COOLING AND DRYING OF HIGH MOISTURE SHELLED CORN IN DEEP BEDS

by

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INTRODUCTION

The storage of food has been a fundamental problem of man since the beginning of recorded history. As population has shifted from rural to urban, the problems of food storage have changed, requiring new technology for their solutions.

Historically, grain has been a basic food for people all over the world. Evidence of sun-drying of cereal grains, and then storage of the grain in small bins made of mud, dates back to the early Egyptians. It is of interest to note that aeration, a process widely used in present day grain storage, was used by the early Egyptians. While most modern aeration systems use forced-draft ventilation, the early Egyptians employed natural draft aeration procedures.

The length of storage time for cereal grain has generally increased with changing civilization and its many technological advances. The introduction of the large capacity grain combine has led to early and rapid harvest of high moisture grain. Longer storage periods, coupled with high moisture grain, have increased the need for further improvements in the technology of grain storage.

It is well known that when high moisture grain is stored at ordinary temperature and in the presence of air, extreme molding occurs. Storage fungi have been found to be the main reason of spoilage of commercially stored grains. The major factors that determine when stored grain will be spoiled by fungi have been found to be moisture content of the grain, temperature in the storage bin, length of time of storage and aeration system used. (4).

Drying of grain for moisture control is the most common way of extending the safe storage time of cereal grains.

Although heated air drying is the most important method of reducing the grain moisture, it has some disadvantages. For example, too rapid removal of moisture causes stress cracks in the grain. These cracks weaken the grain kernels, causing difficulties in both handling and storage of the grain. Damaged kernels are attacked more readily by mold, fungi, and insects than are sound ones. Furthermore, drying at excessively high temperatures reduces the milling quality of cereal grains.

There are sometimes valid reasons for controlling temperature of grain, either in conjunction with drying operations, or as an independent process in which the grain temperature is lowered immediately after harvest (28). Rapid cooling of wet grain to temperatures below 40°F. extends the safe storage time. The use of this method allows the spreading of the loads on driers during rapid grain harvest. Some other advantages of grain cooling would be to reduce stress cracks, to keep the grain at high moisture for animal feed and to retain grain milling quality.

Since temperature control is important in retaining grain quality in storage, it is important to develop methods of accomplishing this control. One way of controlling grain temperature is by forcing cool air through deep beds of the grain. This process is fundamentally one of simultaneous heat and mass transfer. Relations between the parameters which control the heat and mass exchanges between the grain and air are not yet determined. This study was begun to study these relations.

PURPOSE OF STUDY

The purpose of this study was to determine drying and cooling rates at any depth of a bed of high moisture corn during simultaneous cooling and drying with refrigerated air. This was done by:

1. Developing techniques for measuring the various parameters involved in the process of drying and cooling of wet corn.
2. Designing and building an apparatus to accomplish the above.
3. Analyzing data and explaining the physical processes involved in simultaneous cooling and drying during the time before pure drying occurs.

REVIEW OF LITERATURE

Although the theory of grain drying and storage has been largely developed during the past twenty years, the storage of cereal grains is as old as the product itself. The concept, and research related to it, of low temperature (refrigerated) preservation and drying of cereal grain has progressed since the early sixties. It is known that respiration, insect infestation and mold activity are all suppressed when the environmental temperature is reduced below critical levels. However, the mechanics of heat and mass transfer in the cooling and drying process are not well defined. The usual methods of calculating drying rates of agricultural products generally ignore the initial cooling or heating of the product and thus are not completely applicable in the combined cooling-drying process.

Thin and Deep Bed Drying

The first important article introduced in this field was by Hukill (14) in 1947. He proposed a method of calculating drying rates in bulk from exposed thin-layer drying rates. He tried to reduce the problem to a general form covering drying under wide ranges of grain depths, moisture contents, air volumes, temperatures, and humidities.

Many other previous studies on wet materials and drying of other solids and porous materials helped to explain the drying mechanism of grain (2). General discussion of drying wet materials indicated that, in the normal range of moisture content in grain, the rate of drying is limited by the resistance to moisture flow within the kernel to a greater extent than by the resistance to vapor flow from the surface.

In the early 1950's investigators became more interested in the study of thin-layer (a layer one kernel deep) drying with heated air, and the study of the effect of various factors on the drying rates. They tried to relate these studies todeep beds in different ways than Hukill (10, 20, 37, 36). Their experiments have shown that the drying rate is proportional to the difference in moisture content between the grain being dried and the equilibrium moisture content at the drying air state as follows:

$$\frac{dM}{d\theta} = k\ (M - M_E)$$

Which integrated gives

$$\frac{M - M_E}{M_0 - M_E} = a\ e^{-k\theta}$$

Where M_0 = initial moisture content of the grain, % (dry basis)

M_E = equilibrium moisture content, % (dry basis)

M = moisture content after a time θ, % (dry basis)

a = constant, dependent on particle shape

$= \frac{6}{\pi}$ for a sphere

k = drying constant, hr^{-1}

θ = time, hr.

This equation was also evaluated through studies by chemical engineers in their search for general mechanisms of drying (22, 23, 27).

Simonds, Ward and McEwen (31) studied the basic parameters affecting drying rates, and found that variation in air velocity within the range of 32 to 111 ft/min produced little or no change in the rate of drying of thin layers. This indicated that capillary effects play little part in the mechanism. Their results show also that the rate of drying increases with increased air temperatures and that the equilibrium moisture content correspondingly falls. Increasing the air humidity was found to decrease the rate of drying slightly, but this effect is very much smaller than the effect of temperature changes. A three-or four-fold increase in humidity is roughly equivalent to a drop in temperature of $50^{o}F$. An attempt was also made to measure the effect of drying on changes in particle size. It was found for wheat that there is a decrease in diameter but not in length of the kernel during drying. It was also found that most of the shrinkage occurs between moisture contents of 60% to 20% (dry basis), and that shrinkage effects can be neglected for moisture contents below 20%.

In 1961, Henderson and Pabis (11, 12, 25) introduced a series of articles in which they studied grain drying theory. They observed that samples of wheat dried faster with air rates less than 20 ft^3/ft^2min. than did samples with air rates higher than 20 ft^3/ft^2min. Air rates of 20 or more ft^3/ft^2 min. had no apparent effect on drying rate. They also found that variations in air flow rate affects the surface moisture transfer coefficient insignificantly, particularly after the first two hours of drying. Another important conclusion was that for practical purposes the temperature in the kernel of corn at any time during drying may be considered as almost uniform. They also proved experimentally that the drying coefficient, k, is related to drying air absolute temperature, T, by a relation of the form,

$$k = de^{-f/T},$$

where d and f are constants and T is temperature, ^{o} Roukine.

From these studies, it seems that the most likely mechanism of drying is diffusion of liquid water from the grain kernel interior, followed by evaporation at the grain surface.

Hustrulid (15), in 1959, and Henderson (24), in 1961, tried to obtain theoretical drying curves for shelled corn through the application of the diffusion equation, first applied by Babbit in 1949, to data for an agricultural crop. Hustrulid assumed the kernel of corn to be a sphere of homogeneous material with an initial uniform moisture content. He also assumed that as soon as drying starts, the kernel surface is kept at a constant moisture content, called by other investigators the dynamic equilibrium moisture content of the effective surface moisture content. He found the following relationship:

$$\frac{M - M_s}{M_o - M_s} = \frac{6}{\pi} \sum \frac{1}{n^2} e^{-n^2 k\theta}$$

where M_o = initial moisture content of grain, % (dry basis)

M_s = effective surface moisture content, % (dry basis)

M = moisture content after a time θ, % (dry basis)

k = drying constant, hr^{-1}

θ = time, hr

n = an integer

It should be noted that for large values of $k\theta$

$$\frac{M - M_s}{M_o - M_s} = \frac{6}{\pi} e^{-k\theta}$$

which is the equation previously suggested in this discussion. The equation is derived in a number of texts on the mathematics of diffusion (15).

Although Simonds, Ward, and McEwen (31) were able to fit their drying data to the reduced equation, this equation was not suitable for shelled corn. It predicted values of moisture content far too low for the early stage of drying. Rodriguez-Arias (26) has suggested describing the drying curve by a set of equations of the same type with different values of k each applied for a short range of moisture content.

To consider kernels of corn as spheres is a gross approximation. However, if moisture is lost through all surfaces of the kernel, one would expect to get a reasonable approximation. Evidence to support that assumption is given by the reasonably good fit of the theoretical curves (15).

Henderson (24) applied an equation for three-dimensional diffusion which might be more appropriate for shelled corn, since a kernel of corn approaches the shape of a brick. However, certain assumptions which had to be made to obtain the solution could influence the accuracy of the end results. He recommended the use of the spherical model because of its simplicity and good results.

In the early sixties Hustrulid (16, 17) compared the drying rates of thin-layer samples of naturally moist, frozen, and remoistened corn and wheat. Since the availability of naturally moist samples is limited to a short harvest season, such discussion is important to be sure of the reliability of experimentation on remoistened and frozen grain. He concluded that there is no significant difference between the drying rate constants of naturally moist and frozen samples of shelled corn. Remoistened samples, however, dry at slightly higher, statistically significant average rates during the early stage of drying than do naturally moist samples. He pointed out that carefully remoistened corn may be used for drying experiments without great error. For wheat, calculated drying constants are not significantly different for naturally moist and remoistened samples when fully exposed to high speed air. The results of Hustrulid are not in agreement with other investigators who found that remoistened wheat dried more rapidly than naturally moist wheat (18, 34). Their experiments involved larger samples and lower rates of air flow, and so, factors other than basic drying characteristics of the individual kernels might be involved. Hustrulid also noted that bulk drying would be outside the range included in his investigation.

Physical Properties of Grain

Before discussing cooling associated with drying, it might be interesting to review briefly the literature on equilibrium moisture contents and specific heats. Henderson (13) in 1952, introduced an empirical equation to represent conventional equilibrium moisture data established rigorously by thermodynamic procedures. In 1958 Hall and Rodriguez-Arias (8) showed that Henderson's equation is good only for an air relative humidity range from 10-60% and under stated the moistured contents of corn for higher relative humidities. The equation was suitable in heated air drying where air relative humidities are within the 10-60% range. For cool air (for example, $40^{o}F$), the relative humidity range probably will be higher. Treatment of the data by means of the Harkins-Jura equation yielded excellent relationships in the range of 45% to 90% relative humidity (9). Using Smith's equation, the equilibrium moisture content was also found to yield good relationships from 45% to 90% relative humidity (33).

Hall and Kazarian (7), studied the thermal properties of grain. Their results and those of other investigators show that specific heats and thermal conductivities of grains are linear functions of moisture content, while thermal diffusivity is not. Specific heat, C, of yellow dent corn was found to follow the relationship:

$$C = 0.350 + 0.00851 \ m$$

for a temperature range of 54^{o} to $83.8^{o}F$. Thermal conductivity, K, was found to be:

$$K = 0.0814 + 0.000646 \ m$$

for a temperature range of 69.4 to $126.6^{o}F$., where m is grain moisture (% wet basis).

Henderson (25) during his experiments found the following ralations for shelled corn:

a) Average heat capacity of an absolutely dry kernel:

$$C_o = 0.27 \text{ cal/gr } ^oF$$

b) Average heat capacity changes with moisture content M% (dry basis)

$$C = 0.555 \left(0.48 + \frac{M}{100}\right), \text{ cal/gr } ^oF$$

c) Average specific gravity:

$$g_o = 1.28 \text{ (gr/cm}^3)$$

d) Suggested formula of specific gravity:

$$g = 0.9 \ g_o \left(1 + \frac{M}{100}\right)$$

Grain Cooling and Drying

United States Department of Agriculture investigators Thomson and Foster (37) first reported on their work in 1960. Their research on the maximum rate at which grain will cool when exposed to a near unlimited volume of air was undertaken to establish basic data which would contribute to better understanding of the principle of grain aeration. They found evidence that a thin layer which is part of a large bulk cooled with air flow rates commonly used cannot be assumed to cool in the same way as a thin layer under exposed conditions. They also concluded that further study of the effect of air velocity on cooling rates is needed. Another important fact they stated is that the velocity of the air around the grain is a less significant factor in determining drying rates than it is in establishing heat transfer rates.

Neglecting the internal resistance to heat transfer within the kernel, Newton's law of cooling can be applied. The general equation is of the form

$$\frac{d(t-t_a)}{d\theta} = k\,(t-t_a)$$

which leads to

$$\frac{t_g - t_a}{t_{g_i} - t_a} = e^{-k\theta}$$

where:

θ = time

t_g = grain temperature at any time, θ

t_{g_i} = initial grain temperature

t_a = cooling air temperature

k = grain cooling constant

Thomson and Foster (37) determined that the cooling of grain exposed to high air flow is quite rapid. The time required to cool corn through 9/10 of the range from room temperature to 40^oF. is approximately 45 seconds. Oven dried grain was found to cool faster than grain at 9% to 13.6% (wet basis). This difference was attributed to the higher thermal capacity of moist grain. They found that Newton's cooling equation was applicable for the limited scope of their studies.

Literature available on grain cooling and drying leans somewhat toward practical applications; this is expected because refrigerated grain storage cannot be widely applied before field tests show its economical feasibility. Papers published by industry show the possibility and advantage of using refrigeration (6, 21). No definitive study has yet been introduced to analyze and explain the mechanism of drying associated with cooling for grains. In 1967, deep bed cooling and dehydration of biological products was studied by Bakker-Arkema and Bickert (3). In order to develop equations describing the product temperature, the air temperature and specific humidity, and the moisture loss in a deep bed of wet biological products, heat and mass balances were formulated for a differential bed volume. They made many simplifying assumptions in their solutions. One major assumption, which is invalid for grain, was that drying occurs at a constant rate. The assumption of constant rate drying indicates that the absolute humidity in the boundary layer adjacent to the product is a function of corn temperature only, and not of corn moisture.

The idea of conditioned air storage of grain was discussed by McCune and others (19). They found that the most important properties of air to be considered before conditioned air can be used economically are the dry bulb temperature and the partial pressure of the water vapor in the air entering the grain. Results have shown that the relative importance of these two properties is dependent on the initial grain moisture content, desired final moisture content, and the anticipated length of the storage period. Tests also showed that approximately five days were required to reduce the temperature of a 9-feet deep bed of grain from 95°F. to 50°F. when air of constant temperature of 45°F. was circulated at a rate of 0.12 cfm per bushel. The flow of moisture between air and grain is always from points of high to low vapor pressure between the product and the surrounding atmosphere. The wide variation of the moisture content between the top and bottom of a bin does not appear to be a serious problem at low temperatures. The authors recommended that additional tests be made to explain the increase of grain temperature from the 4-feet level up the bin during the first two days of cooling.

Shove (28, 29, 30) explained the importance of cold storage of grain with possibilities of its application and described the mechanism of cooling and drying of grain in bulk. He discussed the idea of initial cooling of high moisture grain immediately after harvest to increase its allowable storage time. An airflow of about 1/2 cfm per bushel will cool freshly harvested grain in about 24 hours. This will also reduce grain molding.

Shove also introduced some figures on the size of refrigerating units to cool certain amounts of grain. He stated that wet, chilled grain will store safely if a low grain temperature is maintained. The capacity of equipment needed to keep the low grain temperature depends directly on the sources of heat that could cause the grain temperature to rise. These sources are

1. Conduction heat transfer through the storage structure, if ambient air temperatures are different from the grain temperature.
2. Heat transfer caused by solar radiation.
3. Heat generated by grain respiration and microflora activity which are usually minor factors since these effects are drastically reduced at low temperatures.

Shove (28) defined "Dehydrofrigidation" as the process of drying a product at a low temperature and divided this process into two phases. First there is a cooling phase, in which the only source of heat for evaporation of moisture is the hot grain, assuming the bin is well insulated. He analyzed this process in order to calculate the amount of moisture removed from each pound of wet grain during cooling. Secondly, there is a drying phase in which a drying zone develops in the grain bed; the drop of air temperature is due to evaporation of moisture. The temperature of the product behind the drying zone approaches the dry bulb temperature of the entering air, with a corresponding equilibrium moisture content of the grain.

The temperature of the product ahead of the drying zone remains at the wet bulb temperature of the air, and no reduction in moisture takes place because the air will be almost saturated after leaving the drying zone. Shove (30) also discussed dehydrofrigidation using both natural and refrigerated air. He suggested that the final moisture content of grain can be determined by considering average air conditions (temperature and relative humidity). Refrigerated air provides better control of inlet air temperature and relative humidity.

FACTORS GOVERNING GRAIN COOLING

AND DRYING RATES

Cooling and drying rates at any location in a deep bed of shelled corn, at a specific time, are functions of several variables which are listed below:

1. Initial Air Conditions: It is well known that the initial conditions of the air play the most important part of the process. The initial air temperature and relative humidity will affect both the cooling rate and the final grain temperature. They will also govern the value of the equilibrium moisture content of the drying grain and hence the drying rate.

2. Air Flow Rate: The rate of cool air flow through the warm grain bed that is losing moisture will govern the amount of moisture the air will absorb. At higher rates the air is expected to pick up less moisture from each layer of grain, forming a deeper drying zone. Faster cooling rates are also expected with increased air flow rates.

3. Initial Moisture Content of the Grain: The initial moisture content of the grain is affected by the possible amount of kernel damage by harvesting and handling equipment. Usually corn is harvested with initial moisture contents ranging from 18% to 30% (wet basis). This variation will affect the time needed to cool the corn and the minimum temperature to which the corn will cool before pure drying begins in the bed.

4. Initial Grain Temperature: Initial grain temperature is governed by the ambient air conditions during the harvest and the handling of the grain. The grain temperature is important because it governs the amount of

heat available in the grain to evaporate moisture and the time needed to cool the grain to the desired storage temperature.

5. Drying and Cooling Rate Characteristics: These are assumed to be governed by the above factors only since each type of grain has specified physical properties.

MATHEMATICAL FORMULATION OF FACTORS GOVERNING HEAT AND MASS BALANCE

Heat and mass balances for a differential volume in a deep bed of corn can be written to describe mathematically the corn temperature and moisture changes with respect to time at any location in the bed. The following assumptions are made in formulating the heat and mass balances.

1. Within the range of temperatures considered, both the grain and air thermal properties are constant.
2. Air flow rate is constant and in one direction; i.e., from the bottom to the top of the grain mass.
3. The temperature gradient is only in the vertical direction, x; i.e., there is no temperature gradient in any horizontal section of the grain bed.
4. Both the initial grain temperature and moisture content are constant throughout the bed.
5. The inlet air temperature and specific humidity are constant with respect to time.

Symbols:

A_{eq} = a surface area of corn from which heat and mass transfer occurs per unit cross-sectional area of the bed, ft^2/ft^2

C = corn specific heat, BTU/lb$^{\circ}$F

H = enthalpy of air, BTU/lb

h = heat transfer coefficient between grain and air, $\frac{BTU}{hr.ft^2\ {}^{\circ}F}$

K = conduction heat transfer coefficient of grain, $\frac{\text{BTU}}{\text{hr.ft.}^{\circ}\text{F}}$

L = heat of evaporation of moisture from the grain, $\frac{\text{BTU}}{\text{lb.}}$

M = absolute humidity of the air, $\frac{\text{lbs. water}}{\text{lbs. dry air}}$

M_{g_s} = moisture content of grain at the surface of the kernel,

$$\frac{\text{lbs. water}}{\text{lbs. dry grain}}$$

T = air temperature, $^{\circ}$F

T_{g_s} = grain temperature at the surface of the kernel, $^{\circ}$F

V_a = air volume flow rate, $\frac{\text{ft}^3}{\text{hr. ft}^2}$

θ = time, hrs.

ρ_a = air density, $\frac{\text{lb}}{\text{ft}^3}$

ρ_g = grain bulk density, $\frac{\text{lb}}{\text{ft}^3}$

σ = mass transfer coefficient from corn to air, $\frac{\text{lb}}{\text{hr ft}^2}$

Air Mass Balance:

The rate of change of mass of air within a differential volume is composed of two components: (1) the net moisture lost from the grain to the air and (2) the difference between the moisture contents of the air entering and leaving the differential volume. The mathematical relationship is

$$\rho_a \frac{\partial M}{\partial \theta} = A_{eq}\sigma(M_{g_s} - M) - \rho_a V_a \frac{\partial M}{\partial x} \qquad (1)$$

Air Energy Balance:

The rate of change in enthalpy of the air within a differential volume is composed of two components: (1) the net energy lost by the corn and (2) the difference in enthalpy of the air entering and leaving the differential volume. The air energy balance is

$$\rho_a \frac{\partial H}{\partial \theta} = A_{eq} h \, (T_{g_s} - T) + A_{eq} \sigma (M_{g_s} - M) L - \rho_a V_a \frac{\partial H}{\partial x} \tag{2}$$

Corn Energy Balance:

The rate of decrease in corn internal energy in a differential volume equals the net heat energy lost from the grain to the air minus the net conduction heat transferred between the differential volume and the adjacent grain. The corn energy balance is given by

$$-\rho_g C_g \frac{\partial T_g}{\partial \theta} = A_{eq} h \, (T_{g_s} - T) + A_{eq} \sigma (M_{g_s} - M) L - (-k \frac{\partial^2 T_g}{\partial x^2}) \tag{3}$$

The equations above describe the unsteady state heat and mass transfer in the grain bed.

In order to solve these equations simplifying assumptions are made. It is assumed that the rate of change of moisture content, M, and enthalpy, H, of the air within the differential volume are very small compared with net change in M and H of the air crossing the control volume. Secondly, it is assumed that the grain temperature is approximately equal to the surrounding air temperature within the differential volume at any instant.

The above equations then may be simplified as follows:

For Air,

$$\rho_a V_a \frac{\partial M}{\partial x} = A_{eq} \sigma (M_{g_s} - M) \tag{4}$$

$$\rho_a V_a \frac{\partial H}{\partial x} = A_{eq} \sigma (M_{g_s} - M) L \tag{5}$$

or,

$$\rho_a V_a \frac{\partial H}{\partial x} = \rho_a V_a \frac{\partial M}{\partial x} L \tag{6}$$

For grain,

$$-\rho_g C \frac{\partial T}{\partial \theta} = A_{eq} \sigma (M_{g_s} - M) L - (-k \frac{\partial^2 T}{\partial x^2}) \tag{7}$$

or,

$$-\rho_g C \frac{\partial T}{\partial \theta} = \rho_a V_a \frac{\partial M}{\partial x} L - (-k \frac{\partial^2 T}{\partial x^2}) \tag{8}$$

where both M & T are functions of time and location in the grain bed.

In order to solve these equations, a function relating air moisture content, M, to temperature, T, for different locations in the corn bed at different times is required. No previous work has been done to determine the nature of that relationship.

One of the long range aims of this study is to develop these needed relationships.

MATERIALS AND METHODS

Equipment

In order to study experimentally the different factors involved in cooling associated with drying, the following equipment was used:

1. Grain bin structure.
2. Strain guage equipment for determination of changes in moisture content of grain.
3. Thermocouples and a recording potentiometer for sensing and recording temperatures of the air at different levels in the bin.
4. Refrigeration for cold air supply.
5. Air rate of flow measuring system.
6. Air oven and scales for determination of initial and final grain moisture contents.

Corn Bin Structure

The bin structure was designed to hold about 19 bushels of corn. It has a cross-sectional area of 4 square feet and a total depth of 6 feet of corn. In order to describe the structure different parts are discussed separately; the whole structure is then described as assembled to show how it functions.

Part A; the Main Structure: The main structure is composed of two parts that when joined together form a square with a square annulus (Plate I). It is made from sheets of 3/4"-thick plywood. The bin is 14 feet high and its outside plan dimensions are 4 feet x 4 feet. The inside plan dimensions

EXPLANATION OF PLATE I

Overall View of Apparatus

Fig. 1 Shows Apparatus assembled for operation

Fig. 2 Shows Apparatus open (Notice the foam rubber on the moving section of the grain bin structure)

PLATE I

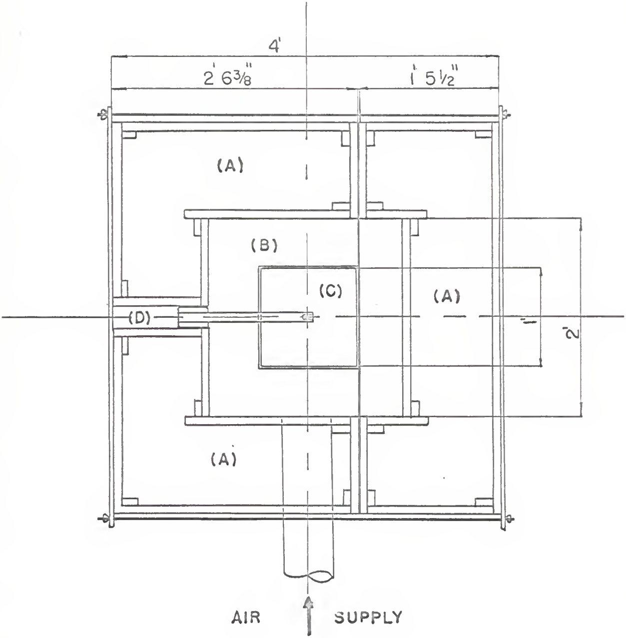
Fig. 1

Fig. 2

EXPLANATION OF PLATE II

A Plan View of Corn Bin structure showing major dimensions (Letters A, B, C & D are used for identification in text)

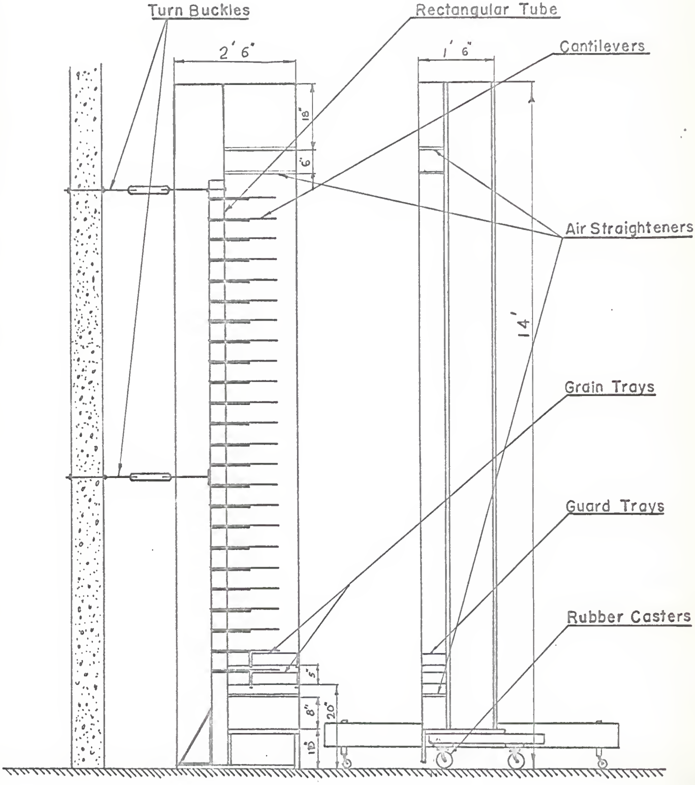
PLATE II



EXPLANATION OF PLATE III

Section Elevation of the Bin structure showing its main parts.

PLATE III


Turn Buckles
Rectangular Tube
Cantilevers
2' 6"
1' 6"
18"
6"
Air Straighteners
14'
Grain Trays
Guard Trays
Rubber Casters
5"
8"
20"
10"

are 2 feet x 2 feet.

The square annulus between the outside and inside sheets of plywood (Space A of Plate II) is filled with fiber glass insulation to minimize heat transfer from the outside.

The moving section of the bin structure is mounted on 4 rubber casters, 4 inches in diameter, and is balanced for safety by 4 small casters mounted at the end of two 2" x 6" wood beams which are glued to the moving section of the structure. The moving section permits access to the inside of the structure (see Plate III).

The fixed section of the structure is separated into two parts by a slot 3" wide from bottom to top space (D of Plate II). This slot holds a rectangular steel tube (see following Part B) upright. The fixed section of the structure is stationary on the floor under its own weight and the weight of both the insulation and grain. The two parts of the fixed section are held in position by wood at the bottom and by four steel (1" x 1/4") strips distributed equally all the way to the top.

The fixed section has a 10" layer of insulation at its bottom to insulate the bin from the floor.

Part B; Rectangular Tubing and Cantilevers: As mentioned before, a 4" x 3" steel rectangular tube, 12 feet long, is fitted in the slot separating the two parts of the fixed section of the bin. Its inner face is flush with the inside face of the plywood in the bin (See Plates II and III).

Twenty-four horizontal steel cantilever beams, spaced 5 inches apart vertically, are attached rigidly to the vertical rectangular tube (Plate III). The first cantilever is mounted 2 feet above the floor. Each of the cantilever beams is equipped with two calibrated strain gauges for weighing a tray of corn attached to it (see Plate IV).

EXPLANATION OF PLATE IV

Fig. 1 Grain Tray hanging in position from cantilever beams

Fig. 2 Cantilever beam showing strain gauges fixed on it and thermocouple wire to measure temperature

Fig. 1

Fig. 2

Each cantilever is composed of two steel strips. The active cantilever has a cross section of 3/4" x 1/4" and the supporting beam has a 1/2" x 3/4" section. The two strips pass through the tubing; they are welded together and to the tube at both sides of it. The active cantilever projects a distance of 12-3/4" and has a 1/4" slot at its end which is centered with the center of the inside square of the bin. The grain trays (see following Part C) are suspended from the cantilever beams (see Plates IV and V). The 5-1/2" long supporting beam is used to minimize deflection of the lever under the tray and grain weight.

The rectangular tubing is fixed in position by two 3/4" diameter turnbuckles fixed to it and to the laboratory wall behind. This fixation prevents the tube from tipping forward under the weight on the cantilevers or backwards in the wall direction. As mentioned before, lateral movement perpendicular to the laboratory wall is prevented by the sides of the fixed bin. A rectangular steel angle is welded at the bottom of the tubing and rests on the bin's floor (Plate III).

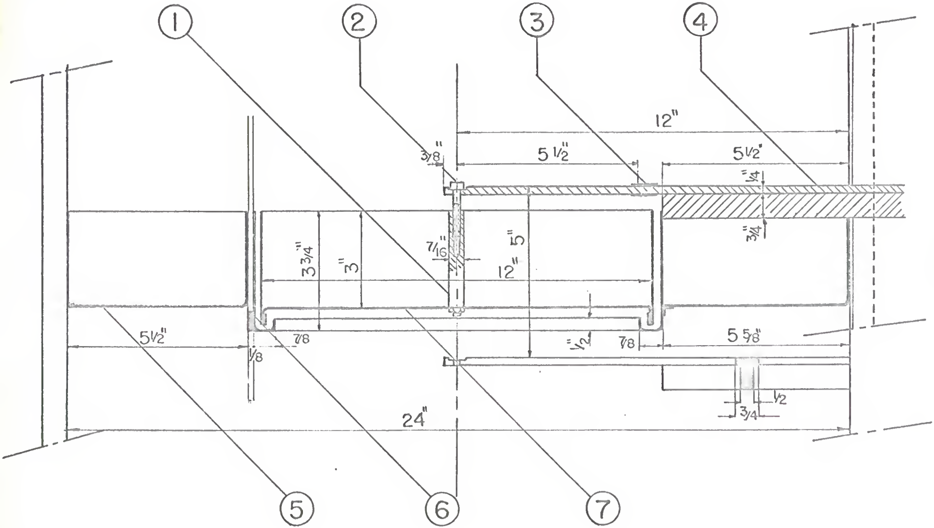
Part C; Grain Trays: The trays are hung on the cantilevers at the center of the bin. The tray dimensions are 1 foot x 1 foot x 3" high and each is capable of holding 1/4 $ft.^3$ of corn. The flat bottom is built of 18-gauge perforated galvanized steel which has 20% open area. The 3" high sides are made of 20 gauge galvanized sheets. The sides of the pan extend 1/2" below the pan bottom, to form an air seal (see Plate V). A 1/2" diameter circular copper rod 3" long is fixed to the center of the bottom of each tray. A 1/4" diameter bolt is screwed into the rod to help adjust the hanging distance. The rod forms a hanger for suspending a tray of corn to the cantilever beam above the tray (see Plate IV).

EXPLANATION OF PLATE V

Section elevation in tray cantilever assembly showing the following parts:

1. Copper rod
2. Adjustable screw
3. Strain gauge
4. Cantilever beam
5. Guard trays
6. Foam rubber air seal
7. Grain tray

PLATE V

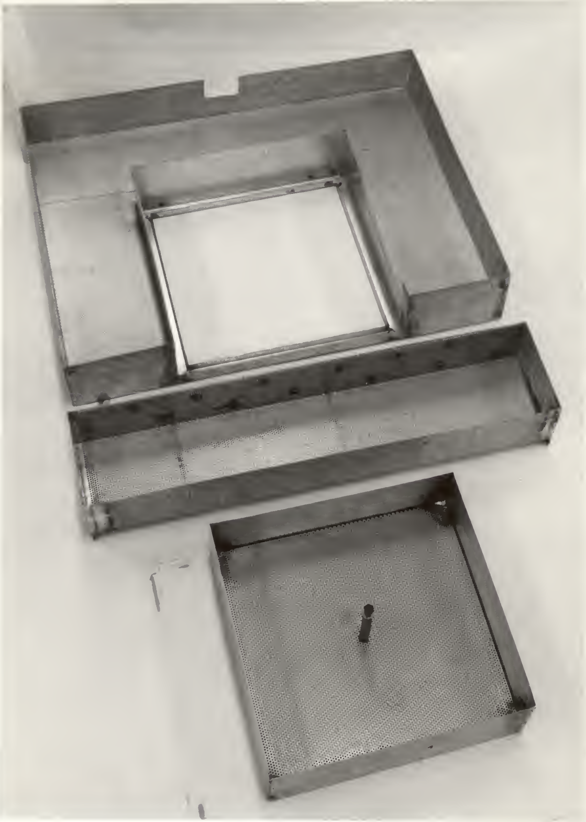


1
2
3
4
5
6
7
12"
3/8"
5 1/2"
5 1/2"
1/4"
3/4"
3 3/4"
3"
7/16"
12"
5"
5 1/2"
7/8
1/8
1/2"
7/8
5 5/8"
1/2
3/4
24"

EXPLANATION OF PLATE VI

Picture showing perforated metal trays

- Guard bin trays (Top)
- Hanging tray (Bottom)



The twenty-four grain trays and the weighing beams represent the main parts of the system for studying moisture changes in the corn during cooling.

Part D; Guard Bin Trays: The guard trays are units that are put around the suspended grain trays. During the tests they are filled with corn and receive the same treatment as do those which are being weighed. This helps insulate the measurement section from outside effects.

There are two different types of guard trays used. One is fitted in the stationary section of the bin structure and the other is fitted to the moving section. The tray fitted to the stationary part is U-shaped (see Plate VI). It is made of 18-gauge perforated galvanized steel sheets with 20% open area. A U-shaped metal channel 7/8" wide and 1/2" deep is spot welded to the inside of the tray. It is filled with oil to act as an air seal between the stationary and suspended trays.

The guard trays fixed to the moving section of the bin are simply 24" x 5-1/2" rectangular units 3" high, made of 20-gauge perforated galvanized steel. When these and the U-shaped trays are put together they form a complete guard around the inside grain trays. (Space B in Plate II).

Description of Assembled Bin Structure.

Starting at 17" from the floor level, a thin sheet of foam rubber 1/2" thick is fixed to form an air resistance throughout the inner cross-sectional area of the bin. This helps to develop a uniform inlet air velocity across the bin area. Two other sheets were fixed 6" apart at the top of the bin to minimize external temperature effects. At a level of 20" from the floor level, strips of plywood (3/4" x 1") are fixed to the inside walls of both the fixed and moving sections of the bin structure for supporting the guard trays of corn. The strips insure a 5" vertical distance between successive tray bottoms all the way to the top tray.

The guard bin trays are filled with corn and then placed on the strips, much as closing a desk drawer. The trays are held in position by spring action locks which are fixed to the plywood at the inside face of the bin.

The center trays are then filled with high moisture corn and suspended from the bolts on the cantilever bars. The grooves on the guard bin trays are filled with light oil to prevent air flow between the guard and suspended trays. When necessary the trays were balanced in a horizontal plane by a slight shifting of grain within the tray or by addition of small steel pellets.

A 1/2" thick layer of foam rubber is fixed to cover the whole face between the fixed and moving bin sections; the foam rubber has holes of the same shape of the areas between trays so that the air can move freely in the horizontal planes between trays (see Plate I). When the moving section is pushed against the fixed section the foam acts as an air seal. The foam is compressed between the faces of the bin by rods and wing nuts which fasten the fixed and movable bin sections together.

The plywood is treated with two coats of varnish to moisture-proof it. The inside corners of the structure are covered with duct tape to prevent leakage of air.

<u>Strain Gauges and Equipment Used for Determination of Changes in Moisture Content of Grain</u>:

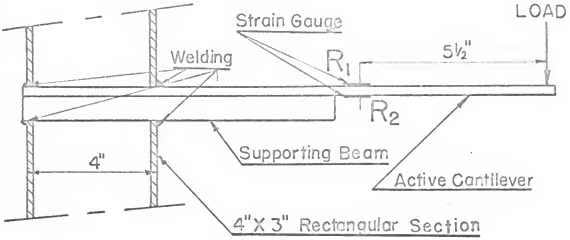
Budd type C6-141B variable resistance strain gauges were used for the measurement of grain weight. The gauges had 120 $\pm$ 0.2 ohms resistance and each gauge had a gauge factor of 2.08 $\pm$ 1/2%.

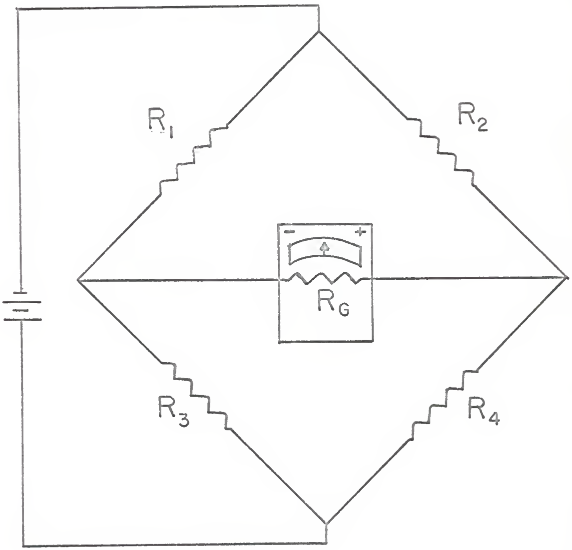
Two strain gauges were applied, one to the top and one exactly opposite on the bottom of each of the twenty-four cantilever beams. Each was applied at a distance of 5-1/2" from the hanging point of the grain trays.

EXPLANATION OF PLATE VII

Physical and Electrical arrangement of strain gauges for indicating the strain in a cantilever beam. R_1 and R_2 are strain gauges and R_3 and R_4 are resistances in the strain indicator.

PLATE VII


Strain Gauge
LOAD
Welding
R1
5½"
R2
Supporting Beam
4"
Active Cantilever
4"X 3" Rectangular Section


R1
R2
RG
R3
R4

When the two strain gauges are connected in the two active arms of the Wheatstone bridge (Plate VII), two significant gains arise: (1) the electrical output of the bridge is twice what it would be for one gauge alone because one gauge is in pure tension and the other pure compression; and (2) both gauges are automatically temperature compensated; that is, resistance variations of the strain gauges due to temperature changes oppose each other and have no effect on the bridge output. This assumes a negligible temperature difference between the top and bottom sides of the beam.

A Baldwin SR-4 type M portable strain indicator was used to indicate strain. This instrument is designed and calibrated to work with resistance wire strain gauges having an initial resistance of 120 ohms.

No. 18 stranded rubber insulated copper wire was used for connecting the gauges to the strain indicator. Since 24 different weights were recorded in a short time, it was necessary to use a set of 12 low-capacity switches to minimize the contact error arising from connection and disconnection of the gauges to the strain indicator.

<u>Thermocouples and Recording Potentiometer for Sensing and Recording Temperature of the Air at Different Levels of the Bin</u>

Average temperatures at four points were measured after each tray or after each thickness of 3" of corn. Copper-constantan thermocouple wire, Type P-30.T (30 Gauge) with a guaranteed accuracy of $\pm$ 1.5 ^{o}F in the temperature range of 0-200 ^{o}F, was used. Four thermocouples were joined in parallel in order to measure the average temperature of four different locations in a horizontal plane on top of the hanging tray. (See Plate IV)

Temperatures were also measured in four other locations (two at the inlet to the bin and two at the top at the air exit).

EXPLANATION OF PLATE VIII

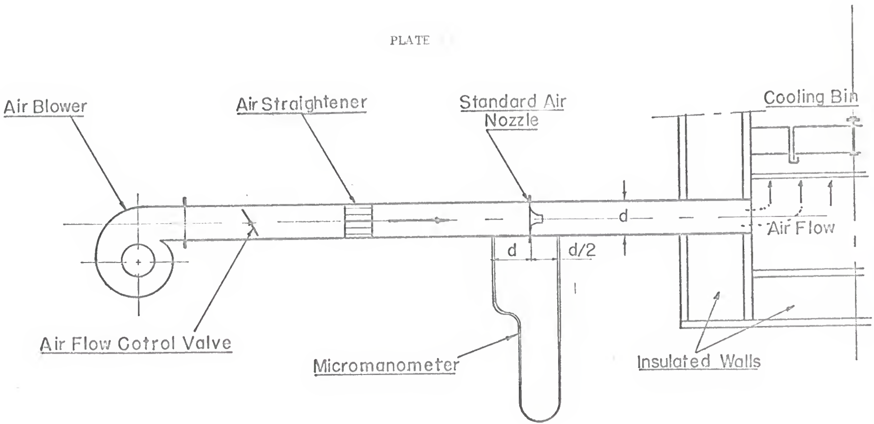
Picture showing Instrumentation used. From left to right are Low-capacity switches, Baldwin SR - 4 type M portable strain indicator, Micromanometer for air flow rates, A single point potentiometer, Honeywell Electronik 16* multi-point strip chart temperature recorder and a psychrometer.

PLATE VIII

PLATE IX

Diagram showing air flow measurement and control system

PLATE


Air Blower
Air Straightener
Standard Air Nozzle
Cooling Bin
d
d
d/2
Air Flow
Air Flow Cotrol Valve
Micromanometer
Insulated Walls

A Honeywell Electronik 16* multipoint strip chart recorder was used to record the temperatures after each tray (24 total points). Temperatures for 24 points could be recorded every two minutes.

A single point potentiometer indicator made by Leeds and Northrup Co. was used to measure the inlet and outlet air temperature as well as the ambient temperature at different times during the tests.

Dry-and wet-bulb temperatures of the air entering the first layer of grain were measured using an air fan psychrometer. (See Plate VIII)

Refrigeration for Cold Air Supply

The cold air supply was available from a source capable of controlling air temperature and humidity to any range needed within the scope of this study. A 10" diameter No. 2E Buffalo constant speed blower was located inside the air supply box to supply the air required for the bin. A 4" diameter air duct was used to carry the air to the bottom of the test bin. The duct was insulated by a 6" layer of Balsam-Wool.

Rate of Air Flow Measurement System

In order to adjust air flows to within the desired range, a spun aluminum nozzle made in accordance with Air Moving and Conditioning Association (AMCA) specifications was used. The nozzle is fixed in the 4" air supply duct. The air duct is built in accordance with the AMCA ducted nozzle standards (1) (see Plate IX). At a sufficient distance ahead of the nozzle an air straightener was fitted. A butter-fly valve was fitted ahead of the straightener to regulate air flow rates.

The pressure drop across the nozzle was measured by a micromanometer. The micromanometer is a model 34FB2 made by the Meriam Instrument Company and has a range of $\pm$ 10" of water. The pressure drop is transformed by standard equations into air flow.

In order to prevent air leakage from the ducts all connections were covered with duct tape.

Equipment for Determination of Initial and Final Corn Moisture Content

A standard air oven was used to dry corn samples for the determination of initial and final corn moisture contents. Grain was heated for 72-96 hours in the oven at a temperature of 103°C. Scales which read accurately to 0.1 of a gram were used to weigh the corn samples.

PROCEDURES

Calibration of Cantilever Beams Used to Detect Weight Changes in Grain Trays

Each of the twenty-four cantilevers was calibrated individually. First, initial readings with no weight on the cantilever were recorded from the strain indicator. Then pre-weighed trays were hung in position, with the guard trays around. Care was taken to make sure that each tray was balanced horizontally and did not touch the guard tray. The strain reading corresponding to the tray weight was recorded. Weights of loose dry sand were added consecutively to the tray. As sand was added, it was spread over the tray area and leveled in order to keep the tray balanced. The strain reading corresponding to the total weight was then recorded.

To insure accuracy the same procedure was repeated four times, twice with the top strain gauge on the cantilever in position R_1 (see Plate VII) and twice with the bottom strain gauge in position R_1. This procedure led to two straight lines, one the mirror image of the other. The straight line relation of the four readings is given by the equation

$$W = A_0 + A_1 (\Delta S)$$

where

W is the weight in lbs.

ΔS is the difference in strain reading from initial strain reading

A_0 is the distance at which the straight line crosses the W axis at $\Delta S = 0$

A_1 is the slope of the straight line

To evaluate the constants A_o and A_1, a least squares regression of the data was calculated. As a measure of the scatter about the regression line, the standard error of estimate of W on (ΔS) $S_{W,\Delta S}$ was also calculated. Values of A_o, A_1 and $S_{W,\Delta S}$ for each of the twenty-four different cantilevers are listed in Table 1.

Preparation of Corn for Experiments

One experiment was carried out with naturally moist corn of 17.7% initial moisture content (wet basis). This moisture content was rather low for the purpose of this study. Since the corn harvesting season was over by the time the apparatus was constructed, remoistened corn was used in two subsequent experiments.

The procedure used to remoisten corn was as follows. Corn was soaked in cold water for a period of six hours. In order to minimize germination the soaking containers were closed to prevent outside light or fresh air. During this period corn gained about 16% moisture (see discussion). In order to rid the corn of surface moisture prior to cooling tests, the corn was dried in the laboratory for about two hours at room temperature.

Preparation of the Bin for Experiments

The temperatures recorded on the recorder at each level were compared with those measured by another thermocouple before each experiment to make sure that the recorder calibration was proper. Then the bin was closed and cold air was allowed to pass through for 24 hours before an experiment was to begin. This was to cool the insulation around the bin and reduce the quantity of heat in the insulation. This helped to avoid, as much as possible, the warming of the air by external heat from the insulated wall

TABLE I

Lever No.	A_o	A_1	Standard Error of Estimate of W on ΔS
1	0.006136	0.019522	0.052233
2	0.043113	0.020100	0.089880
3	-0.000917	0.020712	0.040580
4	-0.007296	0.019856	0.084900
5	0.010413	0.019992	0.056710
6	-0.022783	0.019745	0.069344
7	0.000958	0.020107	0.031375
8	-0.041661	0.019621	0.071559
9	-0.048338	0.020010	0.062066
10	0.048351	0.019164	0.078732
11	0.050312	0.019221	0.067193
12	-0.017622	0.019842	0.055667
13	-0.027500	0.019910	0.073902
14	-0.046669	0.019590	0.070350
15	0.074026	0.020442	0.046872
16	--------	--------	--------
17	-0.015295	0.020205	0.052666
18	-0.019913	0.020183	0.066587
19	-0.031330	0.020220	0.060869
20	-0.013642	0.020231	0.059605
21	-0.014864	0.019744	0.074713
22	-0.019051	0.019544	0.041711
23	-0.033030	0.021647	0.034954
24	-0.080964	0.025508	0.104239

during the initial part of the experiment.

It takes about three hours to fill the bin with corn to its maximum capacity of 24 ft^3 and about 70 minutes to fill it to a depth of three feet (bottom half only). The bottom guard tray is filled with corn, placed on the supporting wood strips in the bin, and clamped in position. Paper tape is used to seal the tray to the bin wall all the way around to prevent air leakage between them. Next, the oil seal groove is filled with light motor oil. After the test grain tray is filled with corn it is hung in position and balanced. The second guard tray receives the same treatment and so on. Samples of corn from each tray are taken for moisture determinations.

Trays on the moving section of the bin are filled and fixed in position at the same time. The foam rubber is then fixed to cover the moving section face and the moving section is pushed against the fixed section and tied against it. Paper tape is used to tape the space between the moving and fixed sections of the bin to insure complete air tightness. This starts the test.

Experimental Procedures

As soon as the bin is closed the air flow is adjusted to the proper value by adjusting the position of the butter-fly valve in the duct. Temperature at each point is recorded once every two minutes during the first part of each test.

The moisture readings were recorded at 1/4 hour intervals at the beginning of a test. The intervals were increased gradually to 1/2, 3/4, 1, 1-1/2, 2, 3, 4, 6 and 8 hours as the test progressed. Grain weights were recorded twice each time, once with the top strain gauge in position R_1 and then with the bottom strain gauge at position R_1.

Dry-and wet-bulb temperatures were recorded once every two hours inside the refrigerated box near the blower intake. The inlet air temperature to the bin was measured every hour to make sure there was no change. Barometric atmospheric pressure was checked once every 6 hours.

RESULTS AND DISCUSSION

Three tests were carried out in this investigation. The average air flows in the three tests were kept constant at a value of 1.3 ft^3/ft^2-min $\pm$ 5%. The inlet air average dry bulb temperature was kept at 37.5°F, $\pm$ 0.5°F.

Naturally-moist corn with 23% (dry basis) initial moisture content was used in the first test with a total depth of 5 feet of corn. Remoistened corn was used in the other two tests. In the second and third tests the moisture was raised to 38.4% and 44% (dry basis), respectively. Remoistened corn is expected to dry and cool faster than naturally moist corn (18, 34), but trends will, in general, be similar. The second and third tests were carried out on corn beds three feet deep.

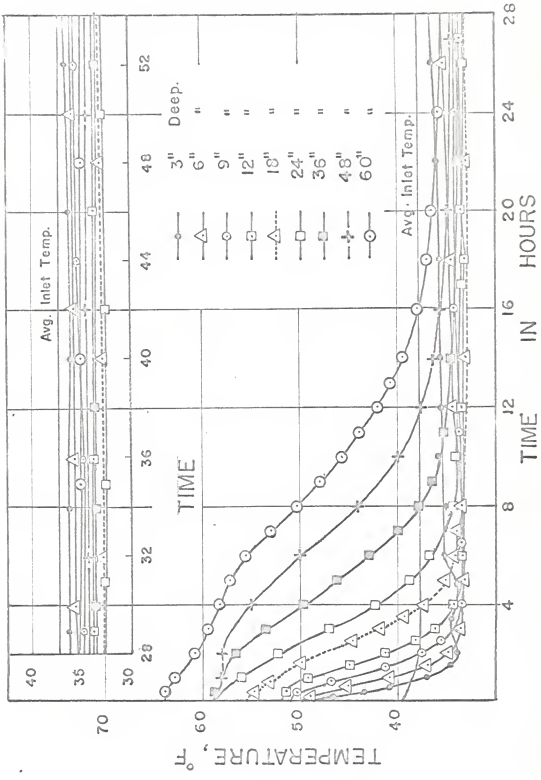
A summary of the conditions for each of the 3 tests is listed in Table II.

Before discussing the results it may be useful to state that the temperature in the laboratory was not uniform. It was approximately 5°F. warmer near the ceiling than at a point 2-1/2 feet above the laboratory floor. It is also important to note that when the same rate of cold air as used for the tests was blown through the empty bin until steady state was obtained the air temperature at the top of the bin was about 3° warmer than the inlet air temperature. This temperature difference is expected because of outside heat effects. Guard corn trays were used to minimize effects of external conditions.

EXPLANATION OF PLATE X

Temperature-time relationship for the first test (corn initial moisture content 23 (dry basis) and air flow rate 13 $ft^3/ft^2 min$) for various depths in bin (Inset at upper part of page is a continuation of lower graphs)

PLATE X



TEMPERATURE, °F
TIME IN HOURS
TIME
Avg. Inlet Temp.
Avg. Inlet Temp.
3" Deep.
6" "
9" "
12" "
18" "
24" "
36" "
48" "
60" "

TABLE II

Summary of Test Conditions

		Test No. 1	Test No. 2	Test No. 3	Range	Units
1.	Depth of corn in bin	5	3	3		ft.
2.	Avg. initial moisture content	23	38.4	44	±3%	% dry basis
		17.71	27.78	30.65	±2%	% wet basis
3.	Corn Condition	Naturally moist	Remoistened			
4.	Initial Corn Temp.	*	70	70		°F (Room Temp.)
5.	Avg. Inlet Air Temp.	37.4	37.5	37.5	±0.5	°F
6.	Avg. Absolute humidity of	16.6	17	17.6		Grains Moisture / lbs. dry air
	inlet air	0.00237	0.00243	0.00251		lbs. water / lbs. dry air
7.	Inlet air relative humidity	50.8	52.1	54		%
8.	Avg. air rate of flow	1.31	1.31	1.3	5%	$ft^3/ft^2 min.$

* See discussion, page 56

Temperature Data

<u>First Test</u>: Results of air temperature changes with time for various depths in the corn bin are shown in Plate X. It is evident that the first layers of corn cool at a faster rate than the following layers. Following the temperature behavior of the first layer (3" from the bottom of the bin) we see that the temperature falls rapidly and approaches a minimum of 33.8°F. after two hours of cooling. The layer then starts to warm up gradually until it reaches the inlet air temperature. The cooling proceeds to the next layer which reaches a minimum of 33.4°F. in about five hours, remains at the minimum for three more hours and then begins to warm again. Temperatures at deeper layers do not fall initially as rapidly as the lower layers. As time goes on, the rate of cooling increases and then again decreases as temperatures approach the minimum temperature of 32.5°F.

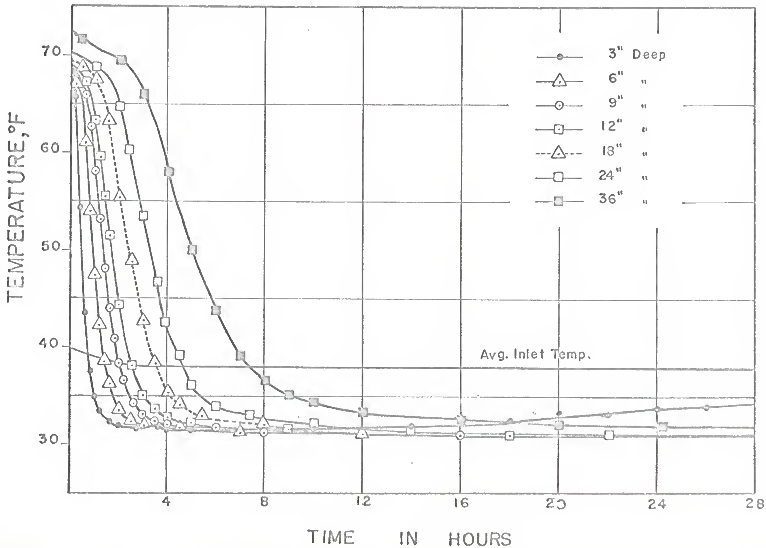
The grain used was stored inside a refrigerated box prior to testing to keep its natural moisture as high as possible. The corn was taken out of the refrigerated box one hour before the process of filling the bin started. Since 2.5 hours were required to fill the bin, the top layers (placed in the bin last) reached a higher initial temperature than did the lower ones.

<u>Second Test</u>: The second test was carried out for a period of 350 hours (14.5 days) in order to cover both cooling and drying periods. Plates XI, XII and XIII show the complete temperature history at different depths of the corn bin. The initial corn temperature had approximately 5°F higher in the top tray than in the bottom. This is the temperature difference of the air in the laboratory. This minimum temperature was found to be the temperature corresponding to the wet bulb temperature of the inlet air. This temperature occurred just before the time pure drying started.

EXPLANATION OF PLATE XI

Temperature-time relationship for second test (corn initial Tmp. 70°F and initial moisture content 38.4% (dry basis) and air flow rate 1.3 ft^3/ft^2min) for various depths in bin from time zero to 28 hours.

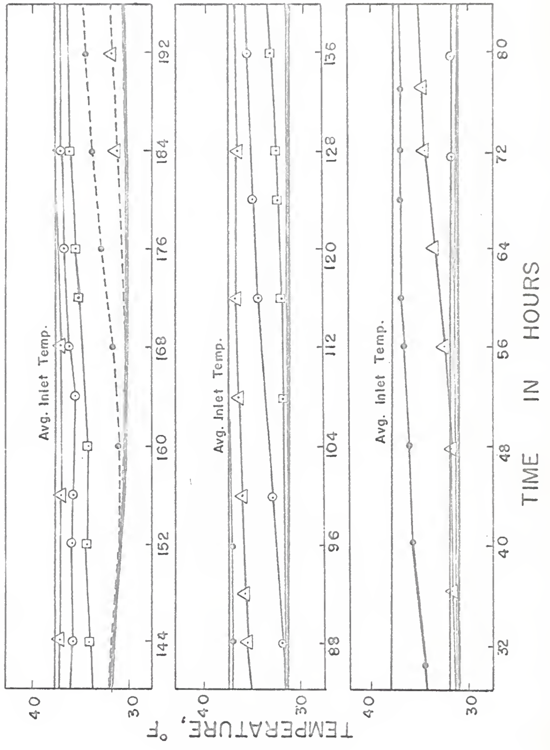
PLATE XI


3" Deep
6" "
9" "
12" "
18" "
24" "
36" "
Avg. Inlet Temp.
TEMPERATURE,°F
70
60
50
40
30
4
8
12
16
20
24
28
TIME IN HOURS

EXPLANATION OF PLATE XII

Temperature time relationship for second test from 28 hours to 199 hours. (Continuation from Plate XI)

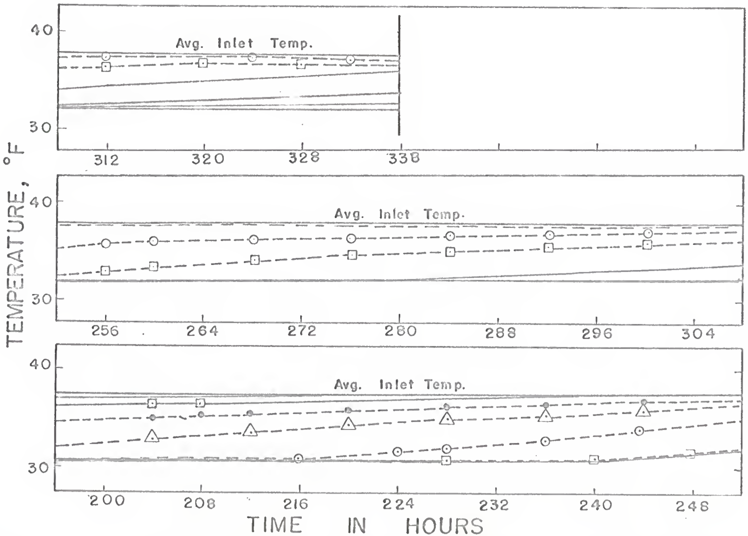
PLATE XII


Avg. Inlet Temp.
Avg. Inlet Temp.
Avg. Inlet Temp.
40
30
TEMPERATURE, °F
144
152
160
168
176
184
192
88
96
104
112
120
128
136
32
40
48
56
64
72
80
TIME IN HOURS

EXPLANATION OF PLATE XIII

Temperature-time relationship for second test from 199 hours to 338 hours. (Continued from Plate XII)

PLATE XIII


Avg. Inlet Temp.
Avg. Inlet Temp.
Avg. Inlet Temp.
40
30
40
30
40
30
TEMPERATURE, °F
312
320
328
338
256
264
272
280
288
296
304
200
208
216
224
232
240
248
TIME IN HOURS

This proves that after the cooling period is finished, a pure drying front is established. The drying front moves slowly and the drying zone is very thin. In this test the rate at which the drying front moved was 0.08 inch per hour and the depth of the drying zone was slightly greater than three inches.

After 140 hours of the test the temperature of the corn ahead of the drying front dropped to 30°F because of a drop in the inlet air temperature. The temperature increased again after 100 additional hours when the inlet air temperature was back to normal. (See Plates XII and XIII)

The above will be discussed again with moisture data.

Third Test: Temperature results from this test are shown on Plates XIV and XV. This test was carried out for 117 hours. The results show a similar trend to the results of test 1 and 2. A better representation of the cooling period is shown on Plate XVI where the time axis is taken as a logarithmic scale. This plate indicates that the cooling period may be divided into two regions. First, there appears to be a constant temperature region in which the temperature drop is negligible. The length of time before this period ends appears to increase linearly with increasing corn depth.

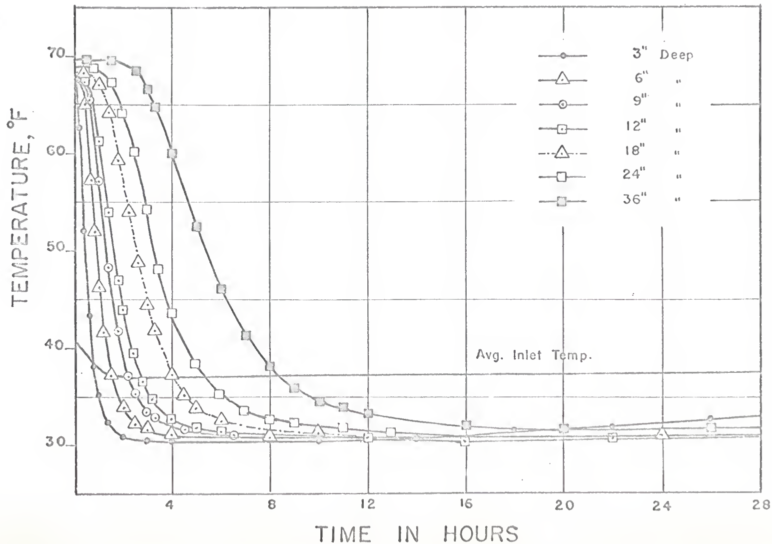
The second region is a decreasing rate region. The temperature starts to fall at an increasing rate, reaches a maximum, and then falls asympotically, reaching the minimum temperature. The time at which the maximum temperature rate of decrease occurs is shown (Plate XVII) to be a linear function of bin depth. It is also noticed that the rate of cooling decreases as depth increases. Results from the first two tests coincide with these results.

It was also found for tests 2 and 3 that the ratio $\frac{T - T_{min}}{T_i - T_{min}}$ plotted as a straight line with time on log - probability paper in the falling rate

EXPLANATION OF PLATE XIV

Temperature-time relationship for third test (corn initial temp. 70°F initial moisture content 44% (dry basis) and air rate of flow 1.3 ft^2/ft^2min. for different depths in the bin.

PLATE XIV

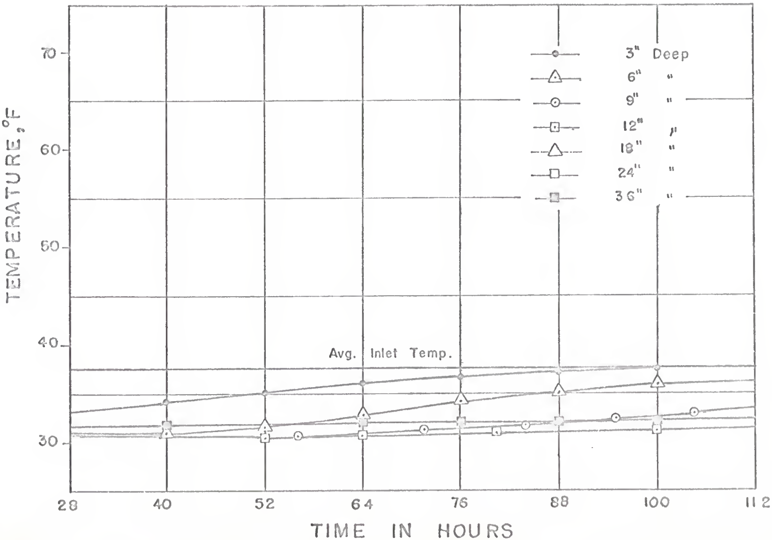


70
60
50
40
30
TEMPERATURE, °F
4
8
12
16
20
24
28
TIME IN HOURS
3" Deep
6" "
9" "
12" "
18" "
24" "
36" "
Avg. Inlet Temp.

EXPLANATION OF PLATE XV

Temperature-time relationship for third test; Time 28 hours to 112 hours. (Continued from Plate XIV)

PLATE XV

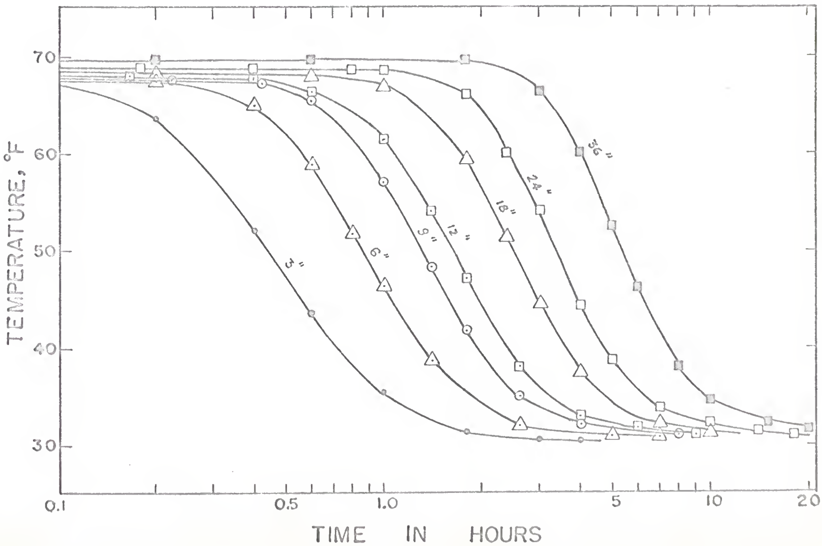


3" Deep
6" "
9" "
12" "
18" "
24" "
36" "
Avg. Inlet Temp.
70
60
50
40
30
TEMPERATURE, °F
28
40
52
64
76
88
100
112
TIME IN HOURS

EXPLANATION OF PLATE XVI

Temperature-time relationship for the falling temperature rate period.

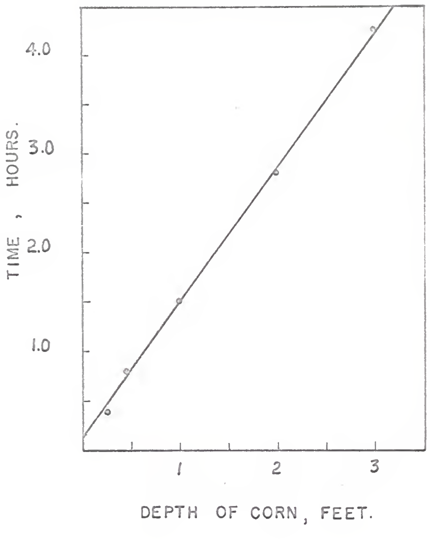
PLATE XVI


TEMPERATURE, °F
70
60
50
40
30
0.1
0.5
1.0
5
10
20
TIME IN HOURS
3"
6"
9"
12"
18"
24"
36"

EXPLANATION OF PLATE XVII

Time at which maximum cooling rate occurred vs. corn depth for the second test.

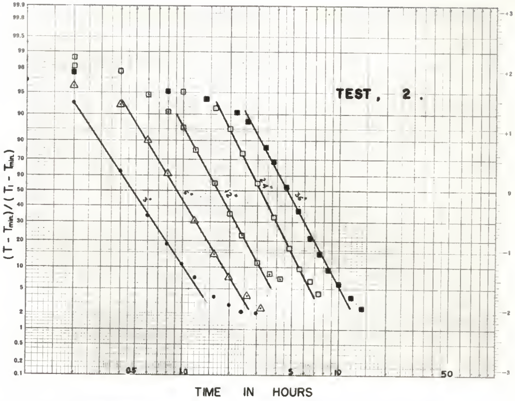
PLATE XVII

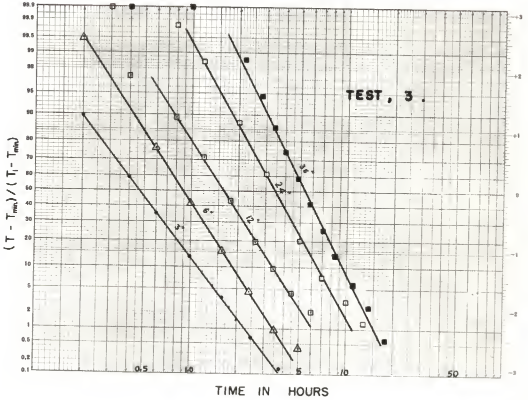


EXPLANATION OF PLATE XVIII

Ratio $\frac{T - Tmin}{T_i - Tmin}$ vs. time on Log-probability paper in the falling rate temperature period.

PLATE XVIII


TEST , 2 .
(T - $T_{min.}$) / (T_1 - $T_{min.}$)
TIME IN HOURS
3"
6"
12"
24"
36"
0.5
1.0
5
10
50


TEST , 3 .
(T - $T_{min.}$) / (T_1 - $T_{min.}$)
TIME IN HOURS
3"
6"
12"
24"
36"
0.5
1.0
5
10
50

region. In this relationship

T_i = initial temperature of grain

T = air and grain temperature after time Θ

T_{min} = the minimum temperature reached before drying starts, which is the wet bulb temperature corresponding to inlet air conditions.

This is illustrated in Plate XVIII.

Moisture Data

First Test: Results of moisture changes of the low moisture corn were not conclusive. The strain gauges recorded a maximum change of 0.05% of the initial dry basis moisture content. The instrumentation was not sensitive enough for measuring accurately the moisture changes for small changes of corn weights.

Second and Third Tests: With higher initial moisture, corn weight changes were checked against initial and final moisture contents as determined by oven drying representative samples from each tray. The results correlated closely for some trays, but not for all. It is concluded that the instrumentation used was not accurate enough to measure precisely changes in corn weights. Good trends of the moisture change history throughout the bin were given, however.

Plates XIX and XX show the ratio M/M_i as a function of time at different depths within the bin, for test 3. (M is corn weight at time Θ and M_i is initial corn weight.) The ratio M/M_i represents the decrease in the average initial corn moisture content (dry basis) in each tray. Plates XIX and XX also show the corresponding temperature history of the air above each tray. Results from the second test show a similar change at different parts of the bin which strengthen the following argument.

Following the first tray from the bottom, the first 3-inch layer, it is seen that a very rapid drop of temperature at the early stage is associated with a decrease in the tray weight from the early stages. The rate of decreasing moisture does not change after the temperature reaches the minimum and starts warming up to the inlet air temperature. The continuous moisture drop in the first 3" of the corn bed is due to both a drying front which starts at the very first corn particles and to the increased drying potential of the air as it gains sensible heat from the corn.

The next 3-inch layer (layer 6" deep on Plates XIX and XX) shows a faster rate of moisture loss during the cooling period due to loss in sensible heat of the corn which enables the moisture to evaporate. As the temperature reaches a minimum, the rate of moisture changes and is almost negligible. After 40 hours of the test, another period of rapid decrease of moisture was evident, since the drying front reached the corn layer, and was well across it. This is shown by the increase of temperature above the corn layer.

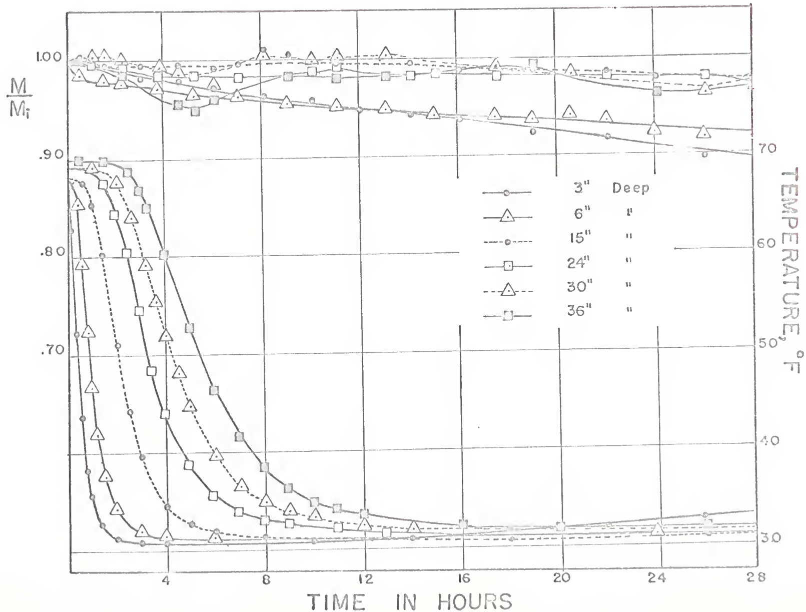
The 3-inch layer of the corn bed above the 1-foot level of the bed is discussed next. A slight drop in moisture was noted during the cooling period. This loss was not great because here two factors were in effect. The first was evaporation by sensible heat stored in the corn which caused a decrease of corn moisture. The second was the high moisture in the air which decreased its drying capacity. When the cooling period ended, corn moisture increased. Further, when the drying front started to cross the layer ahead and warmer air was available, another period of moisture loss started. This was followed by the major loss when the drying front reached the tray. This was evident after 50 hours.

The next layer discussed is the 3-inch layer completing 2 feet of the

EXPLANATION OF PLATE XIX

Temperature vs time and ratio $\frac{M}{M_i}$ vs time for test 3.

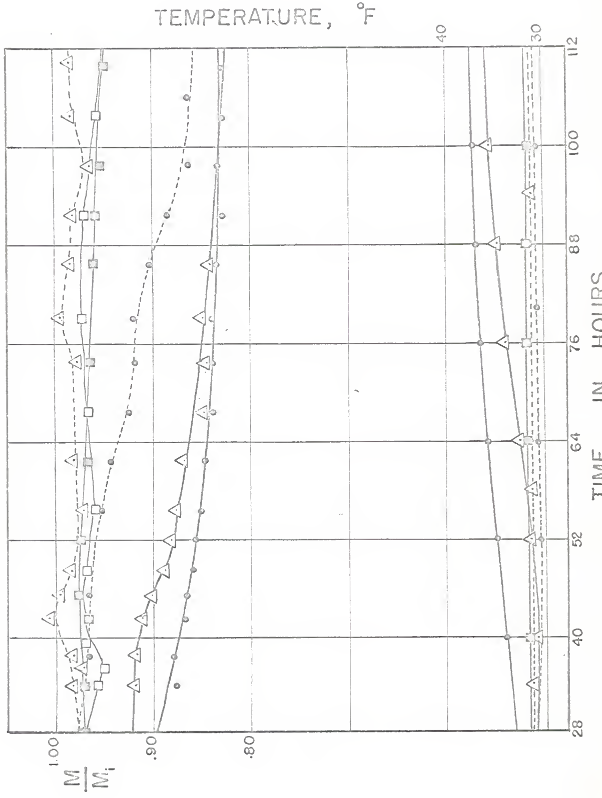
PLATE XIX


M/Mi
1.00
.90
.80
.70
TEMPERATURE, °F
70
60
50
40
30
3" Deep
6" "
15" "
24" "
30" "
36" "
4
8
12
16
20
24
28
TIME IN HOURS

EXPLANATION OF PLATE XX

Temperature vs time and ratio $\frac{M}{M_i}$ vs Time for test 3. (Continued from Plate XIX)

PLATE XX

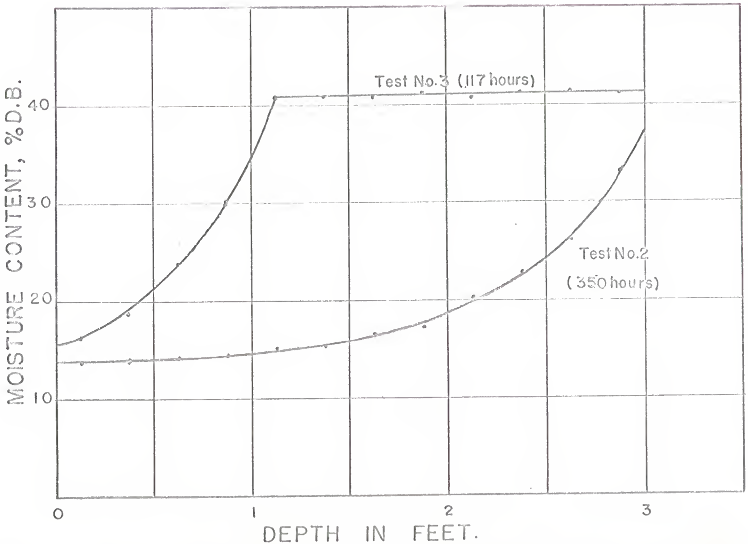


TEMPERATURE, °F
40
30
TIME IN HOURS
28
40
52
64
76
88
100
112
1.00
.90
.80
M/M_i

EXPLANATION OF PLATE XXI

Final Moisture Content (dry basis) vs.
depth corn in bin.

PLATE XXI



Test No.3 (117 hours)
Test No.2
(350 hours)
MOISTURE CONTENT, %D.B.
40
30
20
10
0
1
2
3
DEPTH IN FEET.

bin. This showed a similar behavior to the one previously discussed and the main drying started after 100 hours of the test.

The 2-1/4 to 2-1/2 and the 2-3/4 to 3-foot layers exhibited periods of moisture loss followed by moisture gain. During the cooling period two percent of the weight was lost. Here the air was dry enough to be capable of carrying more moisture. After the initial cooling period, moisture content was variable as shown by Plates XIX and XX. These two layers could be expected to have their main moisture loss when the drying zone is established through them.

Plate XXI shows oven dry moisture content data after the end of both the second and third tests plotted versus depth of corn. For the third test it is shown that after 117 hours the moisture content is almost constant at 41% d.b. for corn above the first 1-1/2 feet. This indicates 2% decrease from the initial moisture of 44%, (dry basis). Results coincide with the average 2% loss in moisture obtained from strain gauge readings for the upper two thirds of the bin.

For the second test, after 350 hours, the first two feet were almost dry while the third foot was still drying. This coincides with the results obtained from the temperature behavior in the pure drying region of the second test.

CONCLUSIONS

Within the limits of these experiments the following conclusions were drawn:

1. During the cooling of corn with air, the air state does not follow an adiabatic saturation line on the psychrometric chart since both latent and sensible heat are added to the air.
2. The final minimum temperature of the air after the cooling period will be the wet bulb temperature corresponding to the inlet air conditions.
3. After the cooling period ends, pure drying theory described by Shove (28) applies until the whole bed of corn is in moisture equilibrium with the incoming air.
4. The amount of moisture lost by the corn during the cooling period increases with increasing initial moisture content and/or initial temperature. This moisture loss occurs in all the corn layers.
5. The rate of cooling increases with increasing initial moisture content of the grain and/or initial grain temperature.
6. Instrumentation for measuring grain moisture changes needs improved sensitivity. During these experiments only trends of moisture change were valid. Better moisture data are required for establishing the moisture-temperature relationship needed to construct a finite difference solution of the equations on page 19.

7. The rate of temperature drop during the cooling period may be divided into two phases: (1) the constant temperature period in which negligible drop of temperature occurs. This period appears to increase as a linear function of grain depth in the bin.. (2) the falling temperature rate period which appears to follow a straight line relationship in log-normal probability paper shown on Plate XVIII. More experimental and mathematical study is needed to explain this behavior. During the second period, the time at which the maximum cooling rate is achieved was found to increase linearly with bin depth.

SUGGESTIONS FOR FUTURE RESEARCH

The review of literature indicated that the area of refrigerated grain storage has many unsolved problems. The problems which appeared during this investigation also suggest areas in which more detailed research is needed.

In order to explain in more detail the physical behavior of high moisture corn during the cooling period more accurate methods of measuring weight changes must be introduced.

Further studies to detect the effect of changing the main factors governing grain drying and cooling rates must be carried out. This is achieved by changing air flow rates, initial air conditions and grain initial temperature and moisture content. Mathematical models and equations describing the cooling and drying rates must be derived and enough data are needed to evaluate the constants in those models. A dimensional analysis may be helpful in evaluating the parameters governing the values of such constants in the formulas.

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COOLING AND DRYING OF HIGH MOISTURE SHELLED CORN IN DEEP BEDS

by

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B.Sc., Mechanical Engineering
University of Assiut, Assiut, U.A.R., 1965

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requirements for the degree

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ABSTRACT

The purposes of the study were (1) to determine drying and cooling rates at any depth of a deep bed of high moisture corn during simultaneous cooling and drying with refrigerated air; (2) to design and build an apparatus for measuring the various parameters involved in the process; and (3) to analyze data and explain the process involved during simultaneous cooling and drying.

The main factors affecting the process are: (1) initial air conditions, (2) air flow rates, (3) initial moisture content of the corn, (4) initial grain temperature, and (5) drying and cooling rate characteristics. Number 5 above, is generally governed by the other four for a specific grain.

A bin with a cross-sectional area of four square feet capable of holding a bed of corn six feet deep was built. The bin, insulated from outside environmental conditions, contained 24 test trays, each 3" deep and one foot by one foot in plan. Each tray was suspended from a cantilever beam fitted with strain gauges for weighing of the corn. The weight changes were recorded as a function of time to evaluate the drying rate of the corn. The test trays were surrounded by guard trays filled with corn to minimize outside effects.

Refrigerated air was passed vertically through beds of high moisture corn. Temperatures of the air were recorded at selected time and location intervals in order to know the air temperature history throughout the bed of corn. Copper-constantan thermocouples and a recording potentiometer were used for recording the temperatures.

Three tests were carried out in this investigation. The air rate of flow in each experiment was 1.3 $\pm$ 5% ft^3/ft^2-minute. Average inlet air

temperature was $37.5 \pm 0.5^{\circ}F$. The average initial moisture contents of the grain for the three tests were 23, 38.4 and 44% (dry basis), respectively. Naturally moist corn was used in the first test and remoistened corn was used in the other two.

Results from tests with initial corn temperature of $70^{\circ}F$. showed that during the simultaneous drying and cooling period the air state does not follow an adiabatic saturation line on the psychrometric chart, since both latent and sensible heat were added to the air. After the cooling period ended, the air temperature reached the wet bulb temperature of the incoming air and a pure drying front moved slowly through the grain.

Moisture sensing instrumentation failed to measure moisture changes accurately, but results were adequate to describe qualitatively the mechanism of moisture change with time. For the third test, an average moisture loss of about 2% of the initial weight occurred throughout the entire bed. Some moisture addition to grain at layers above 1 foot deep was noted during the early parts of the test. These layers started to dry again as the drying front moved across them. Generally the moisture loss during cooling increases with higher initial moisture content or initial grain temperature.

The rate of cooling of corn was found to increase with increasing initial moisture content and, or, initial temperature.

The time for initiating the falling rate of temperature decrease was found to increase with bin depth. The falling rate of temperature decrease increases to a maximum then decreases until the temperature asymtotically reaches the wet bulb temperature of the inlet air conditions. The maximum rate of temperature decrease at each location in the corn bed was found to be a linear function with time.

Further study varying initial corn temperature, initial moisture content, air flow rates and initial air properties are suggested for better understanding the mechanism of cooling associated with drying.