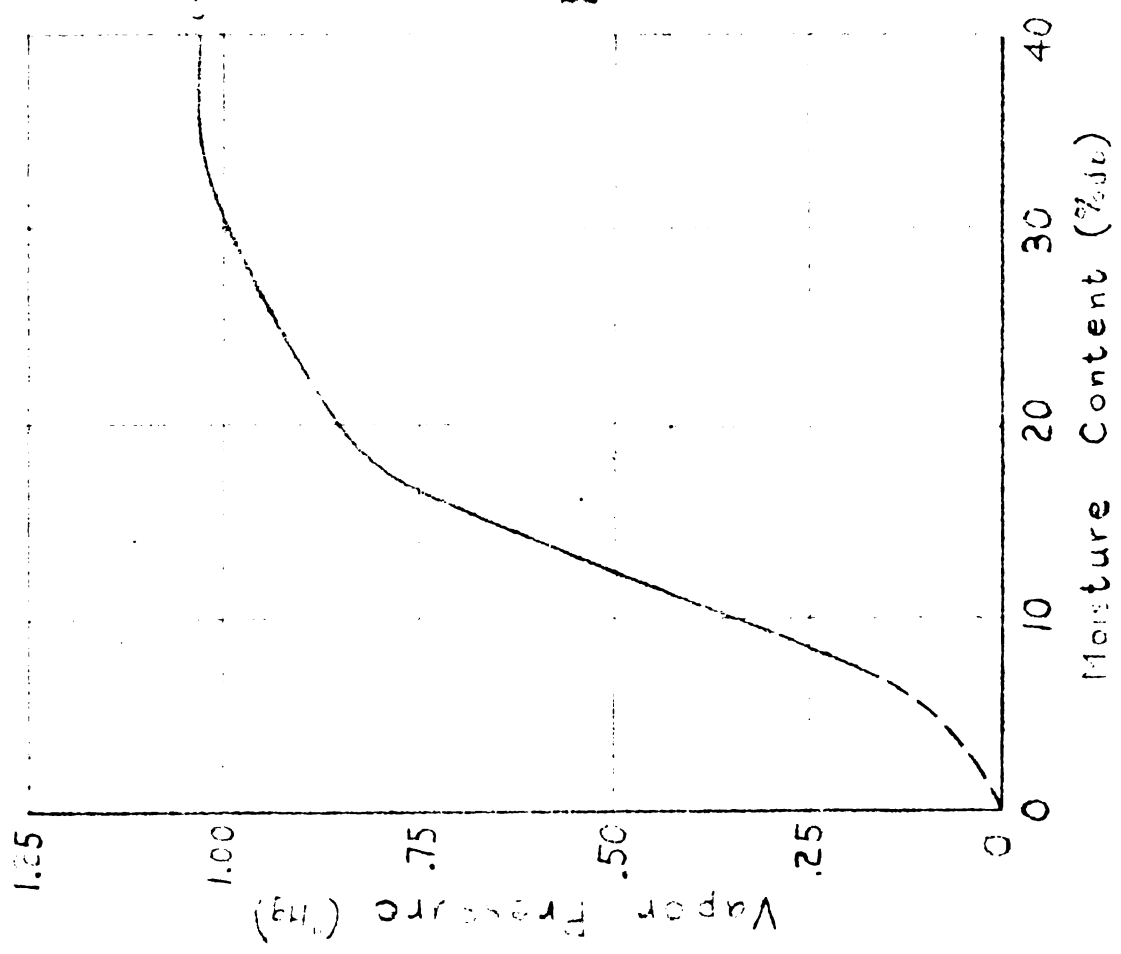


Figure 5. - Vapor Pressure of Hard Red Winter Wheat at 80°F.

determined from the psychrometric chart for the given humidity and the 80°F dry bulb temperature. This vapor pressure is that of the wheat at that moisture content and at 80°F.

Table 1 presents an easy manner of calculating the vapor pressures for various moisture contents. The first two columns are arbitrary points taken from the data used for figure 4. Notice that the moisture content is expressed on a dry basis. The dry basis facilitates comparison and is considered the best method by most investigators. The first value in the vapor pressure column is the saturation vapor pressure at 80°F. The remaining values in the column are simply the first value multiplied by the corresponding relative humidity as a decimal. The resulting vapor pressure curve is shown in figure 5. Its height is limited by the maximum vapor pressure in the table. If the moisture content is increased, the vapor pressure curve remains level. This is the vapor pressure of free moisture and it can not go any higher for this temperature. All moisture above the 34% value is of course free moisture. The reduction of the vapor pressure, as the moisture content decreases (due to absorptive effect of the material), is readily seen. In all probability this curve goes to the origin as indicated by the dotted line. It is hard to visualize water that does not exert at least some small vapor pressure. The curve, therefore, is quite well defined and can be a big help in understanding the process of drying.

TABLE 1. - VALUES OF VAPOR PRESSURE OF WATER AND AIR AT 10°C

Moisture Content (%)	Relative Humidity (%)	Vapor Pressure (mmHg)
24.0	100	1.03
22.2	90	.93
17.1	70	.72
14.3	60	.62
11.8	45	.47
8.7	30	.31
3.0	10	.10

TABLE 2. - TEMPERATURE CALCULATIONS FOR THE AIR-DRYING TUBING SYSTEM

$$p - p_a = 2.5 \times 10^{-4} (t_s - t_w)$$

$$p - p_a = 2.57 \times 28.30 (t_s - t_w) \times 10^{-4}$$

$$p - p_a = \frac{2}{51.6} (t_s - t_w)$$

$$p = \frac{100 - t_w}{51.6} + .41$$

Temperature of Heat, t_w	$100 - t_w$	$\frac{100 - t_w}{51.6}$	Vapor Pressure of Heat, p
			$\frac{100 - t_w}{51.6} + .41$
70	30	0.58	0.99
80	20	.39	.80
90	10	.19	.60
100	0	.00	.41

It is interesting to see what the vapor pressure curves are like for this same winter wheat at other temperatures. By assuming the given curve in figure 4 to be reasonably correct for other temperatures within 10-20°F, new vapor pressure curves can be quickly calculated. This is done by adding another vapor pressure column to table 1 for the new temperature. Figure 6 shows the vapor pressure curves for temperatures of 70, 80, 90, and 100°F. The increase in vapor pressure with temperature is quite noticeable and is important in drying.

Change in Vapor Pressure as Drying Progresses

If the temperature of a commodity remained constant as drying progressed, its vapor pressure would follow a constant temperature line such as given on figure 6. Experience has shown, however, that the temperature of a substance varies as it dries. A water surface assumes the wet bulb temperature as it evaporates.⁷ Likewise, an agricultural commodity is at wet bulb temperature when it has free moisture evaporating from it. As drying progresses and hygroscopic water is removed, the temperature of the commodity rises until it reaches the dry bulb temperature at the equilibrium moisture content. As the temperature changes, so does the vapor pressure. Carrier shows that equation 12 may be used to calculate the actual values of vapor pressure as drying progresses.⁷ For this use, t_w is the temperature of the material which varies from the wet bulb temperature to the dry bulb temperature and p is the vapor pressure of the material corresponding to its temperature.

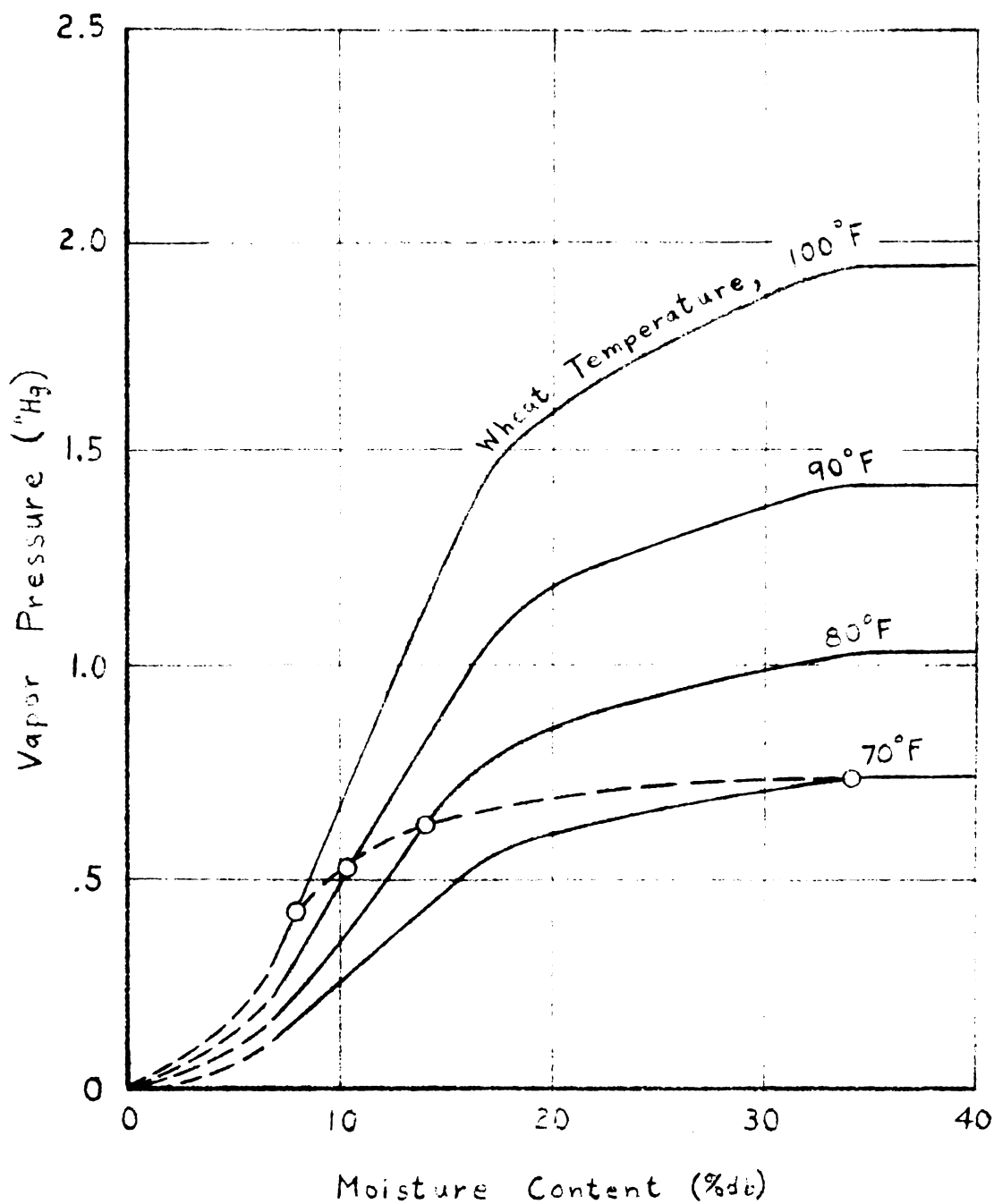


Figure 6.— Vapor Pressure of Hard Red Winter Wheat at Various Temperatures.

As an example, assume a drying air with $t_d = 100^{\circ}\text{F}$ and $t_w = 70^{\circ}\text{F}$ for the hard red winter wheat of figure 6. From the psychrometric chart p_a is read as .41"Hg. Table 2 shows how the formula may be used. The resulting values of vapor pressure have been plotted on the curves of figure 6. The dashed line drawn through them represents the true value of the vapor pressure as drying progresses.

THERMODYNAMICS OF DRYING

Heat Required and Sources

When agricultural crops dry, the water in them is evaporated and dispersed into the surrounding air. Great quantities of heat are required to vaporize this water. In general there are two primary sources of heat for this purpose; heat in the surrounding air, and heat from respiration processes during which dry matter is consumed. Terry says that 6300 B.T.U. are released per pound of dry matter consumed.²³ Heat may also be conducted and radiated to the material from surrounding warmer bodies. Crops in the field receive great quantities of radiant energy from the sun. For artificial drying, however, heat supplied by convection from the air is most important. The air may be either at the ambient temperature or higher because of some supplementary heat source.

Determination of Heat of Adsorption

The heat required to vaporize a unit quantity of water from a farm commodity is called the heat of adsorption. Its value is greater than the heat of vaporization for free water. The heat of vaporization can be read directly from the steam tables but the heat of adsorption is not so easily obtained. It is different for each material considered and also varies with the moisture content and temperature.

Accurate values are not available and have been holding back drying research. However, if accurate values of vapor pressure are known for a substance, the heat of adsorption can be calculated. An equation developed by Othmer²⁴ provides a convenient method.

$$\log p \text{ (of free water)} = \frac{\text{heat of vaporization}}{\text{heat of adsorption}} \times \log p \text{ (of material)} + c \quad (13)$$

This indicates that the slope of a log-log plot of commodity vapor pressure vs free water vapor pressure is equal to the ratio between the heat of adsorption and the heat of vaporization.

In order to use equation 13, values of vapor pressure measured at different temperatures are required. Davis of the U.S.D.A. at Virginia gathered such data for alfalfa. Table 3 shows some of his data. It will be used to illustrate the procedure for determining the heat of adsorption. Figure 7 shows a log-log plot of alfalfa vapor pressure vs free water vapor pressure. The values plotted give reasonably well defined straight lines. Their slopes can be measured to get the ratio between the heat of adsorption of alfalfa and the heat of vaporization of pure water. The data indicate that over a wide range there is some curvature to these lines. Therefore, the resulting slopes are good only for the range of from about 85 to 110°F which was plotted. Figure 8 shows the variation of the ratio with moisture content. As the moisture content decreases, it takes considerable more heat to vaporize the

TABLE 3. - VAPOR PRESSURE OF ALFALFA

(from tests by Roy Davis of the USDA at Blacksburg, Virginia)

Moisture Content (%db)	Vapor Pressure ("Hg)						
	120°F	116°F	112°F	108°F	104°F	100°F	98°F
Free Water	3.45	3.08	2.75	2.45	2.18	1.93	1.82
40		2.86	2.42	2.03	1.73	1.60	1.50
30		2.77	2.17	1.89	1.68	1.49	1.40
20	2.74	2.22	1.87	1.67	1.47	1.30	1.22
15	2.24	1.85	1.60	1.40	1.22	1.06	1.00
12	1.88	1.57	1.35	1.19	1.03	.91	.83
10	1.55	1.33	1.16	.98	.85	.73	.63
8	1.26	1.05	.88	.71	.54	.40	.35
7	.83	.59	.36				

Moisture Content (%db)	Vapor Pressure ("Hg)						
	96°F	94°F	92°F	90°F	88°F	86°F	84°F
Free Water	1.71	1.61	1.51	1.42	1.34	1.25	1.18
40	1.42	1.35	1.27	1.19	1.12	1.05	.99
30	1.32	1.24	1.17	1.10	1.03	.96	.89
20	1.15	1.08	1.00	.93	.88	.83	.78
15	.94	.88	.82	.76	.72	.67	.64
12	.79	.74	.69	.64	.60	.56	.52
10	.63	.58	.52	.47	.42	.38	.33
8	.26						

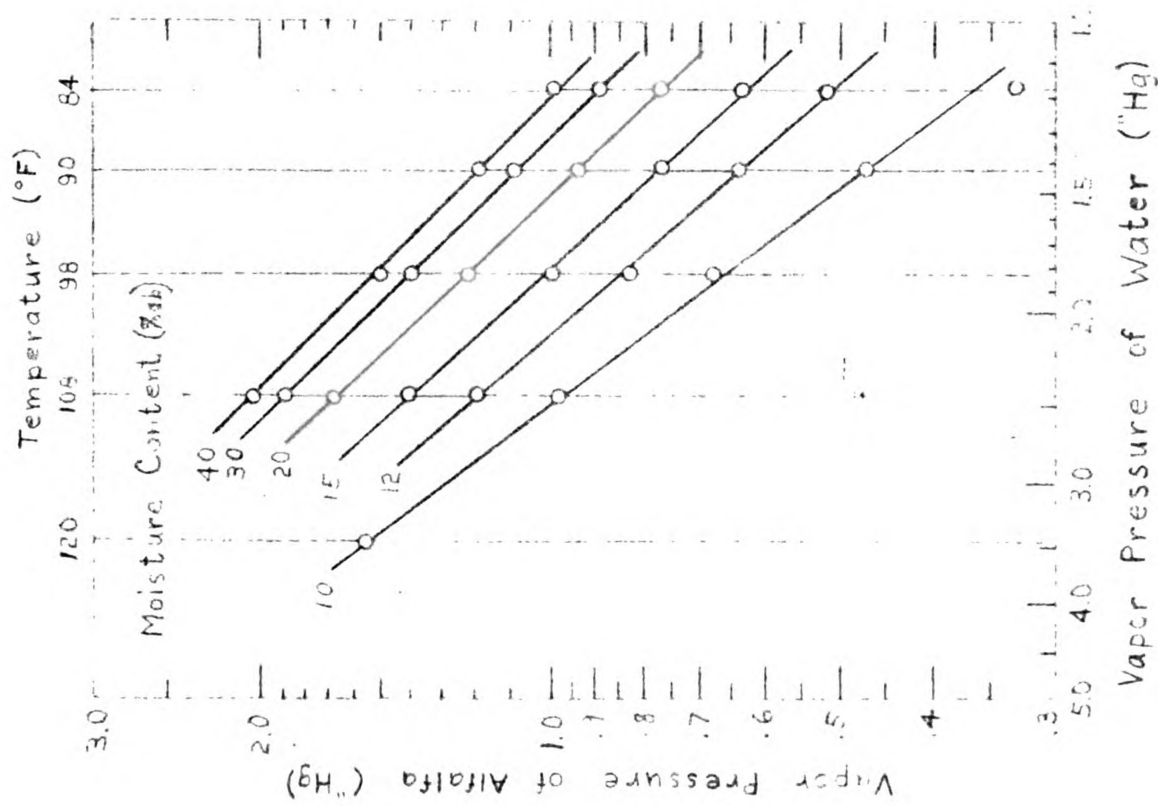


Figure 7. - Log-Log Plot of Alfalfa Vapor Pressure.

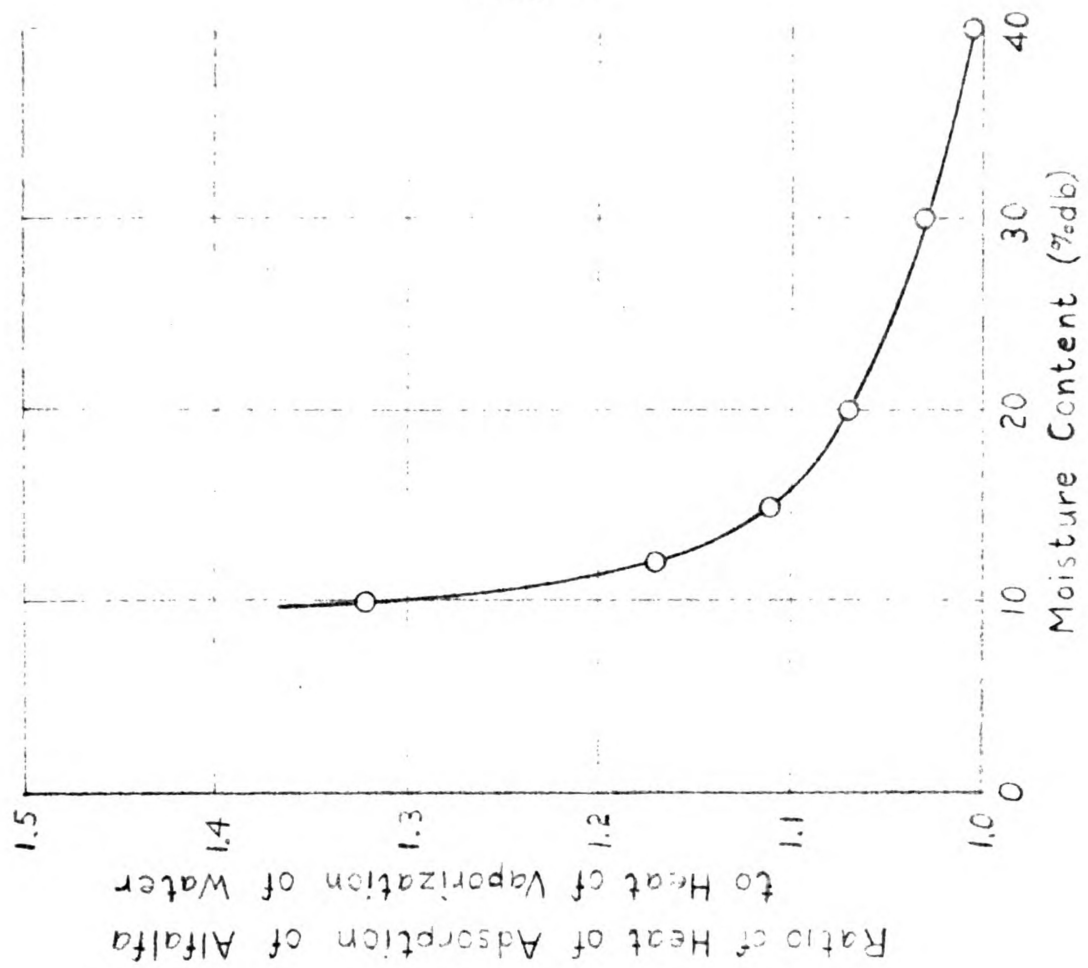


Figure 8. - Variation of Heat of Adsorption with Moisture Content for Alfalfa.

water in the alfalfa.

The data on hard red winter wheat previously given is not complete enough to make such calculations. It was determined at one value of temperature only. The small differences in the equilibrium moisture content curve with temperature are needed to determine the heat of adsorption. If there was no difference, the heat ratio would be unity.

Constant Wet Bulb Process

Consider air rising up through a bin of drying grain. Heat is required for the moisture in the grain to evaporate into the air. If the heat supplied by respiration of the grain is small, and conduction and radiation losses are also small, most of the heat required for vaporization will come from the air. Therefore, as the air rises its temperature will decrease. On the other hand, the amount of water in the air will increase. The sensible heat of the air lowers as it rises through the grain, but the latent heat keeps increasing. The total heat of the air remains constant. As previously stated, the wet bulb temperature lines on the psychrometric chart are lines of constant total heat. Therefore, under ideal conditions, drying may be considered a constant wet bulb process. Hukill does this in his investigations.³ It helps greatly in visualizing what happens to the air during drying operations.

Efficiency of Drying

The overall efficiency of drying may be computed in a number of different ways. In fact each writer seems to have his own method. Fundamentally, efficiency equals useful output over input. The useful output for drying is the pounds of water evaporated. The input equals the cost of operating fans, supplying external heat, special equipment, etc. Labor may even be considered. It is easy to understand why there are many ways of computing efficiency. Since some drying will occur without man's influence, efficiency calculated on this basis may even be over 100 percent in some instances.

The thermal efficiency is a better measure of the actual drying efficiency. It is the ratio of heat usefully employed in evaporation to the heat supplied. If radiation losses are neglected, the heat usefully employed is measured by the difference between the entering and leaving temperatures ($t_1 - t_2$), while the heat supplied can be measured by the difference between entering air temperature and dew point temperature ($t_1 - t_o$).

$$\text{Theoretical thermal efficiency} = \frac{t_1 - t_2}{t_1 - t_o} \times 100 \quad (14)$$

It is not possible to obtain 100 percent theoretical thermal efficiency even though the exit air be saturated and there are no radiation losses. The smallest value that t_2

can have is the wet bulb temperature of the leaving air which is always greater than t_o .

SOLUTION FOR THE DRYING TIME

Formula 2 gives the drying rate as

$$W = K (p - p_a) \quad (2)$$

W (change in moisture content per hour) may be written as dm/dt where M is the moisture content (%db) and t is time in hours.

$$\frac{dm}{dt} = K (p - p_a) \quad (15)$$

This expression could be integrated directly for M if an analytical expression for $(p - p_a)$ in terms of t were available. Such an expression is not known, however, and other means of determining the drying time must be resorted to.

The reciprocal of equation 15 is

$$\frac{dt}{dm} = \frac{1}{K (p - p_a)} \quad (16)$$

A typical variation of p with M has been shown in figure 6. With such information and K, a curve of dt/dM vs M can be computed. As an example, assume K as 10.0°/(hr)("Hg). Then the dt/dM curve for the dashed line of figure 6 is as shown in figure 9. The integral of this curve with respect to M is equal to time. Exact integration again cannot be accomplished but may be approximated by summing areas under the curve.

$$\text{Area} = \int \frac{dt}{dM} \times dM = t \quad (17)$$

Starting at the maximum value of M the area or time increases as M decreases. Practically any degree of accuracy can be obtained if small enough area increments are used. The

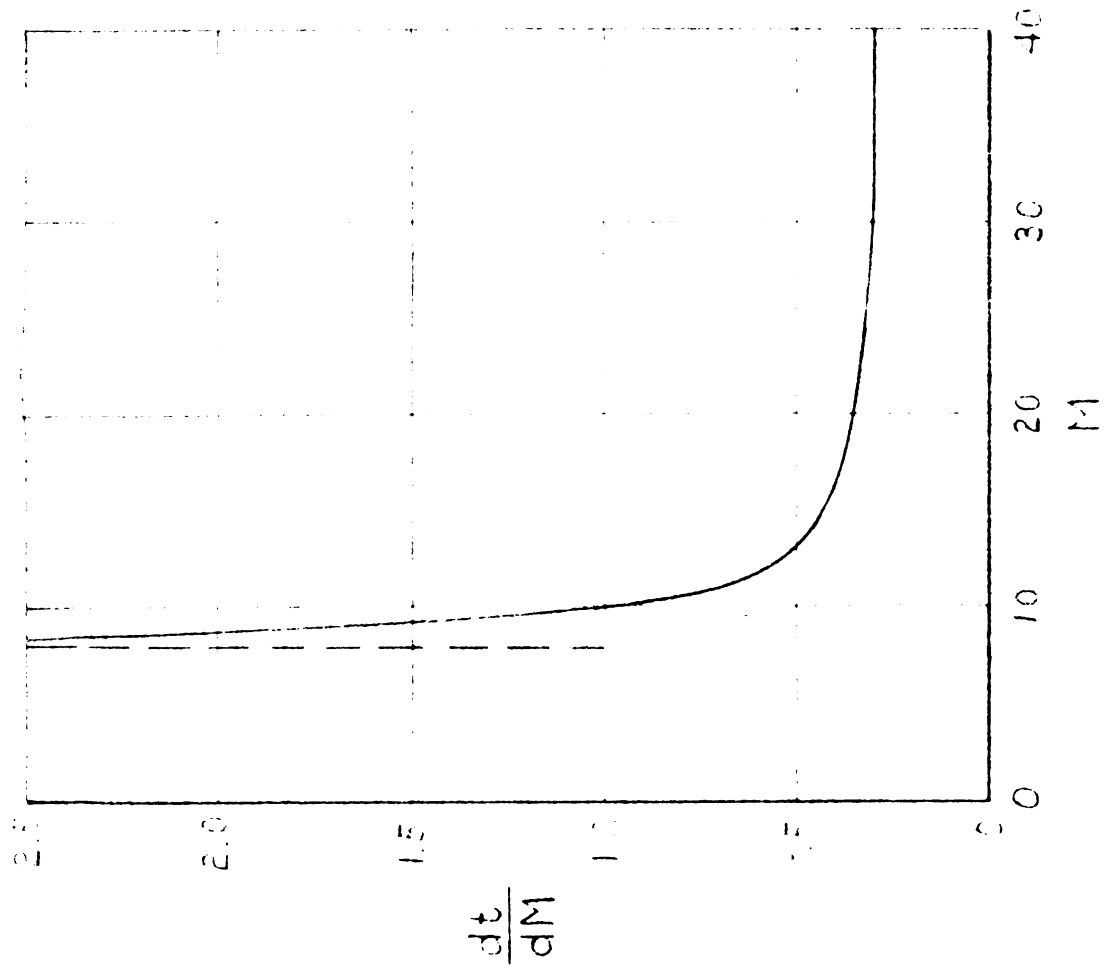


Figure 8.— Illustrative Curve of Drying Rate Reciprocal vs Moisture Content.

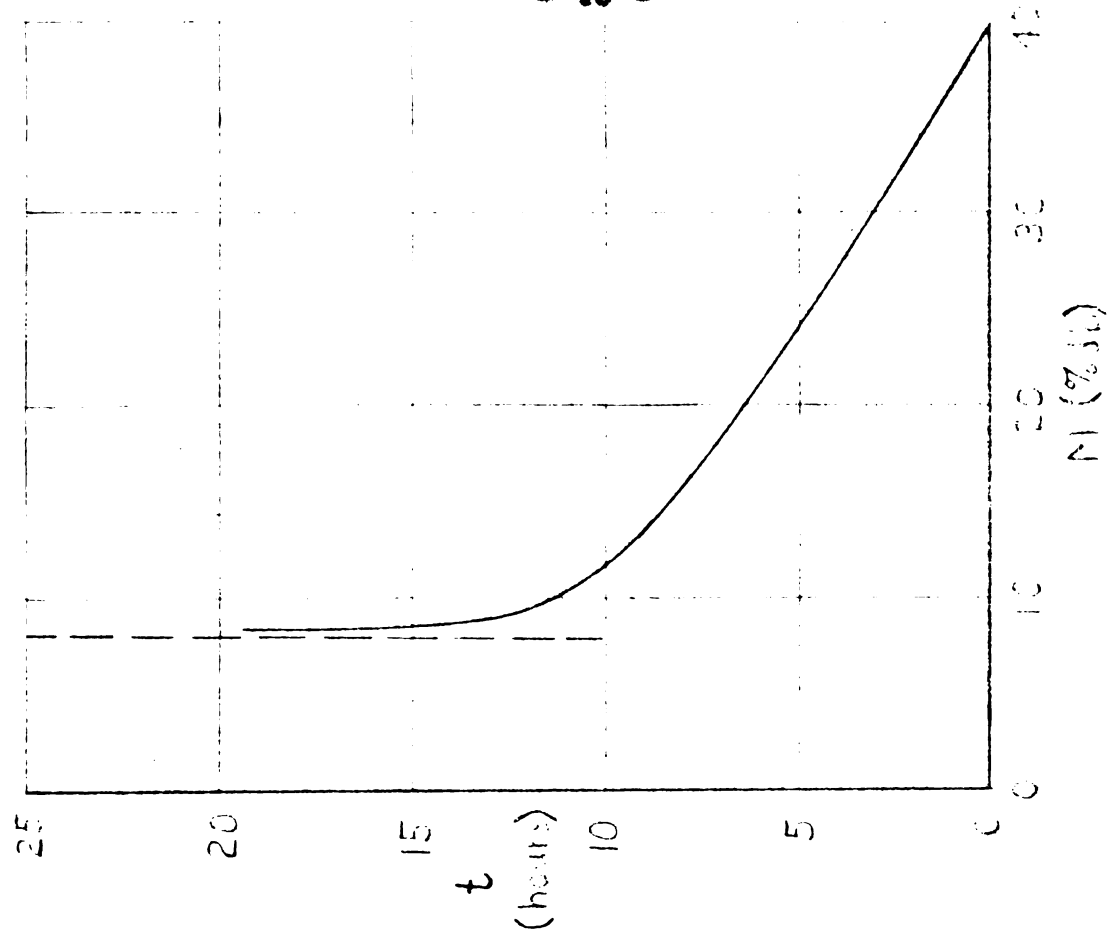


Figure 10.— Typical Drying Time Curve.

resulting time vs M curve is given in figure 10. With such a curve it is possible to obtain the time required to dry from one moisture content to another for the given drying conditions.

This whole procedure of determining the drying time can be carried out quite simply in tabular form. Table 4 shows the values used in the illustrative examples of figures 6, 9, 10. The first five columns are self explanatory. In order to get the sixth column accurately a curve of column 5 vs column 1 as in figure 9 is necessary. The area under this curve between the various values of M can be approximated quite accurately. The time value in column 6 for a given value of M equals the area under the curve between the given value of M and M equals 40%. If it was found that (other things being constant) K varied somewhat with M , this variation could also be accounted for in column 5.

The above discussion assumes a layer of material under uniform drying conditions. That is, p and p_a are the same for all parts of the layer. Under actual conditions p and p_a are not the same for all parts of the layer. p_a will vary as the air progresses through a drying material. As the air picks up moisture its vapor pressure, p_a , increases. Therefore, the above calculations are good only for the layer of material next to the point where the drying air enters. Additional calculations are necessary for obtaining the drying rate of that material which makes up the successive layers of the material.

TABLE 4. - METHOD OF COMPUTING DRYING TIME FOR WHEAT

Assume: $K = 10\% / (\text{hr})(\text{"Hg})$

①	②	③	④	⑤	⑥
M	p	$p - p_a$	$\frac{1}{p - p_a}$	$\frac{1}{K(p - p_a)}$	t
(%db)	(from fig. 6)	($p_a = .41\text{"Hg}$)		(or dt/dM)	(Area under dt/dM curve)
40	0.74	0.33	3.03	0.303	0.00
34	.74	.33	3.03	.303	1.82
30	.74	.33	3.03	.303	3.03
25	.72	.31	3.23	.323	4.59
20	.69	.28	3.57	.357	6.29
15	.64	.23	4.35	.435	8.24
12	.59	.18	5.55	.555	9.68
9	.47	.06	16.67	1.667	12.68
8	.41	.00	∞	∞	∞

TABLE 5. - COMPUTATIONS FOR LEAVING VAPOR PRESSURE

①	②	③	④	⑤	⑥	⑦
t	p of first layer	p_a entering	$p - p_a$	$\frac{\text{grains } H_2O}{\text{pound air}}$	increase in p_a	p_a leaving
(hours)	("Hg)	("Hg)		$70(p - p_a)$	$\frac{⑤}{150}$	($③ + ⑥$)
0.00	0.74	0.41	0.33	23.1	0.15	0.56
1.82	.74	.41	.33	23.1	.15	.56
3.03	.74	.41	.33	23.1	.15	.56
4.59	.72	.41	.31	21.7	.14	.55
6.29	.69	.41	.28	19.6	.13	.54
8.24	.64	.41	.23	16.1	.11	.52
9.68	.59	.41	.18	12.6	.08	.49
12.68	.47	.41	.06	4.2	.03	.44
∞	.41	.41	.00	0.0	.00	.41

Consider air being forced up through a bin of grain. The drying time for the bottom layer is as just described. In order to get the drying time of the grain at various distances above this bottom layer it is necessary to consider the grain as divided into layers of arbitrary thickness. The thinner the layers the more accurate will be the calculations for drying time. After the drying rate of the first layer is computed, the increase in p_a leaving the first layer can be established. The resulting value of p_a leaving the first layer will be the p_a for the air entering the second layer.

The value of p varies with M in all succeeding layers just as it does in the first layer. One might think that because t_d decreases as the air rises, the value of p would also decrease. Because drying is a constant wet bulb process, however, and the value of p is determined from the equation involving t_w (equation 12), it can be shown that p varies only with M for any given drying condition. Therefore, the values of p and p_a are known for the second layer.

Calculation of the drying time for the second (and successive) layer is not the same as for the initial layer. p is given vs M while p_a is now given vs time. The procedure is not difficult but is rather tedious. To illustrate, the following example is given:

Consider the problem previously worked for hard red winter wheat. Assume a bottom layer with 10 pounds of wheat (dry weight) all of which undergoes drying according to figure 10. Also assume an air flow through this wheat of

100 lb dry air/hr. It is first necessary to establish the value of p_a leaving this layer. Since the drying rate is known, the grains of water picked up per pound of air can be calculated.

$$\frac{K(p - p_a) \text{ lb H}_2\text{O}}{100 \text{ lb dm, hr.}} \times \frac{7000 \text{ grains}}{\text{lb H}_2\text{O}} \times \frac{10 \text{ lb dm, hr.}}{100 \text{ lb air}}$$

$$= 7 K(p - p_a) \frac{\text{grains}}{\text{lb air}}$$

With this expression and the psychrometric chart, the value of p_a leaving the first layer can be determined. Table 5 gives this in tabular form for various values of t . The above calculations show that if the air flow is increased or the amount of dry matter in the layer decreased, the grains of moisture picked up per pound of air will be less. This would result in less raising of p_a leaving the first layer and would make the drying rate of the second layer faster.

Table 6 presents a convenient method of using the new values of p_a to compute the drying rate of the second layer. The calculations are a step by step procedure which repeats itself. Column A gives values of time which have been computed for the first layer and the first value of M in column B is the original moisture content. A study of the table is self explanatory. Columns A and B provide the drying curve for the second layer. Calculations for other layers are similar. Figure 11 shows the resulting curves for several equal 10 pound layers. Figure 11 has been rotated 90° so that the time is the abscissa scale. This is the common method of presentation.

TABLE 6. - DRYING TIME FOR SECOND LAYER

[illegible]

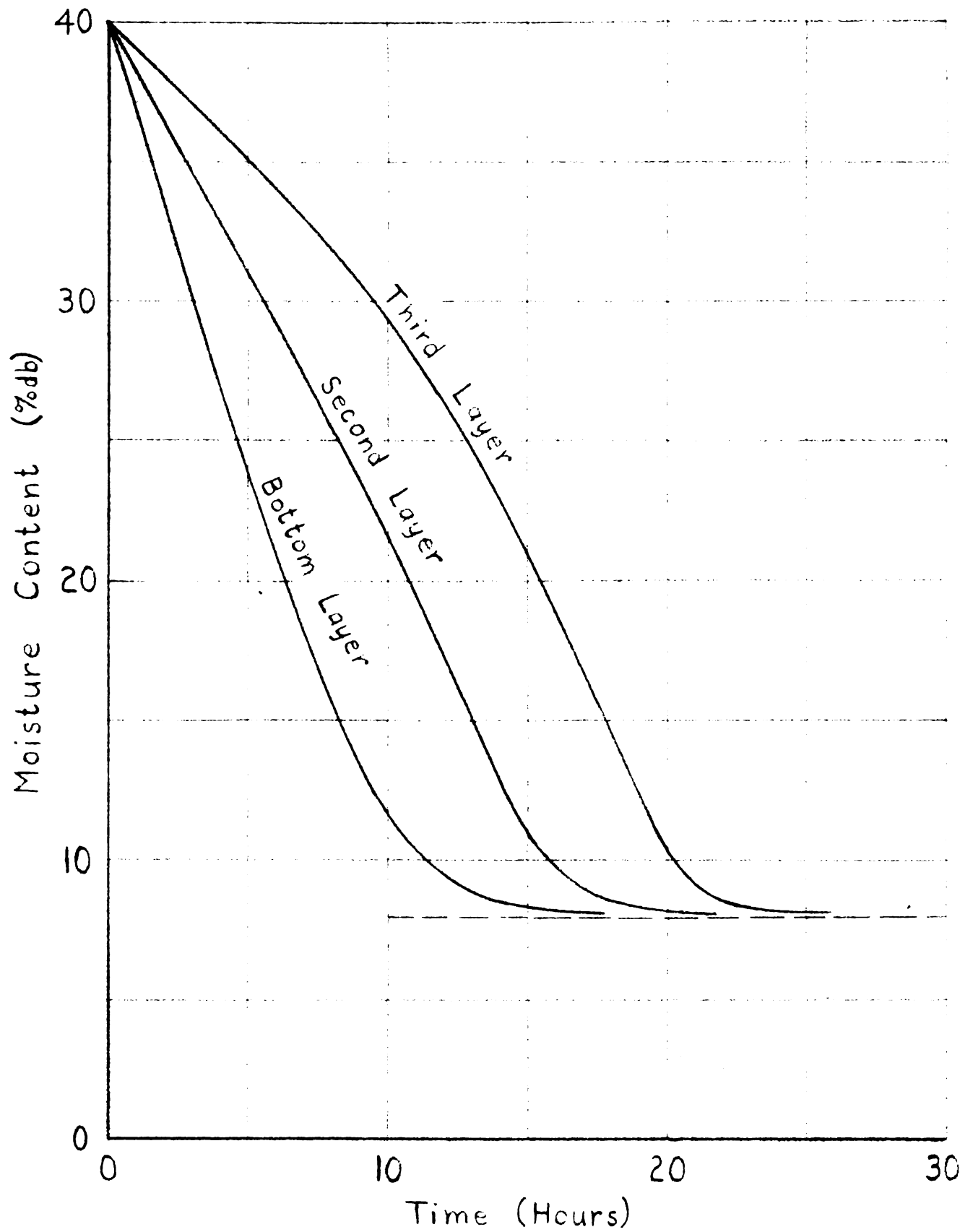


Figure 11. - Drying Curves for Several Layers.

EXPERIMENTAL PROCEDURE

During the spring of 1949 the author designed and built a small scale experimental apparatus for drying agricultural crops. It was constructed so that the temperature, humidity, and amount of drying air could be carefully controlled. Funds for constructing the equipment were furnished by the J. I. Case Company of Racine, Wisconsin. The J. I. Case Company was interested in the comparative drying rates of various types of bales of hay. The equipment was operated for this purpose throughout the summer of 1949. A series of tests on individual bales of hay were made. Each test was conducted under constant drying conditions and the resulting loss of moisture with time was recorded. The data provided a very good overall drying curve for each bale. These tests are used in this thesis for comparison with the theory. Because they were not conducted exclusively for this one purpose, the tests do not supply the exact kind of data desired. However, the data are sufficient to provide a comparison of experimental and theoretical values. The theory deals with the drying rate at various layers such as encountered in a mow of hay, while the data shows the overall drying rate for an individual bale of hay.

DESCRIPTION OF THE APPARATUS

Details of the Equipment

A side view of the test apparatus for drying is shown in figure 12. It consists essentially of a fan, a duct for conditioning the air, a plenum chamber, and test section. Figures 13 and 14 are overall photographs of the apparatus from opposite ends. Details of the individual parts are described below.

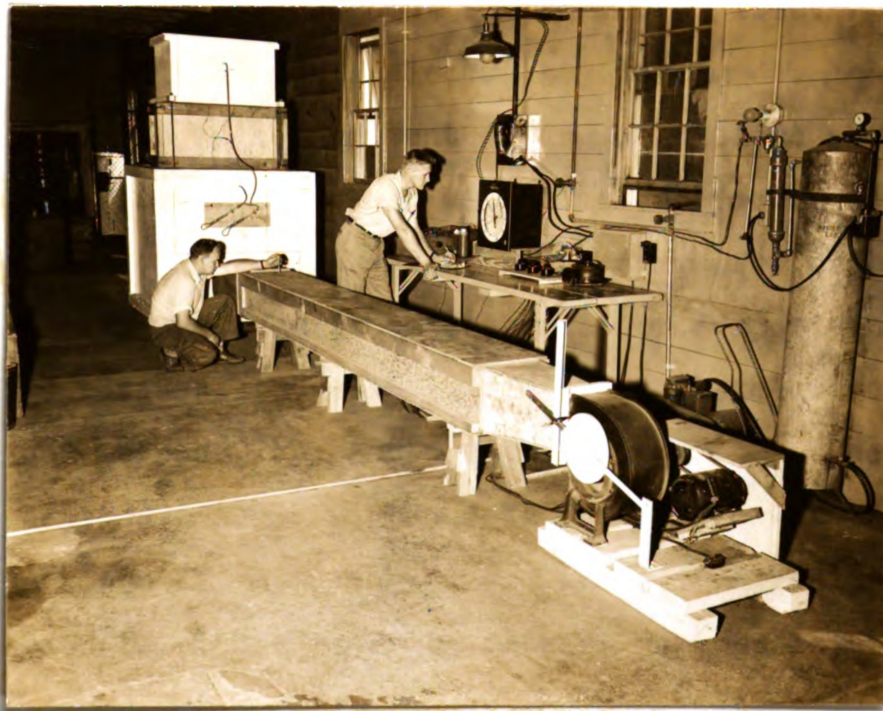


Figure 13. General View of Apparatus from Fan End

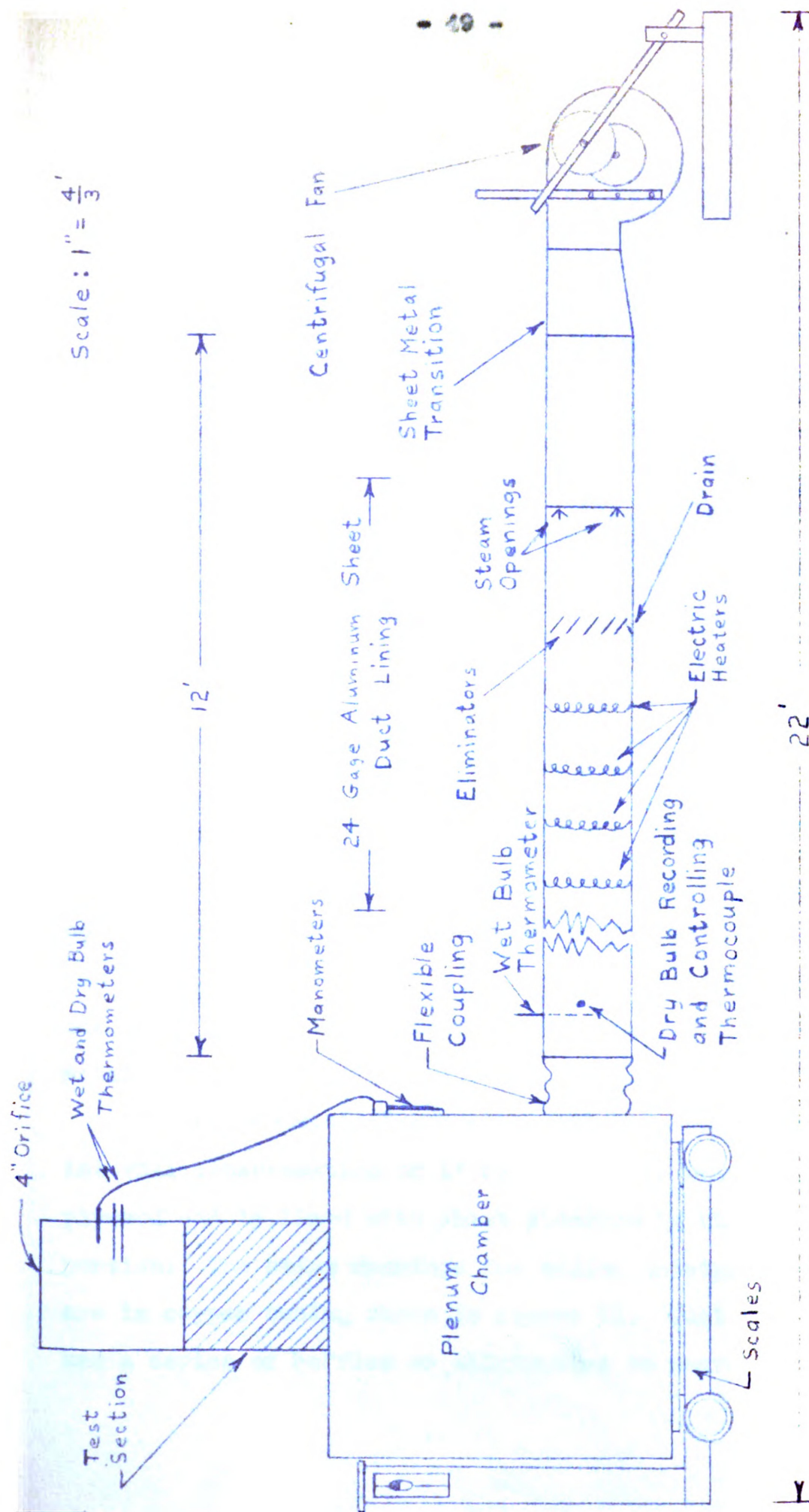


Figure 12. — Sketch of Laboratory Drying Apparatus.

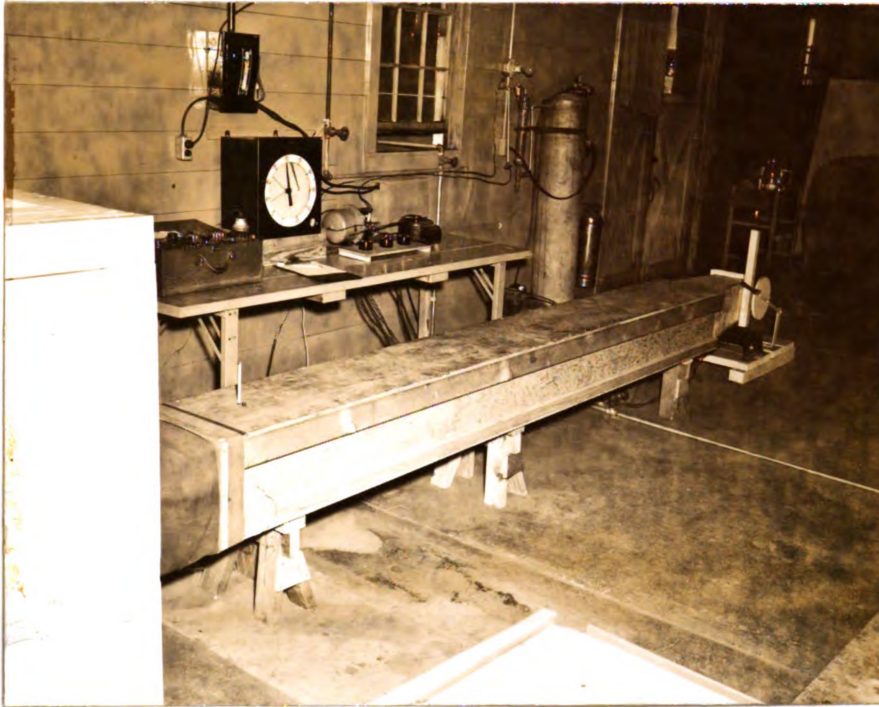


Figure 14. General View of Apparatus from Plenum End

A Clarage size 3/4 centrifugal fan with forward curved blades is used. The fan is driven by a 1/2 HP single phase motor with a V-belt drive. The size of the inlet opening can be varied with a damper as shown in figure 15. The fan discharge is led to the conditioning duct through a sheet metal transition.

The air conditioning duct is 12' long and has an internal cross-section of 1' by 1'. It is made of 1/2" plywood and is lined with sheet aluminum in the center portion. The steam openings for adding moisture to the air are in copper tubing shown in figure 16. Just beyond them are a series of baffles or eliminators to prevent any

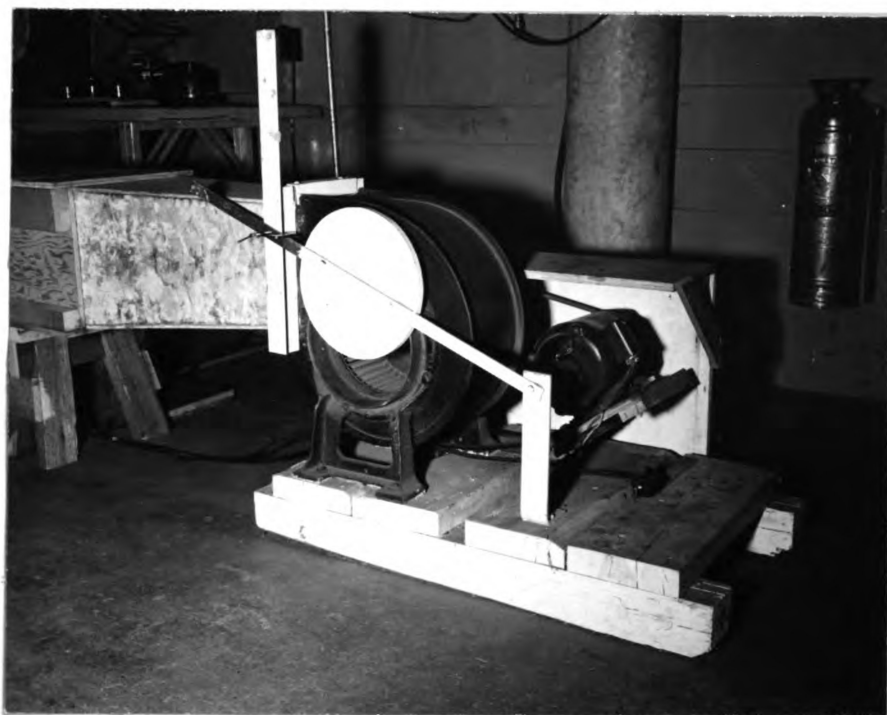


Figure 15. Closeup of Fan

condensed moisture from passing through the duct. The condensed moisture is collected and drains through a hole in the bottom.

The coiled wire heater used to heat the air is shown in Figure 17. Three of the four heater elements each have a maximum of 2000 watts with intermediate steps of 500 and 1000 watts. The fourth heater element is variable from 0 to 1000 watts. This gives a continuous range from 0 to 7000 watts for heating the air.

The control section is the last part of the duct just before the air enters the plenum chamber. The air temperature and humidity are maintained constant at this point for the tests. The dry bulb temperature is recorded with the



Figure 16. Steam Inlet for
Humidifying the Air

thermocouple shown in figure 18. The wet bulb temperature is read manually with a thermometer at regular intervals.

The plenum chamber is a 4' x 4' x 4' box made of plywood and rests on platform scales (see figure 19). The scales can be read to a quarter of a pound. The air entering the plenum comes through a flexible canvas coupling from the duct. The inside of the plenum was sealed against moisture to prevent loss or gain in weight of the plenum itself.



Figure 17. Electric Heater Coils



Figure 18. Control Section

The test section is mounted on top of the plenum so that as the hay dries out the weight on the scales below is reduced. The unpainted portion of figure 19 is the test section. The test section is adjustable in cross-section from 15" x 32" to 20" x 37".



Figure 19. Scales and Plenum

The air that comes through the hay in the test section is collected and exhausted through a 4" sharp edged orifice. Figure 20 shows the orifice from above. It also shows the two thermometers used to determine the exit air dry bulb and wet bulb temperatures.

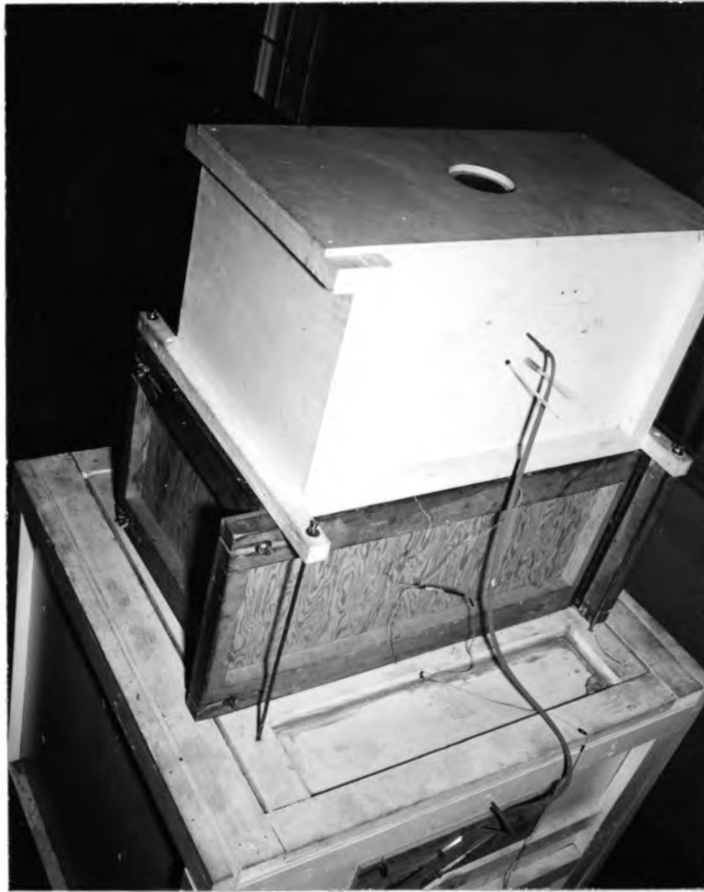


Figure 20. Orifice and Exit
Air Assembly

A supply of compressed air is necessary to operate the automatic temperature controls. Figure 21 shows this equipment. The compressor motor has an automatic switch which maintains the pressure in the reservoir above 20 psi. The air leaving the tank is reduced to 15 psi by a pressure reducing valve. A dehydrator is also in the supply line to keep the air dry.



Figure 21. Air Compressor
and Supply

Measuring and Control Devices

Two slanting tube manometers are used to measure the static pressure for determining air resistance and static pressure for determining air velocity. Figure 22 shows these manometers along with the calipers and engineers' scale used to get readings.

The thermocouple in the control section actuates the Brown temperature recorder-controller. This instrument operates on 15 psi air pressure. It controls the air



Figure 22. Manometers

pressure to a Minneapolis-Honeywell Grad-U-Motor. The position of the Grad-U-Motor arm varies from minimum to maximum displacement as the controlled air varies from 0 to 15 psi. This arm in turn varies the rotary position of the variac through a rack and pinion gear linkage. The variac is a variable A. C. transformer which alters the voltage to the 1000 watt heater element from 0 to 115 volts. Once set at a given temperature this system will maintain that temperature at the control section automatically. This apparatus is shown in figure 23.

The humidity is controlled manually with 20 psi steam from the heating main. Part of the steam to the steam jets is by-passed out the window. Figure 23 shows the piping and

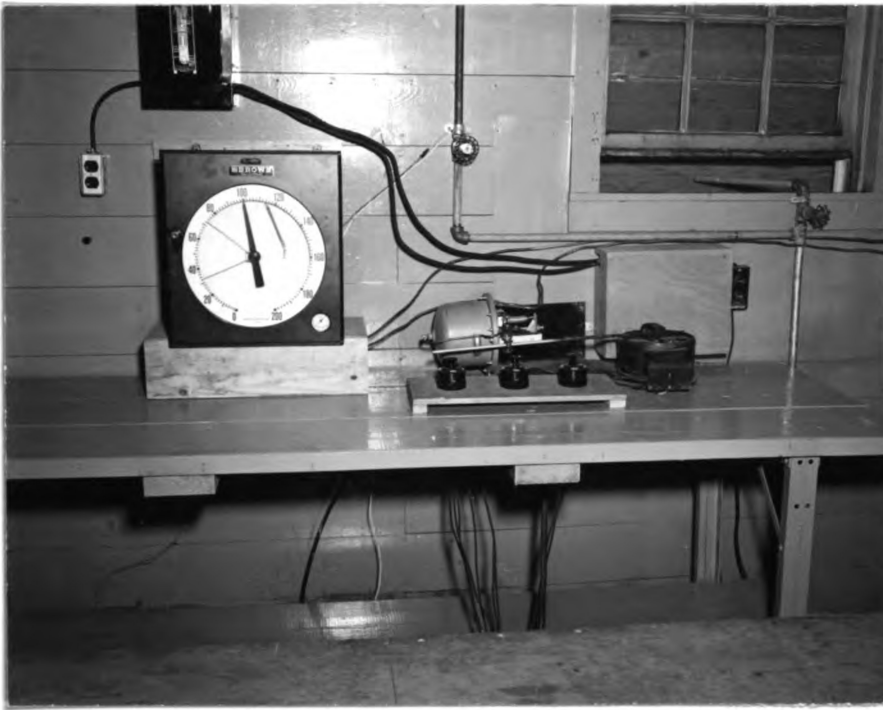


Figure 23. Control Apparatus

valve which is varied to allow different amounts of steam to be by-passed. Another pipe carries off the condensate from the lowest part of the system.

Safety Devices

The electrical power to the heaters passes through two low-voltage, no-voltage relays that are located behind the cover next to the starting switch in figure 23. The starting switch is wired to the holding coils of the relays so that the fan motor must be running before the heaters can be turned on. In case the V-belt breaks, the motor will drop on a switch (Rockwood drive, figure 15) which opens the relays. Also the duct lining and other apparatus is grounded. In

case of a short, the instantaneous drop in voltage through the holding coils will open the relay.

METHOD OF TESTING

The bale to be tested was squeezed into the adjustable test chamber as illustrated in figure 24. Any holes or loose spaces where air might slip around the bale were packed with loose hay. The test section was then weighed on the Toledo scales shown in figure 25. The tare weight of the test section was known so that the original bale weight could be determined.



Figure 24. Squeezing Bale
into Test Section



Figure 25. Weighing the Bale

Three thermocouples were placed in the bale when it was placed in position on top of the plenum chamber. One in the bottom, middle, and top of the bale. The dimensions of the bale in the test section were 35" x 18" x 15" with the flat side down. The exhaust section with the orifice was mounted on top of the test chamber and was clamped down with wing nuts. Weather stripping was used to seal the joints.

Before the test was started the manometer tubes were checked for levelness and zero reading. Also the thermometers were put in place. When everything was ready, the

fan was started, the heaters turned on and the automatic temperature control set. It generally took a few minutes to get the steam regulated so that the air had the correct humidity. The volume of air was adjusted with the damper on the fan inlet.

When air temperature, humidity, and volume were adjusted to the desired values the weight was read and this time was recorded as the start of the test. Throughout each test these values were maintained constant. The tests were run continuously until the drying curve started to flatten out. When the weight did not change much from one reading to the next the test was stopped.

When the nights were cold it was necessary to turn on more heaters to keep the air temperature high enough. The automatic control kept the temperature constant within plus or minus 2 degrees. The absolute humidity of the outside air did not vary much throughout the day and with slight adjustments of the by-pass steam valve, every hour or two, the entering wet bulb temperature could be kept quite constant. As the hay dried out it was easier for more air to pass through it so that the air entrance to the blower had to be closed slightly every couple of hours in order to keep the air volume constant.

When a test was completed the bale was removed from the test section and again weighed. Figure 26 shows a bale just removed from the test section. Four samples were taken from each bale in order to get a representative final moisture

content throughout the test. The value of the moisture content was known only approximately at the start of the tests.



Figure 26. Bale Removed
from Test Section

PRESENTATION OF THE DATA

The tests were on individual bales dried under constant conditions. Their overall drying rates were determined. The method of drying used made it impossible to establish drying rates by layers which is what the theory gives. Therefore, correlation of the test data and theory is rather difficult. Various methods of doing this were attempted. After considerable study it was decided to alter the drying rate equation so that it represents the overall drying rate of the material being dried. This could be done only approximately, but was the best method of showing the relationship between theory and test.

It has already been shown that the drying rate above the bottom layer increases with increasing air flow. It was also shown that the greater the amount of dry matter passed through, the lower the drying rate. These two facts can be combined into the term, lb dry air/(hr)(lb dry matter). The overall drying rate is roughly proportional to this factor. Actually the factor changes the drying rate by altering the value of p_a at various layers. For a given quantity of material, however, the overall drying rate may be given approximately by including this factor in the equation and considering p_a constant. This puts the drying equation in the following form:

$$\frac{dM}{dt} = C' \times \frac{\text{lb dry air}}{\text{hr., lb dry matter}} (p - p_a) \quad (18)$$

where C' is an experimental constant. The product of $C' \times \text{lb dry air}/(\text{hr})(\text{lb dry matter})$ is not the same as the factor K in equation 2 so it will be called K'' in order to differentiate between the two.

The above equation includes all of the terms previously considered but in a slightly different manner. p_a is the entering air vapor pressure to the quantity of material under consideration. The variation in it which actually occurs is taken care of by the $\text{lb dry air}/(\text{hr})(\text{lb dry matter})$ factor. dw/dt represents approximately the overall drying rate which is known experimentally. With such a relationship it is possible to study the drying results of the tests.

Table 7 is a summary of six drying tests which are used to show the correlation of data with theory. They cover a wide range of air flow per pound of dry matter, and considerable variation in original moisture contents. Five of the tests are for 100°F drying air and the sixth is for 120°F drying air. The change in moisture content with time for these tests is given in table 8. The data in table 8 represent the actual readings taken during the tests. These data can be plotted to give experimental drying curves.

In order to compute drying curves for these tests it is necessary to have a value of C' for alfalfa, and the variation in alfalfa vapor pressure as drying progressed. The drying temperatures for the first five tests were 100°F dry bulb and 84°F wet bulb and for the sixth test 120°F dry bulb and 88°F wet bulb. With these values and formula 12 the

TABLE 7. - SUMMARY OF TESTS

①	②	③	④	⑤	⑥	⑦	⑧	⑨
Test No.	Dry Matter (lb)	Vapor Pressure of Air ("Hg)	Air Temperature (°F)	Equilibrium Moisture Content (%db)	Original Moisture Content (%db)	Air Flow $\frac{\text{lb air}}{\text{hour}}$	Air Flow $\frac{\text{lb air}}{\text{hr.}}$	K"
							$\frac{\text{lb air}}{\text{hr.}}$	$\frac{\text{lb air}}{\text{hr.}} \times \text{K}$
1	55.95	1.0	100	13.5	35.8	451	6.85	9.92
2	39.11	1.0	100	13.5	42.5	633	16.20	23.50
3	61.20	1.0	100	13.5	37.4	451	7.39	10.71
4	36.62	1.0	100	13.5	48.1	463	12.60	18.25
5	43.10	1.0	100	13.5	42.6	451	10.44	15.14
6	42.55	1.0	120	7.4	29.8	435	10.20	14.80

* lb dm represents pounds of dry matter (column 2).

Test No. 1		Test No. 3		Test No. 5	
Time (hrs)	Moisture Content (%)	Time (hrs)	Moisture Content (%)	Time (hrs)	Moisture Content (%)
0.0	31.0	0.0	37.4	0.0	40.0
1.0	31.3	0.0	38.0	0.0	40.0
2.0	32.6	0.0	38.1	1.0	40.4
3.0	32.5	0.0	38.3	2.0	39.1
4.0	31.0	0.0	38.0	3.0	38.1
5.0	32.0	1.0	38.3	4.0	37.3
6.0	29.1	2.0	38.4	5.0	36.5
7.0	27.3	3.0	38.3	6.0	35.8
8.0	27.4	4.0	37.1	7.0	34.1
9.0	25.4	5.0	36.3	8.0	33.7
10.0	23.0	6.0	36.0	9.0	34.0
11.0	24.0	7.0	34.0	10.0	34.1
12.0	24.0	8.0	33.0	11.0	31.0
13.0	22.7	9.0	33.0	12.0	30.1
14.0	21.7	10.0	31.0	13.0	28.0
15.0	20.3	11.0	30.5	14.0	28.3
16.0	19.0	12.0	29.7	15.0	27.7
17.0	18.0	13.0	28.4	16.0	27.2
18.0	18.1	14.0	27.1	17.0	26.0
19.0	17.1	15.0	27.7	18.0	25.4
20.0	17.8	16.0	26.1	19.0	24.9
21.0	16.1	17.0	25.7	20.0	24.3
22.0	15.1	18.0	24.0	21.0	24.3
23.0	15.0	19.0	24.4		

Test No. 2		Test No. 4		Test No. 6	
Time (hrs)	Moisture Content (%)	Time (hrs)	Moisture Content (%)	Time (hrs)	Moisture Content (%)
0.0	40.5	0.0	40.1	0.0	28.0
0.0	40.0	1.0	43.1	1.0	26.0
1.0	37.0	2.0	41.0	2.0	22.1
1.0	33.0	3.0	39.0	3.0	19.2
2.0	34.7	4.0	36.0	4.0	16.3
3.0	31.7	5.0	32.2	5.0	14.3
4.0	29.0	6.0	27.3	6.0	11.0
5.0	27.0	7.0	24.5	7.0	10.0
6.0	23.0	8.0	22.3	8.0	9.5
7.0	24.0	9.0	20.0	9.0	8.5
8.0	22.1	10.0	18.5	10.0	8.0
9.0	20.0	11.0	17.0	11.0	8.0
10.0	19.0	12.0	16.2	12.0	8.0
11.0	19.0	13.0	15.4	13.0	7.5
12.0	17.6	14.0	15.4		
13.0	17.0	15.0	14.7		
14.0	16.7				
15.0	15.0				
16.0	14.0				
17.0	13.0				

vapor pressure during drying can be computed. The method is the same as illustrated in table 2 for wheat. Figure 27 shows the vapor pressure of alfalfa at various temperatures and moisture contents (from table 3), and the dashed lines represent the computed values of alfalfa vapor pressure during the tests.

The value of C' for alfalfa was determined from a careful study of the test data. The value finally established was $C' \approx 1.45$. K'' was computed using this value in the last column of table 7. The complete computations for drying time for all six tests are given in table 9. The last column, time in hours, was calculated in the same manner as the illustration for wheat in table 4. The resulting computed drying curves are given in figures 28, 29, and 30. The test points shown on the figures are the values from the data of table 8.

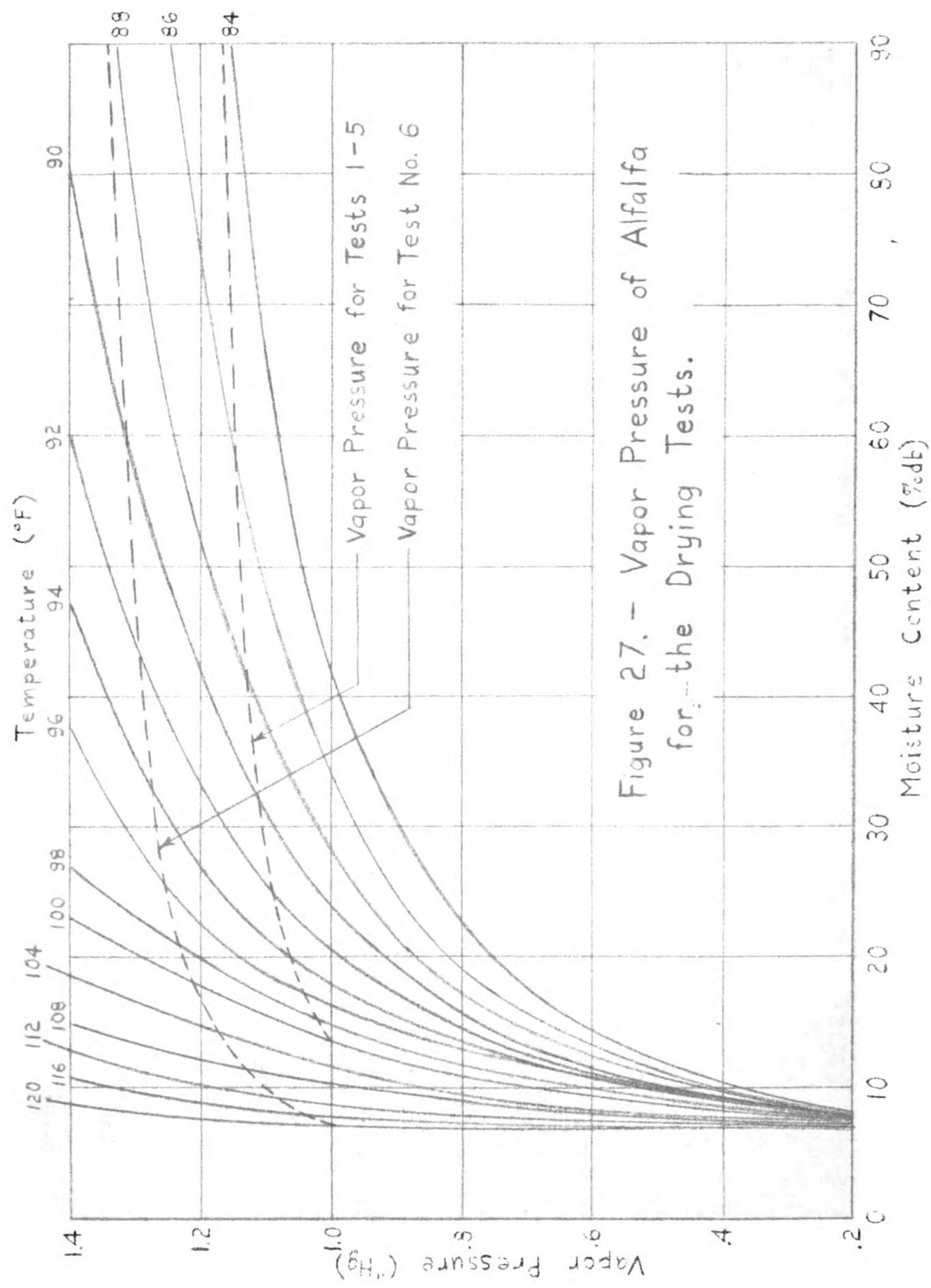


Figure 27. - Vapor Pressure of Alfalfa
for the Drying Tests.

TABLE 9. - COMPUTATIONS FOR DRYING TIME

Test No. 1

 $p_a = 1.0^{\circ}\text{Hg}$ and $K'' = 9.92$

M	p	$\frac{1}{K''(p - p_a)}$	t	(hrs)
(°db)	(°Hg)			
35.8	1.122	0.826	0.00	
35.0	1.120	.840	.67	
30.0	1.105	.960	5.07	
25.0	1.090	1.12	10.13	
20.0	1.065	1.55	16.52	
17.5	1.045	2.24	21.20	
15.0	1.020	5.04	30.00	
14.0	1.010	10.10	37.10	
13.5	1.000	∞	∞	

Test No. 3

 $p_a = 1.0^{\circ}\text{Hg}$ and $K'' = 10.71$

M	p	$\frac{1}{K''(p - p_a)}$	t	(hrs)
(°db)	(°Hg)			
37.4	1.125	0.746	0.00	
35.0	1.120	.777	1.81	
30.0	1.105	.889	5.85	
25.0	1.090	1.04	10.51	
20.0	1.065	1.44	16.50	
17.5	1.045	2.07	20.80	
15.0	1.020	4.67	29.00	
14.0	1.010	9.32	35.40	
13.5	1.000	∞	∞	

Test No. 5

 $p_a = 1.0^{\circ}\text{Hg}$ and $K'' = 15.14$

M	p	$\frac{1}{K''(p - p_a)}$	t	(hrs)
(°db)	(°Hg)			
42.6	1.133	0.436	0.00	
40.0	1.130	.503	1.31	
35.0	1.120	.550	3.95	
30.0	1.105	.629	6.83	
25.0	1.090	.734	10.14	
20.0	1.065	1.02	14.33	
17.5	1.045	1.47	17.33	
15.0	1.020	3.30	23.15	
14.0	1.010	6.60	27.70	
13.5	1.000	∞	∞	

Test No. 2

 $p_a = 1.0^{\circ}\text{Hg}$ and $K'' = 23.50$

M	p	$\frac{1}{K''(p - p_a)}$	t	(hrs)
(°db)	(°Hg)			
42.5	1.133	0.320	0.00	
40.0	1.130	.327	.81	
35.0	1.120	.354	2.50	
30.0	1.105	.405	4.36	
25.0	1.090	.472	6.49	
20.0	1.065	.654	9.18	
17.5	1.045	.945	11.15	
15.0	1.020	2.12	14.86	
14.0	1.010	4.25	17.81	
13.5	1.000	∞	∞	

Test No. 4

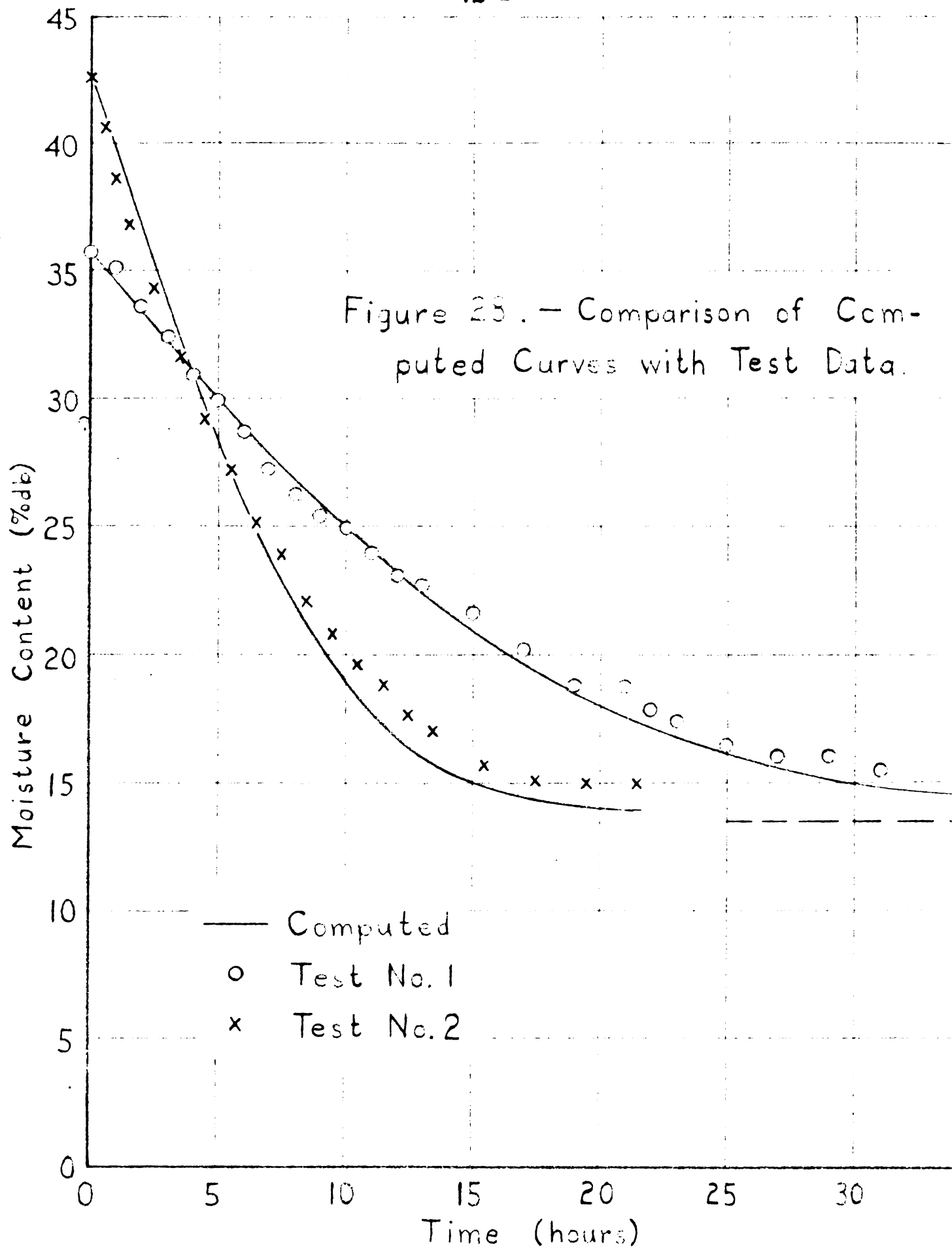
 $p_a = 1.0^{\circ}\text{Hg}$ and $K'' = 18.25$

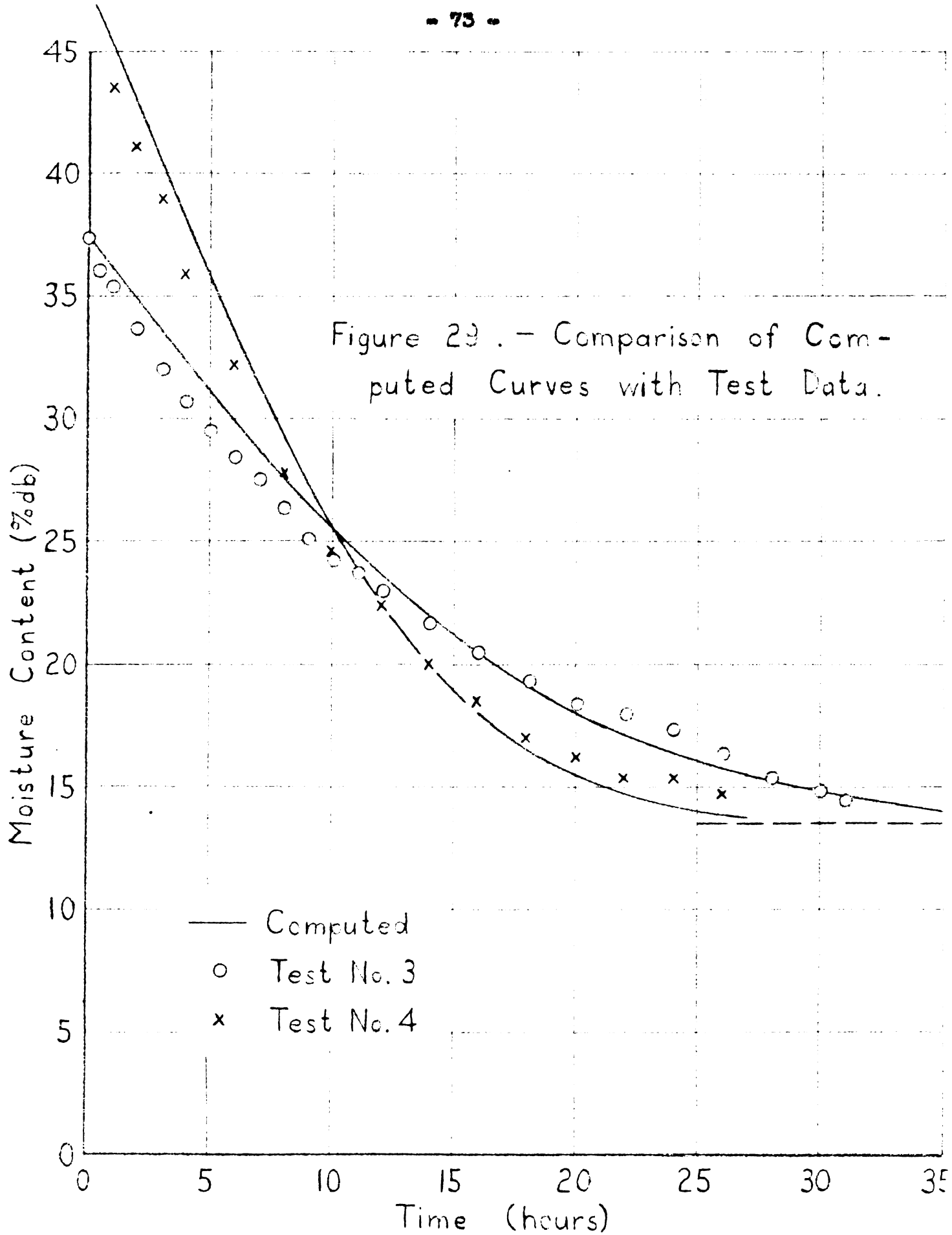
M	p	$\frac{1}{K''(p - p_a)}$	t	(hrs)
(°db)	(°Hg)			
48.1	1.133	0.396	0.00	
45.0	1.135	.405	1.24	
40.0	1.130	.421	3.29	
35.0	1.120	.456	5.45	
30.0	1.105	.521	7.81	
25.0	1.090	.609	10.55	
20.0	1.065	.842	14.02	
17.5	1.045	1.22	16.54	
15.0	1.020	2.74	21.30	
14.0	1.010	5.47	25.20	
13.5	1.000	∞	∞	

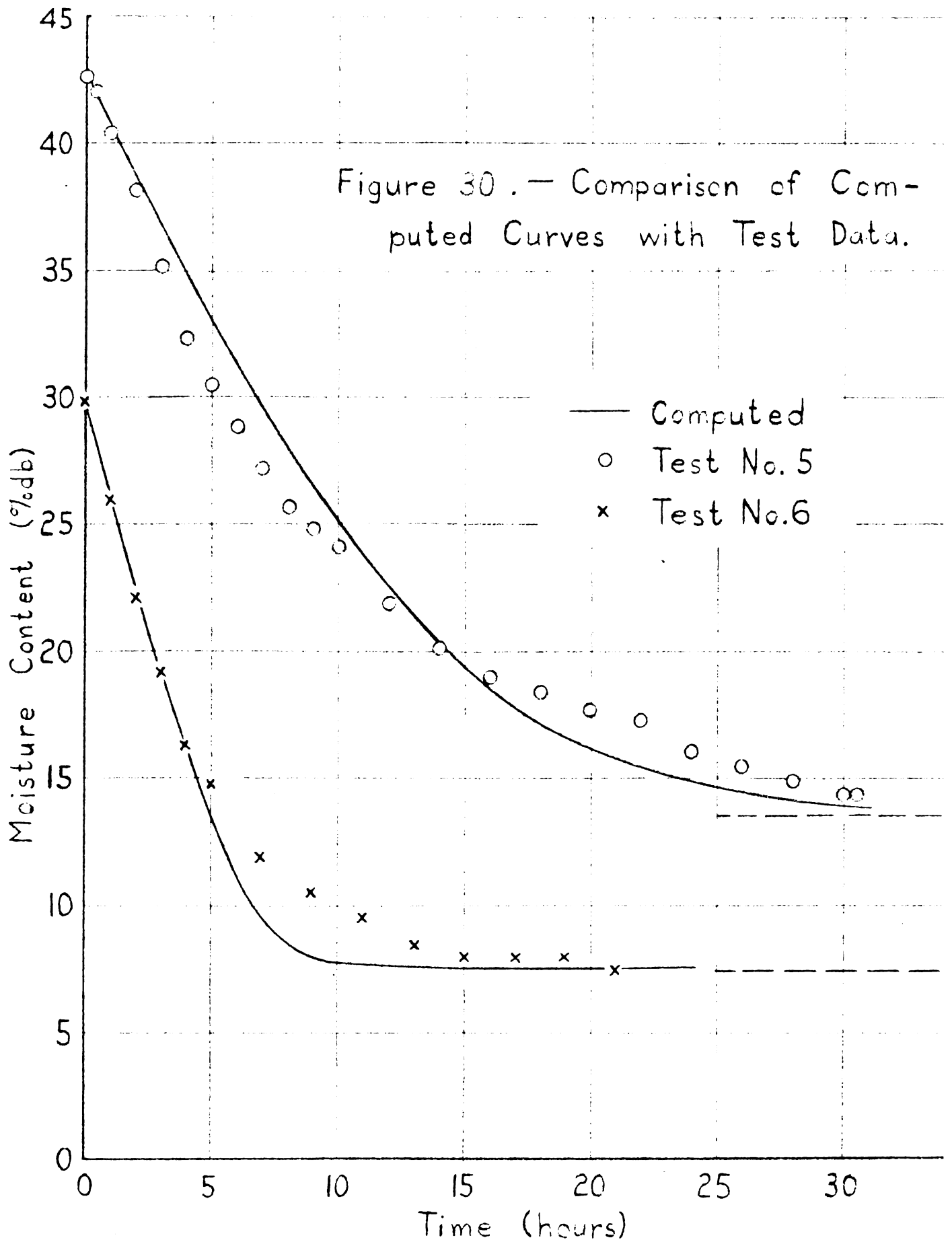
Test No. 6

 $p_a = 1.0^{\circ}\text{Hg}$ and $K'' = 14.80$

M	p	$\frac{1}{K''(p - p_a)}$	t	(hrs)
(°db)	(°Hg)			
29.8	1.270	0.250	0.00	
25.0	1.250	.270	1.24	
20.0	1.225	.300	2.66	
15.0	1.180	.375	4.34	
12.0	1.140	.482	5.60	
10.0	1.100	.675	6.63	
8.0	1.040	1.63	8.71	
7.4	1.000	∞	∞	







DISCUSSION OF THE RESULTS

Agreement of Data and Theory

The data in figures 28, 29, and 30 are for tests made under widely varying conditions. The air flow varied from 8.85 to 16.20 lb of air/(hr)(lb dry matter). The original moisture contents for the tests varied from 29.8% to 48.1%. Two air temperatures were used, 100°F and 120°F. The test data agree fairly well with the computed curves in all cases.

Figure 28 shows the results for two tests which were alike in every respect except original moisture content and air flow. Test no. 2 has an air flow per pound of dry matter over twice as great as for test no. 1. Tests 3 and 4, given in figure 29, are for other values of original moisture content and air flow. Tests 5 and 6, given on figure 30, represent two tests that were practically alike in every respect except temperature of the drying air and original moisture content. The agreement of theory and data is quite good even with all these variations in test conditions.

One very noticeable characteristic of the computed curves is that they all tend to lie above the test data at first and then below the test data when the drying approaches the equilibrium value (represented by the horizontal dashed line). There may be several reasons for this tendency. The

equation used to compute the curves (equation 13) is only approximate and this fact may account for some of the discrepancy. Another possibility is that K'' may vary slightly during the drying process. It has been pointed out that the "velocity effect" may cause some variation in drying rate. The velocity tends to influence the drying rate at high moisture contents while at low moisture contents its effect is negligible. This would cause the actual drying rate to decrease faster than the computed value which assumes the velocity effect constant. This is the trend in the data.

Before the theory can be properly judged it will be necessary to have considerable more test data. The small amount of data included herein only serves to show that the theory does have possibilities. Drying tests with other values of absolute humidity and other crops are necessary. Also, the tests should give the moisture contents at various levels instead of the overall values. Regardless of this lack of substantiation, the theory is developed in a sound logical manner and can be used to show the relative importance of various factors to drying. The data does substantiate the theory sufficiently to enable one to use it to predict the effect of temperature, humidity, air flow, etc. on drying.

Influence of Temperature

If the temperature of a commodity is increased, its dry-

ing rate increases. Figure 6 shows that the vapor pressure of a substance increases rapidly when its temperature increases and as p increases the drying rate W increases according to equation 2.

Heating of the commodity is the result in convection drying when the air is heated. Actually the heated air itself has no real advantage (provided it had sufficient moisture carrying capacity). It is the consequent heating of the product which produces the desired increase in drying rate. It would be much more efficient to heat the material to be dried directly rather than to heat the air. On the psychrometric chart it can be seen that the process of heating air only results in moving horizontally to the right across the chart. True, the relative humidity is lowered, but the vapor pressure which influences the drying is not changed.

Influence of Humidity

It is the absolute humidity and not the relative humidity that is the important factor in drying. As the absolute humidity decreases the vapor pressure p_a decreases and this means an increased drying rate. A low relative humidity, however, does not necessarily indicate a low vapor pressure. The psychrometric chart shows that air with a low relative humidity can have a high vapor pressure if the temperature of the air is increased. Therefore, when talking

about low relative humidity being good for drying it is also necessary to specify the temperature.

Effect of Depth

The depth of grain or hay is an important factor in drying. Consider air rising up through a bin of grain. When drying first starts, the moisture content of the product being dried is uniform and if it is high enough, the temperature of the grain throughout the bin assumes the wet bulb temperature of the drying air. The vapor pressure of the grain, therefore, is constant throughout. The vapor pressure of the air, however, varies as it rises through the grain. As the air picks up moisture in the lower areas, its vapor pressure is increased and gradually gets greater as the air rises. The difference in vapor pressure and therefore the drying rate decreases as the air rises through the grain. This fact causes uneven drying.

Influence of Air Flow

Increased air flow will result in more even drying and a faster overall drying rate. The data show this quite clearly. As mentioned above, the vapor pressure of the air increases as it rises through a bin of grain. More air means less moisture to carry per pound of air and this means less rise in vapor pressure. This accounts for the increased drying rates of the upper layers with high air flow.

A disadvantage of high air flow is that the efficiency of drying will be low. The air will not have enough time to pick up its maximum quantity of moisture.

Effect of Density

Varying density does not effect the drying rate as long as the pounds of dry matter remains constant. For example, varying the volume occupied by ten tons of hay will not change the drying rate of ten tons if the air flow remains constant. The bottom, middle, and top layers, etc. will still dry in the same manner. This is so regardless of whether the ten tons of hay is in a tall narrow mow or a wide low mow.³ However, if a given volume of hay is considered and the pounds of hay in this volume vary while the air flow remains constant, the more pounds the lower the drying rate in the upper layers. This is understandable because the air will pick up more moisture as it rises and p_a will be higher in the upper layers.

One important factor against high densities is that the greater the density, the more static pressure required to force a given amount of air through it. This results in high priced fans and large power bills. Also, uneven drying may result because the air will tend to go through any channels of lower resistance that may occur and not penetrate the dense areas.

Type of Material

The drying characteristics are different for each material being dried. In fact they vary within a material when it is prepared in a different manner. Crushed hay for example dries differently from regular hay. The reason is probably the more exposed water surface area and less distance for the moisture to diffuse through to reach the surface. The factor K in the drying rate expression is to take care of these differences between materials. Also the vapor pressure vs moisture content curve varies somewhat with different materials. This makes p in the drying rate expression different for various materials and helps to account for the many shapes of the drying curve.

Moisture Content

When a material being dried has free moisture, its vapor pressure and drying rate remain constant as the moisture content decreases. After the free moisture has been evaporated, however, the vapor pressure of a material varies with its moisture content. If everything else is held constant less moisture means less vapor pressure. Since the drying rate is proportional to the difference between the commodity and the surrounding vapor pressures, the drying rate decreases as the moisture content decreases.

CONCLUSIONS

1. A material will dry when the vapor pressure of the water in the material is greater than the vapor pressure of the water in the air surrounding the material.

2. The rate of drying is proportional to the difference between the vapor pressure of the material and the vapor pressure of the surrounding air. This relationship may be expressed as

$$\text{Drying Rate} = K (p - p_a)$$

where K is a proportionality factor, p is the vapor pressure of the material, and p_a is the vapor pressure of the water in the air. The experimental results conducted on alfalfa hay indicate that this relationship is approximately true. Considerable more data is necessary to establish it definitely.

3. If the proportionality factor is known for a given material the expression for the drying rate, given above, can be solved for the time required to dry from one moisture content to another.

4. When the temperature of a material is increased, its vapor pressure increases, and the result is a faster drying rate.

5. When the absolute humidity of the air is lowered, the vapor pressure of the water in the air decreases, resulting in faster drying.

6. The vapor pressure of the air is increased as it passes through a drying material at a rate which decreases as the air flow increases. The result is faster overall drying when the air flow is increased.

7. As the moisture content of a drying material progressively decreases, its vapor pressure decreases, resulting in slower drying rates. When the vapor pressure of a drying material has decreased to that of the surrounding air, the drying rate is zero and the material is at the equilibrium moisture content.

8. The density of a material does not influence the drying rate as long as the pounds of air/(hour)(pound of dry matter) remains constant. If the pounds of dry matter in a given volume is increased, however, while the air flow is held constant (such as so many cfm/ft² of flow area), the drying rate will decrease.

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