CHILLING OF HIGH MOISTURE CORN

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ABSTRACT

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by Moedjijarto Pratomo

The preservation of product quality during storage is a problem confronting all segments of today's agricultural industry. The losses or changes which may occur due to insect and mold deterioration in product quality during storage are not only of economic importance, but can also have an influence on the safety and health of animals and humans. The growth of microflora and resultant deterioration of wet (high moisture) grain can be slowed or inhibited by holding the grain at low temperature (chilling).

Cooling wet shelled corn to a temperature of 40 degree F immediately after harvest greatly increases the allowable storage time over that possible at higher temperatures. Increasing the holding time of wet (high moisture) corn is advantageous in any method of drying, since drying cost decreases as available drying time increases.

This study concerns with the analysis of the cooling process in a deep granular bed in relation with the temperature and air flow as the parameters.

A cooling bin was designed and connected with a refrigeration system which provided air down to 35 degree F. This chilled air was forced through a vertical column

of high moisture corn starting with an initial uniform product temperature. The temperatures throughout the bed were measured at intervals of twenty minutes by sixteen copper-constantan thermocouples connected to a recording potentiometer through a multi-point contact connector. Interstitial air velocities of 0.67, 1.85, 1.95 and 12.35 ft/min were investigated.

Plots of temperature-time curves from the experimental temperature history data were presented and comparative plots between the highest and the lowest air velocities were drawn for the deep bed of high moisture corn (27 to 29 % moisture, wet basis). The plots indicate that with the increasing airflow, the time required fro the cooling zone to move through the corn was reduced. Equations for predicting the cooling time was presented. Recommendations based on this study are proposed for improving the analysis.

APPROVED: Fred W. Bakker-Arkema
Major Professor

June 8, 1967

CHILLING OF HIGH MOISTURE CORN

By

Moedjijarto Pratomo

A REPORT

Submitted to

Dr. Fred Wilte Bakker-Arkema
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Department of Agricultural Engineering
Michigan State University

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This work is dedicated to his mother Mrs. M. Pratomo and sister Mrs. S. M. Soetoto. Their encouragement, love and sacrifice have been a great asset to him.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SYMBOLS

T_a = temperature of the air, degree F

T_i = initial temperature of the product, degree F

k = proportionally constant

A = product surface area per cubic foot, ft^{-1}

d = particle diameter, ft

V_a = interstitial air velocity, ft/min

f = porosity of packed bed, dimensionless

ρ_p = product density, lb/ft^3

ρ_a = air density, lb/ft^3

C_p = specific heat of the product, Btu/lb ^oF

C_a = specific heat of the air, Btu/lb ^oF

v_a = specific volume of the air, cu. ft/lb

θ = time, hours

X = coordinate distance from air inlet, ft

N_{Bi} = Biot number, = hL/K

K = thermal conductivity, Btu/hr ft ^oF

h = convective heat transfer coefficient, Btu/hr ft^2 F

T_L = time for leading edge, hour

T_T = time for trailing edge, hour

Q = air flow rate, CFM/bu

Re = Reynolds number

e = base of natural logarithm

INTRODUCTION

During the past quarter of a century the increase in field culture mechanization and, especially the advent in the past decade of the picker-sheller, has forced the corn grower to look for a new means of harvesting and storing corn. This change in technology in general has led to an increasing amount of "high moisture" corn being harvested each year. By "high moisture corn" is meant corn with a too much moisture content that it cannot be stored safely by conventional methods.

The technological changes have not been limited to an increase in mechanization. The use of hybrid varieties with long growing seasons has increased the total corn production and made harvesting at high moisture content practically a necessity in many localities.

Reports of work regarding storage, cooling and chilling of grains in this country indicate that little work has been done in this field and most of the work has occured in Great Britain.

The storage of moist grain by chilling has been practiced in Western Continental European countries for more than five years, but was not used in Great Britain until 1963. Since that time considerable interest has been shown by farmers, maltsters and corn merchants.

Chilling is the lowering of the temperature of fresh produce to inhibit the growth of microorganisms and to preserve its quality.

Chilled high moisture shelled corn has an allowable storage time of several weeks, during which various conditioning or marketing options can be applied. These options include (1) reducing the moisture contents of the corn by dehydrofrigidation, (2) arresting respiration and subsequent deterioration of the grain for longer storage by lowering the grain temperature to 32 degree F or below, (3) drying the corn at a more leisurely rate with conventional heated air drying equipment, (4) marketing the wet grain through regular marketing channel, and (5) selling and delivering wet, partially dried, or dried corn to a grain processor.

REVIEW OF LITERATURE

The growth of microflora and resultant deterioration of wet (high moisture) grain can be slowed or inhibited by holding the grain at a low temperature (Shove, 1966). Increasing the holding time of wet corn is advantageous in any method of drying, since drying cost decreases as available drying time increases.

In storing and drying wet grain it is important to know how long the grain can be held without excessive damage (dry matter loss). This information is particularly needed for in-storage drying. The time available for drying depends on the relation between the temperature of the grain and its moisture content (Beaty et al., 1965). Wet corn harvested and stored at 70 F must be dried in a few days to prevent deterioration (Figure 1). This relatively short drying period can create a bottleneck in the flow of corn at harvest time.

As shown in Figure 1, the safe storage time for wet grain varies with moisture content and grain temperature. Corn harvested at 30 percent moisture and 80 F must be dried in about 2 days; however, if the same corn is harvested and stored at a temperature of 40 F, the drying time can be extended to 20 days. If 18 to 20 percent corn is harvested and stored at 30 to 40 F it can be kept 2 or 3 months.

Shelled corn that is to be fed to livestock does not have to be dried if it is field-shelled when temperatures are low or is cooled after it is stored. However, it will have to be fed during the safe storage period (Figure 1) or dried to a

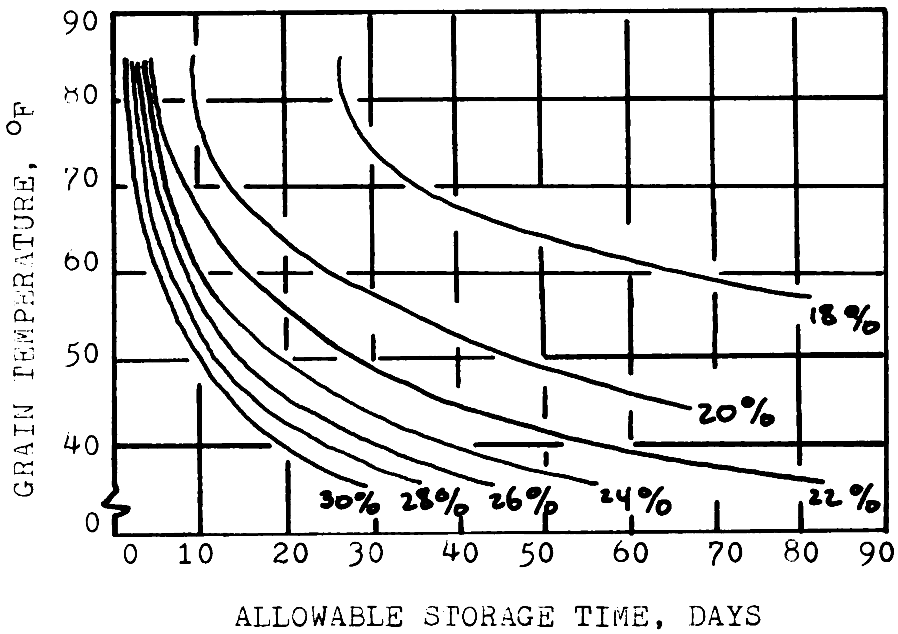

Figure 1. Allowable storage time for shelled corn at various temperatures and moisture contents. During this time the grain will lose ½ percent in dry matter, but will still be acceptable. Data are from the U.S. Department of Agriculture Grain Storage Research Laboratory, Ames, Iowa.

moisture content of 12 to 13 percent for safe longer term storage (Beaty et al., 1965).

Grain deterioration is related to respiration of the grain itself and of the accompanying microorganisms, and the production of carbon dioxide is a product of this respiration (Steele et al., 1962). Since the evolution of carbon dioxide can be measured readily, measurements of carbon dioxide were used by Steele et al. (1962) as an index of deterioration. Such measurements can also be translated to loss in dry matter in the grain. For the purpose of their study, aerobic respiration with the complete oxidation of carbohydrates to carbon dioxide and water was assumed.

The complete combustion of a typical carbohydrate is represented by the following equation:

$$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O + 677.2\ \text{Cal}$$

From this equation it may be computed that one percent loss in dry matter in the grain is accompanied by the evolution of 14.7 grams of CO_2 per 1,000 grams of grain dry matter (Steele et al. 1962).

Three ways of decreasing the respiration rate of grain according to Haugh (1964) are:

(1) to decrease the moisture content of the grain,

(2) to decrease the temperature, and

(3) to decrease the available oxygen supply.

These three factors, moisture, temperature and oxygen are all inter-related.

Milthorpe et al. (1948) reported that moisture content is the most critical of these three factors.

In connection with the safe storage, insect heating, fall in germination and fungal heating, Burges and Burrell (1964) produced a useful diagram (Figure 2) on the relatinn of storage temperature and grain moisture content. It was compiled from a large number of sources. Thus, at moisture contents up to about 22 %, grain can be stored safely for a reasonable time at temperatures of 41 F. or below, which can be obtained by refrigeration (chilling). Insects will not develop if the temperature is below 63 F. This is true of dry or wet grain, and therefore reduction to this temperature is a method of insect control. To control molds, bacteria and mites a much lower temperature must be used, dependent on the moisture content of the grain.

A study of the effect of temperature on the radial growth of the fungus on agar by Tuite et al. (1966) revealed low temperature to be an importance limiting factor. Growth was markedly decreased at 12 C (53.6 F) and below.

Development of molds and insects in grain, and their control, can be related to three different levels of moisture content as follows (Hyde, 1965):

Moisture content of the grain	Insects and Micro-organisms controlled by
a. Up to 15 percent	Low moisture content; cooling with untreated air.
b. 15 to 25 percent	Drying; refrigeration (only up to 20-22 percent moisture content); ordinary airtight storage.
c. 30-40 percent	"Silage" techniques (and unstable form of airtight storage).

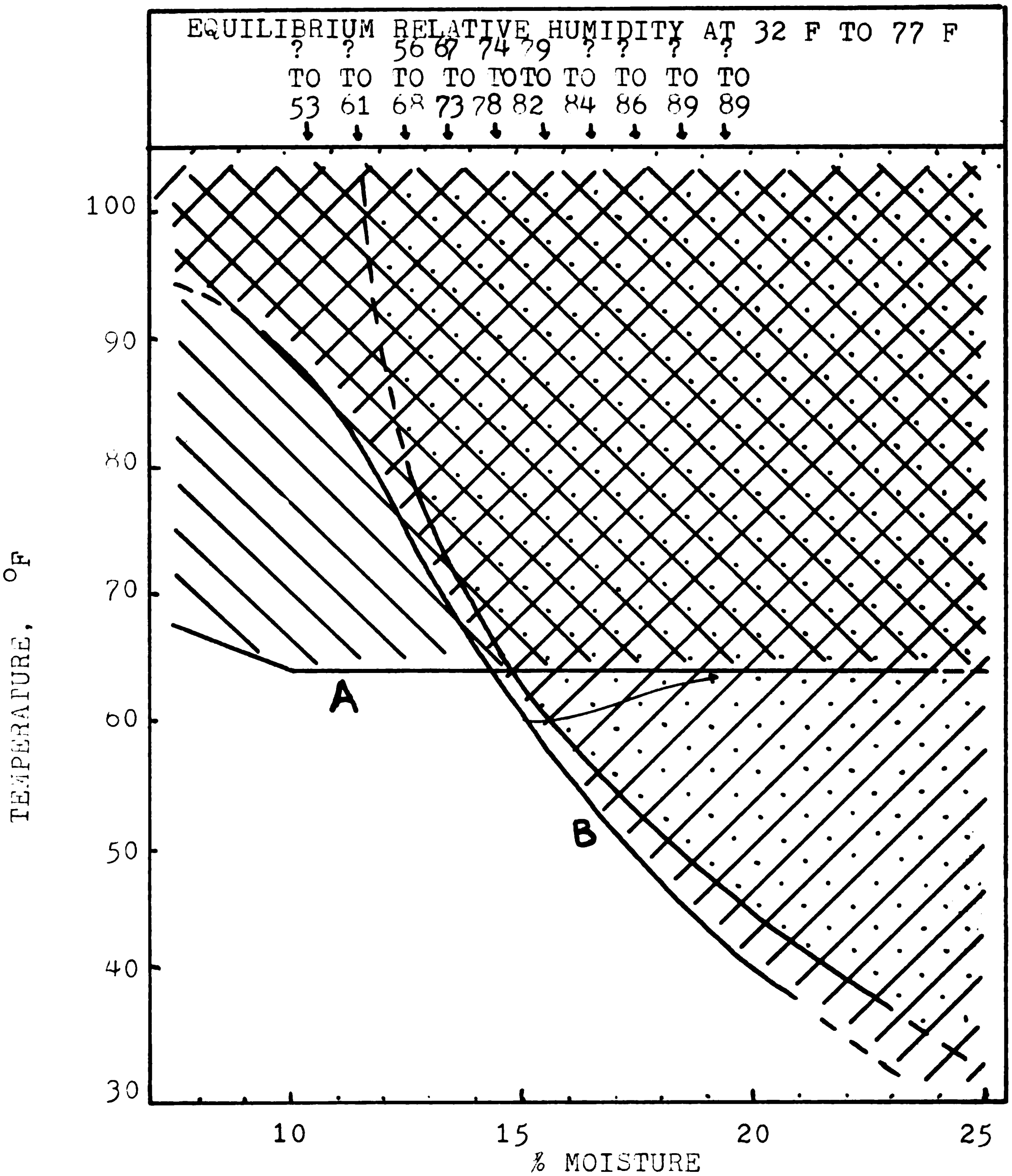

Figure 2. Relations of storage temperature and grain moisture content to insect heating, fall in germination (to 95% in 35 weeks storage) and damp grain (fungal) heating. Broken lines indicate extrapolation. (Burges and Burrell, 1964).

Experience so far suggests that different species of micro-organism are involved at the different moisture levels. Those growing at moisture contents up to 25 percent are mold fungi that require oxygen for growth, and die in its absence (Semeniuk, in Anderson and Alcock, 1954). The organisms (probably bacteria) active at the higher moisture levels are less dependent on oxygen and flourish under acid conditions such as develop during the production of silage (Hyde, 1965).

Four fungi grew in high moisture corn (23 - 28 %) stored in the presence of low oxygen and high carbon dioxide concentrations at 60 and 73 F (Tuite et al., 1966). They were, in the order of their anaerobic ability; Yeast, Mucor, Fusarium Moniliformae and Penicillium. Only the last two affect the feeding value although there are no specific studies on Mucor and the species of yeasts found in high moisture corn. Bacteria as observed by Burmeister et al. (1966) indicated their presence at substantial numbers (10^8 per gram) at moisture contents of 28 % and above.

Mold will develop on the surface of shelled corn when the temperature and humidity of the air in contact with the corn is favorable to mold growth (Dexter, 1957). Shelled corn, therefore, will keep without molding, regardless of its internal moisture content, so long as the grain is in an environment unfavorable to mold growth.
Semeniuk (in Anderson and Alcock, 1954) found that a minimum relative humidity of 80 percent (at 85 F) in bulk bins is required for continued growth of molds. A relative

humidity of 80 percent corresponds to an equilibrium moisture content of about 15.6 percent, wet basis, for corn at 77 F (Hall, 1957). In these tests, there was no evidence of mold.

OBJECTIVE

In order to obtain quantitative information on the time required for a cooling zone to move through packed beds of agricultural grains, it was found necessary to undertake an experimental study.

High moisture corn were used in this investigation. The product temperature at difference longitudinal locations in a deep bed was measured at regular time intervals. Experimental temperature-time curves were plotted and equations for predicting the time required for a cooling zone to move through corn grains were derived. From this preliminary study, it is hoped that conclusions can be reached which will provide direction in the endeavor to improve the present analysis.

EXPERIMENTAL

Material

The high moisture shelled corn used in this study had been harvested with a picker sheller, and was obtained from a local elevator in Mason, Michigan. It was cleaned of trash and small pieces of corn kernels which included some damaged kernels (less than 5 %) were removed. Moisture content at shelling was about 29 percent, wet basis.

It was then placed in gunny bags (80 - 90 lbs weight) and stored without a preservative in a walk-in cold storage chamber maintained at 20 F until the time the grain was needed for chilling tests.

Initial moisture contents were 27 to 29 percent for all tests. In this study it was necessary to rewet the grain until the average moisture content for all materials had reached 28%. Hukill et al. (1960) reported that rewetted grain dried somewhat more rapidly than naturally wet grain. Findings by Hustrulid (1963) indicated that naturally moist corn, frozen and thawed kernels, and carefully remoistened kernels all had the same drying characteristics.

The rewetting was done by carefully remoistening the kernels in a rotating drum for about 15 minutes. Preliminary work verified that after 15 minutes rotation the materials had been thoroughlywetted. After each thorough wetting, the materials were put back in the freezer for a week before being used. At this time two bags of the frozen grain were removed out of the 20 degree F freezer, spread on a canvas and allowed to thaw and warm to room temperature. As the corn was removed from cold storage, ice crystals were noticed on the grain surface. However, after the grain had come to room temperature without any further exchange of air, there was no noticeable surface moisture.

The moisture content of each sample of corn was determined before and at the end of each test by using a one stage oven procedure (Figure 3). A 20-gram grain sample was weighed with an analytical Mettler balance. The balance was a fast-reading type with an accuracy of $\pm$ 0.05 mg. The samples of corn (four replications for each moisture level) were placed in the oven for 24 hours and the temperature of the oven was maintained at 200 degrees F.

Chilling Bin and Refrigeration Unit

The deep-bed chilling of high moisture corn was studied using a double-insulated column of dimensions: 1'x 1'x 4' deep (Figures 4 and 5). The column was filled with approximately 3.2 bushels of corn for each test. The bed was connected to a fan and refrigeration system which provided air down to 35 degree F.

Chilled air was forced through the column of material, and temperatures thoughout the bed were measured at intervals of 4 minutes by 16 copper-constantan thermocouples.

The refrigeration system was of the direct-expansion type. The condenser was of the air-cooled type and the compressor was totally enclosed, hermetic type, with the electric motor as an integral part of the compressor casing. The expansion valve was thermostatically operated. Air was drawn over the evaporator from the room through door D_1 (Figure 5). After passing through the fan F_2, this chilled air partially was exhausted through the deep bed into the room and partially was recirculated back over the evaporator from door D_3 to door D_2 thus repeat the cycle. This makes a considerable saving on the harsepower of the refrigeration plant, since the air drawn in from the plenum chamber is cooler than the air drawn in from the room.

The centrifugal fan was placed after the evaporator in the chilled air duct, thus automatically reheating the air by 1 to 2 degrees F. This caused the chilled air to drop from a relative humidity of about 100 - 95 percent to 85 - 80 percent relative humidity. A thermostatic expansion valve with its sensing bulb located in the air-stream just after the evaporator was used to maintain a relatively constant air temperature during a given test (Figure 5). At temperatures approaching freezing the evaporator coils in the chilling unit might freeze up. An automatic defrost system was installed to avoid this and operated for about three minutes per hour. A water collecting tray mounted beneath the cooling coil collects the water and allows it to drain away through a drain hose connection (Figure 5). During the defrosting period the air from the evaporator was exhausted through fan F_1 directly into the room rather than passing through the deep bed. The operation of the defrost system can be described as follows:

Figure 3. Equipments used. From left to right:

A. Mettler Balance Model K-7T
B. Mettler Balance Model B-5
C. Oven

Figure 4. General View of the Experimental Set-up.

(Arrow indicates the direction of Airflow).

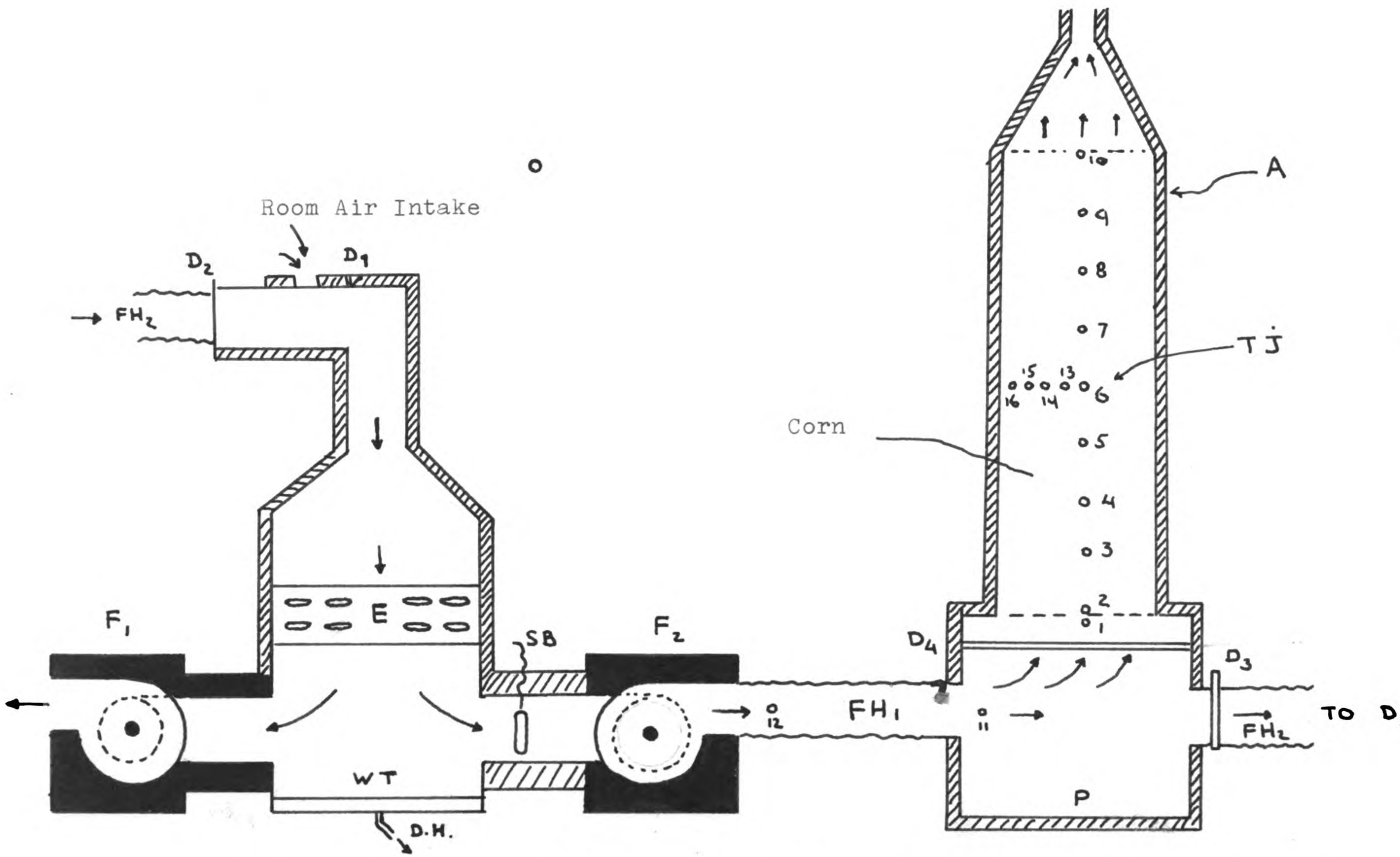

Figure 5. Diagram of the Experimental Deep Bed Chilling of Corn Equipment.

Figure 5.

Diagram of the Experimental Deep Bed Chilling of Corn Equipment

A = Insulated Column (3/4" Styroform Sheet and Glass Fibre on the inside).

TJ = Thermocouple Junction

D_1, D_2, D_3, D_4, = Sliding Doors

FH_1 , FH_2 = Flexible Hose insulated with Glass Fibre on the outside.

F_1 = Exhaust Fan

F_2 = Corn Fan

E = Evaporator Coil

WT = Water Tray mounted below the Evaporator Coil.

P = Plenum Chamber

SE = Sensing Bulb (Thermostatic Expansion Valve).

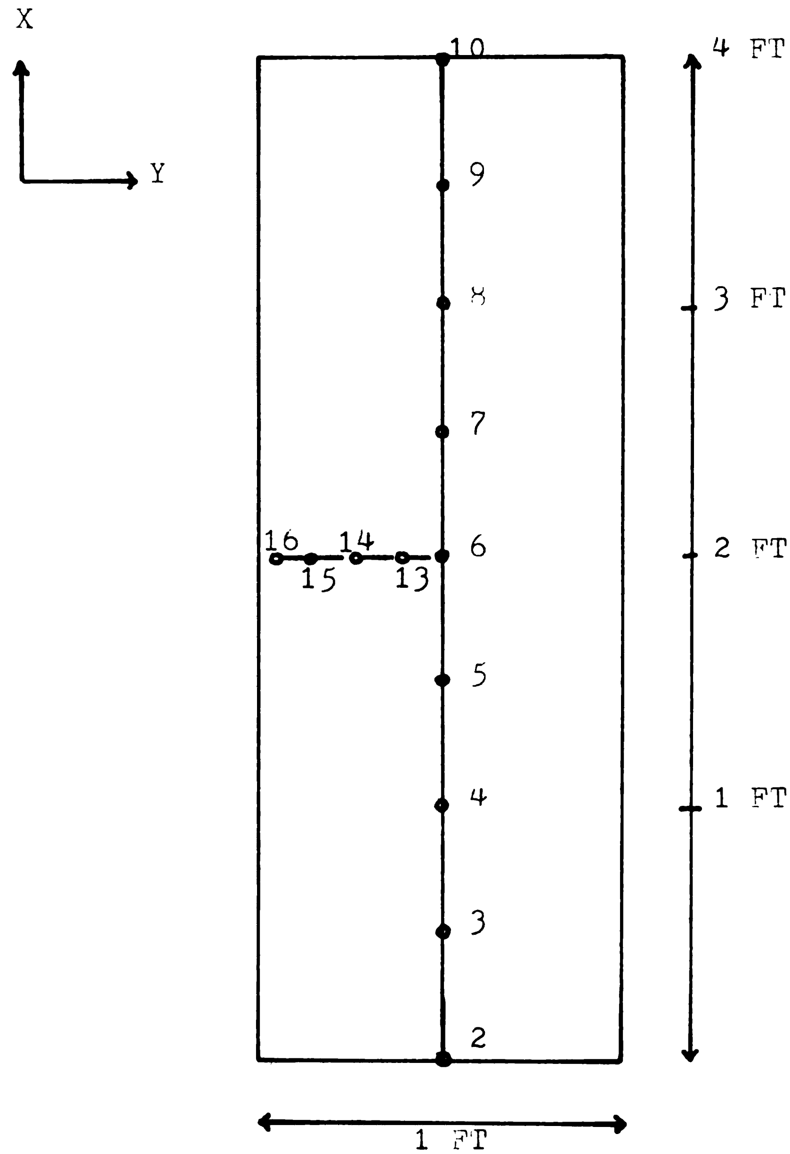

Figure 6. Thermocouple Location in the Deep Bed of Corn.

Operation	Corn Fan F_2	Exhaust Fan F_1	Hot Gas (Refrigerant)
1. Cooling	ON	OFF	OFF
2. Start to defrost	OFF	ON	ON
3. After 3 minutes	OFF	ON	OFF
4. After 2 minutes	ON	OFF	OFF

The capacity of the refrigeration unit was one ton and the horsepower of the centrifugal fan was o.5 HP.

The temperature of the air entering the granular bed was 40 °F ± 1 °F for all tests. To maintain this temperature throughout the test was not an easy job. The initial corn temperatures were 80 °F ± 1 °F and moisture contents varied from 27 to 29 percent, wet basis.

The copper-constantan thermocouple junctions were located every 6 inches along the vertical X-axis of the column. Four thermocouples were located in the middle of the column along the Y-axis 1½ " appart. One was located just before the chilled air entering the grain column and one each in the plenum chamber and after the corn fan. The remaining 9 thermocouples were installed along the vertical X-axis of the column as shown in the diagram (Figures 5 and 6).
The co-planar thermocouples were spaced to verify the assumption that there was no lateral temperature gradient within the deep bed. The thermocouples were connected to a 16-point recording potentiometer through a multipoint contact connector. During the tests, the temperature recorder made a continuous

record of the temperatures throughout the grain column for the first three hours, and then a time clock on the potentiometer was used to allow one complete cycle of points to be recorded each twenty minutes.

The airflow was varied by sliding the control door D_1. Doors D_2 and D_3 were employed to direct the air flow. Door D_4 was used to control the incoming air flow to the test bin. Before starting a test and filling the bin, the whole unit has been cooled for about one hour to make sure that the bin and the ducts were at the cooling temperature. The chilled air was passed through the bin and out to the room by opening D_4 until the thermocouple in the plenum chamber registered 40 degree F. Filling was then began, and interstitial air velocities of 0.21, 0.58, 0.61 and 3.86 CFM/bushel were investigated. After the grain column had been filled, the air flow rate for each test was adjusted by changing the volume of the air until the proper amount of CFM was obtained.

For each test, the mean interstitial velocity was determined by two methods and the results averaged. One method was by direct measurement of mean air velocity ($\bar{V}$) before and after the grain column using a hot wire anemometer. The mean interstitial air velocity was then computed by the relation: $V_a = \bar{V}/f$

where: V_a = Interstitial Air Velocity, ft/min.

$\bar{V}$ = Mean Air Velocity, ft/min.

f = porosity, dimensionless, where f is observed to be 0.40 (Thompson ans Isaacs, 1966).

The second method consisted of a chemical smoke tracer; the smoke was injected into the air stream at the bottom of the grain column. The time at which the first trace of smoke emerged from the top of the grain column was clocked with a stop watch. This method gave a direct value for V_a.

The hot-wire anemometer was calibrated in a wind tunnel using a pitot tube and a micro-manometer. Readings for zero velocity or still air and for maxima velocity were taken and the necessary calibration curve of I^2 versus $V^{\frac{1}{2}}$ was drawn as shown in Figure 7.

Experimental Difficulties

The difficulties in this form of experimentation are numerous, and most of them are not encountered in steady state measurements.

1. Care must be taken to ensure that the thermocouples are reading accurately. The thermocouples should be checked for accuracy by taking readings for ice at 32 degree F and for boiling water at 212 degree F. Accuracies for the thermocouples readouts should be at most ± 1% of the full scale. Considerable improvement in accuracy is achieved by careful calibration of the instrument in the operating range.
2. Because of the small size of the corn kernels, it was not possible to locate the thermocouple junctions inside the individual seeds. Instead, intergranular space temperatures were measured. These measurements are at best bulk values

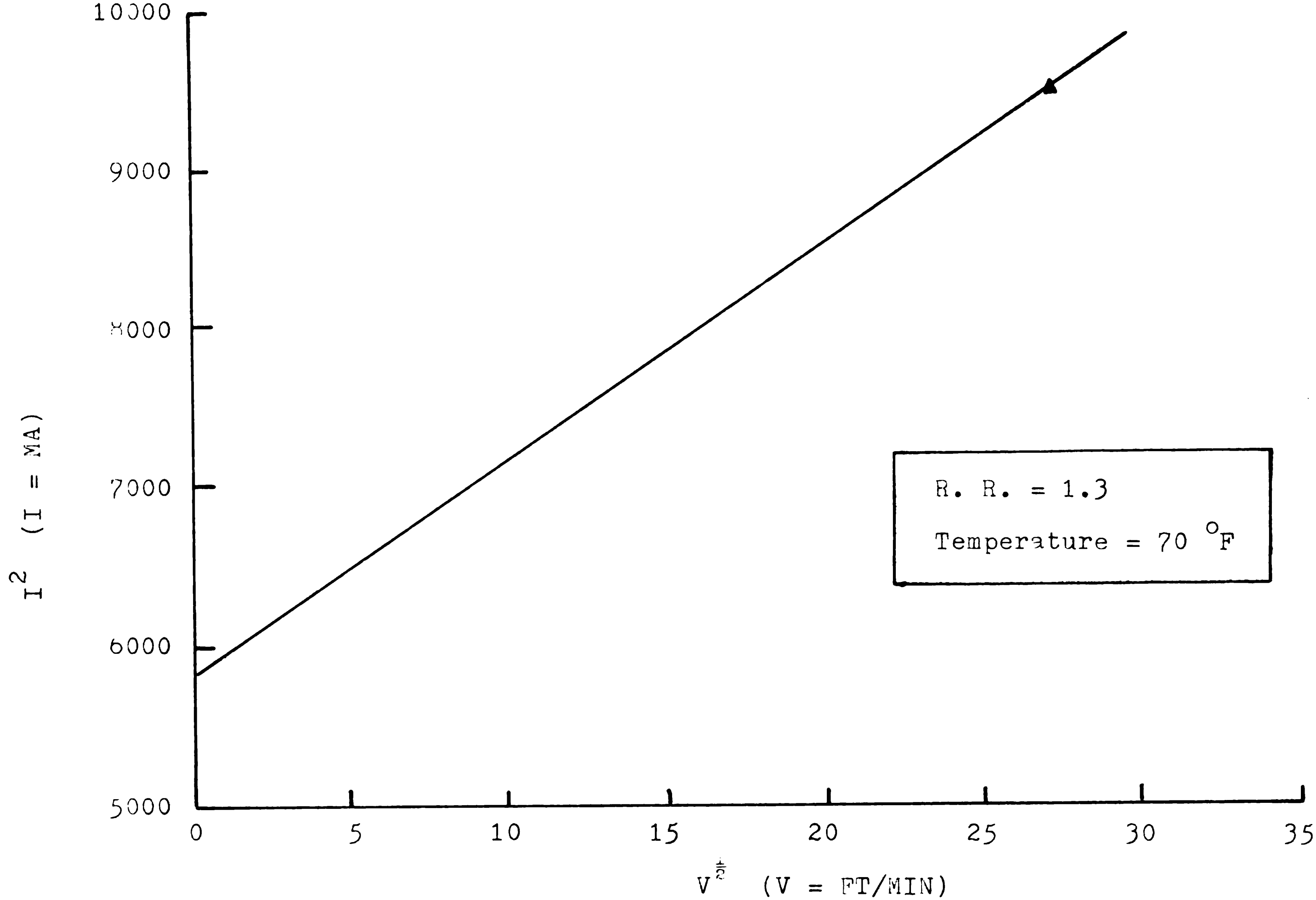

Figure 7. Hot Wire Anemometer Filament Calibration Chart.

for the air stream and grains and are inadmissible where the exclusive air or grain temperature is to be determined.

3. Special care is needed to ensure a uniform air velocity distribution in the bed. This is not an easy task. Furnas (1930), reports that even in beds of solids which were apparently uniform, it was virtually impractical to maintain a uniform fluid flow over the entire cross section. In beds of non-uniform products, this may lead to erratic errors.

4. One of the procedural problems involved in analyzing the results of the laboratory tests was determining when the grain was cool. Theoretically, the time required to cool the grain exactly to cooling air temperature is infinite. As the cooling zone moves out of the corn, the rate of heat removal drops and the cooling time is increased proportionality. In these tests the corn was considered cooled when the top layer (thermocouple no. 10) had cooled two-thirds of the way from its initial temperature to the cooling air temperature . At this point, between 85 to 95 percent of possible cooling had been completed.

ANALYSIS

Mathematical Consideration of Cooling.

When cool air is forced through a mass of grain, a cooling zone will develop and progress through the grain in the direction of airflow. The thickness of the zone and the speed at which it can progress through the grain mass depends upon some function which describes the cooling rate of grain in relation to air velocity.

At any instant of time, Newton's law of cooling describes the rate of change of grain temperature for any point in the mass (Hall, 1957). This is given by:

$$\frac{dT}{dt} = -k\,(T - T_a) \qquad (1)$$

where
- t = time, hrs.
- T_a = air temperature, degree F
- T = grain temperature, degree F
- k = proportionality constant.

The solution of equation (1) is as follows:

$$1/k \frac{dT}{dt} + T = T_a$$

$$T = ce^{-kt} + T_a$$

when $t = 0$, T = initial grain temperature, T_i

so that

$$T_i = c + T_a$$

$$c = T_i - T_a$$

then

$$T = (T_i - T_a)\,e^{-kt} + T$$

This is recognized as the half-response equation :

$$\frac{T - T_a}{T_i - T_a} = e^{-kt} \qquad (2)$$

However, since it is impractical to supply the volume of air required to maintain the air temperature surrounding each kernel of grain at a constant level, equation (2) cannot be applied directly but must be related to airflow and air temperature. It appears that the effect of airflow rate or cooling time must be described by two different time periods (Sorenson et al., 1966). The first period is the time for the leading edge of the zone to move through corn grain (T_L) and can be described as the time at which the air exhausted from the grain first starts to decrease in temperature. The second period, the trailing edge period, would be determined by the depth of the zone and the rate at which it moves.

Under the conditions of this study, the author found, that the first period is closely approximated by:

$$T_L = 0.48\, Q^{-0.1495} \qquad (3)$$

where T_L = time for leading edge to move through the grain, hours.

Q = flow rate of air entering the grain, CFM/bu.

The time indicated in Figure 10 for the trailing edge to move through the grain represents the total cooling time required. Under the conditions of these tests, this time can be expressed as:

$$T_T = 3.22\, Q^{-0.324} \qquad (4)$$

where T_T = time for trailing edge to move through the grain, hours.

Q = flow rate of air entering the grain, CFM/bu.

RESULTS AND DISCUSSION

The experimental data obtained for the packed bed are presented in Tables 1a through 1d. Four different airflows were employed, and the cooling air temperature was 40 degree F for all tests. Initial grain temperature were 79 to 80 degree F and the moisture contents varied between 27 to 29 % wet basis. These data are plotted as temperature-time curves in Figures 8a through 8d. These curves indicate the temperatures of shelled corn at different heights in the packed bed as a function of time. The corresponding temperature history curves between the highest airflow rate for this experiment, (12.35 ft/min), are plotted along with the lowest airflow rate (0.67 ft/min) for purposes of comparison (Figure 9). These comparative curves and their significance will now be discussed.

1. The effect of air flow on cooling time:

The temperature-time curves were drawn at 3 ft, 2 ft and 1 ft from the inlet air. It is suspected that the somewhat erratic nature of some of the recorded data (Tables 1a, b, c, d) stems in part, from the irregularity of the grains. This irregularity makes the passage of air and the transfer of heat a very uncertain and changing process. To have any significance, it is necessary to obtain data which are the statistical averages of the temperature of an entire plane. Furnas (1930) suggests for example, that the only practical way to obtain an acceptable value for the temperature at any given position, is to force all the air passing a given plane in the bed through a small

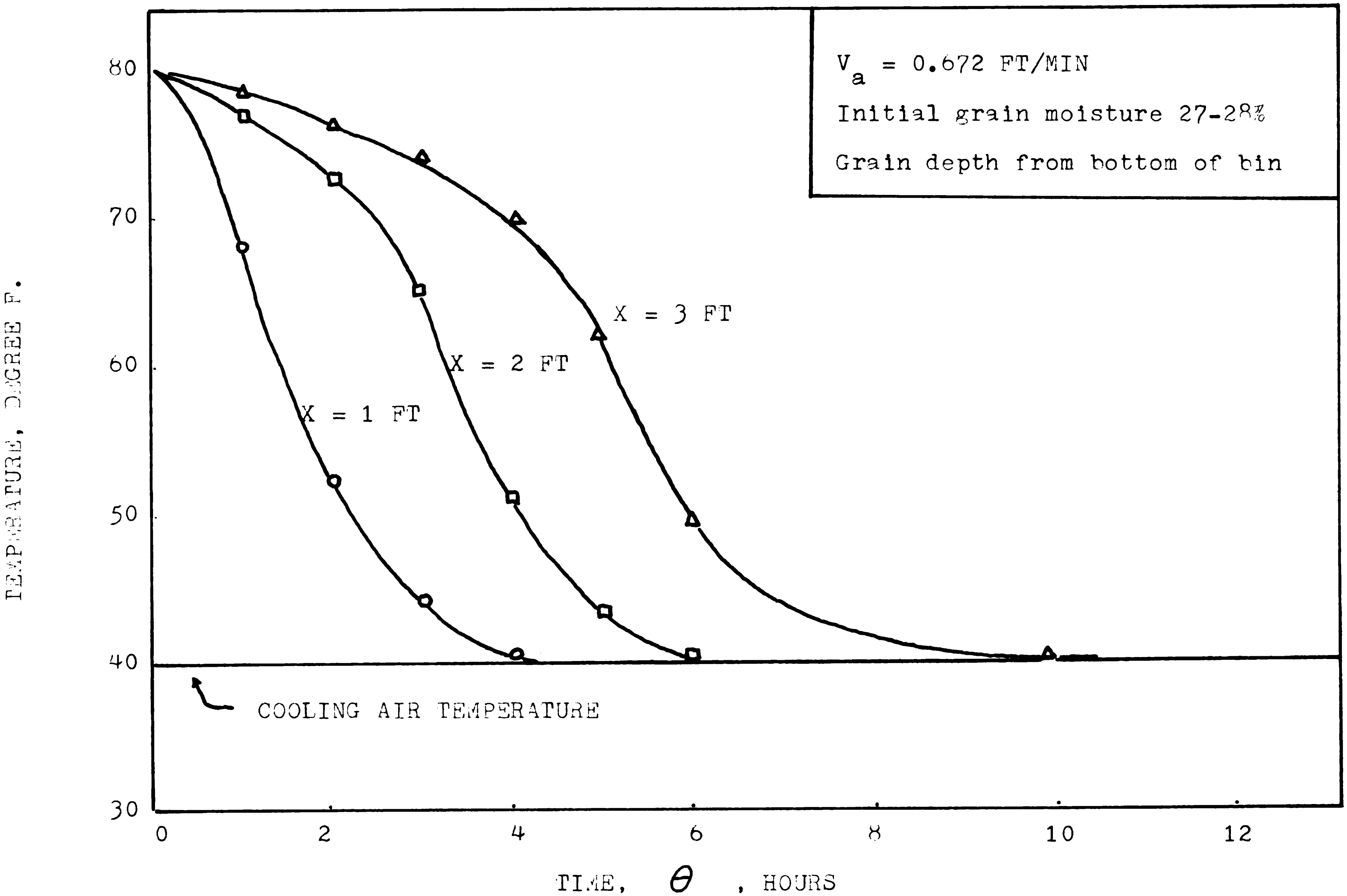

Figure 8a. Experimental Temperature History Curves.

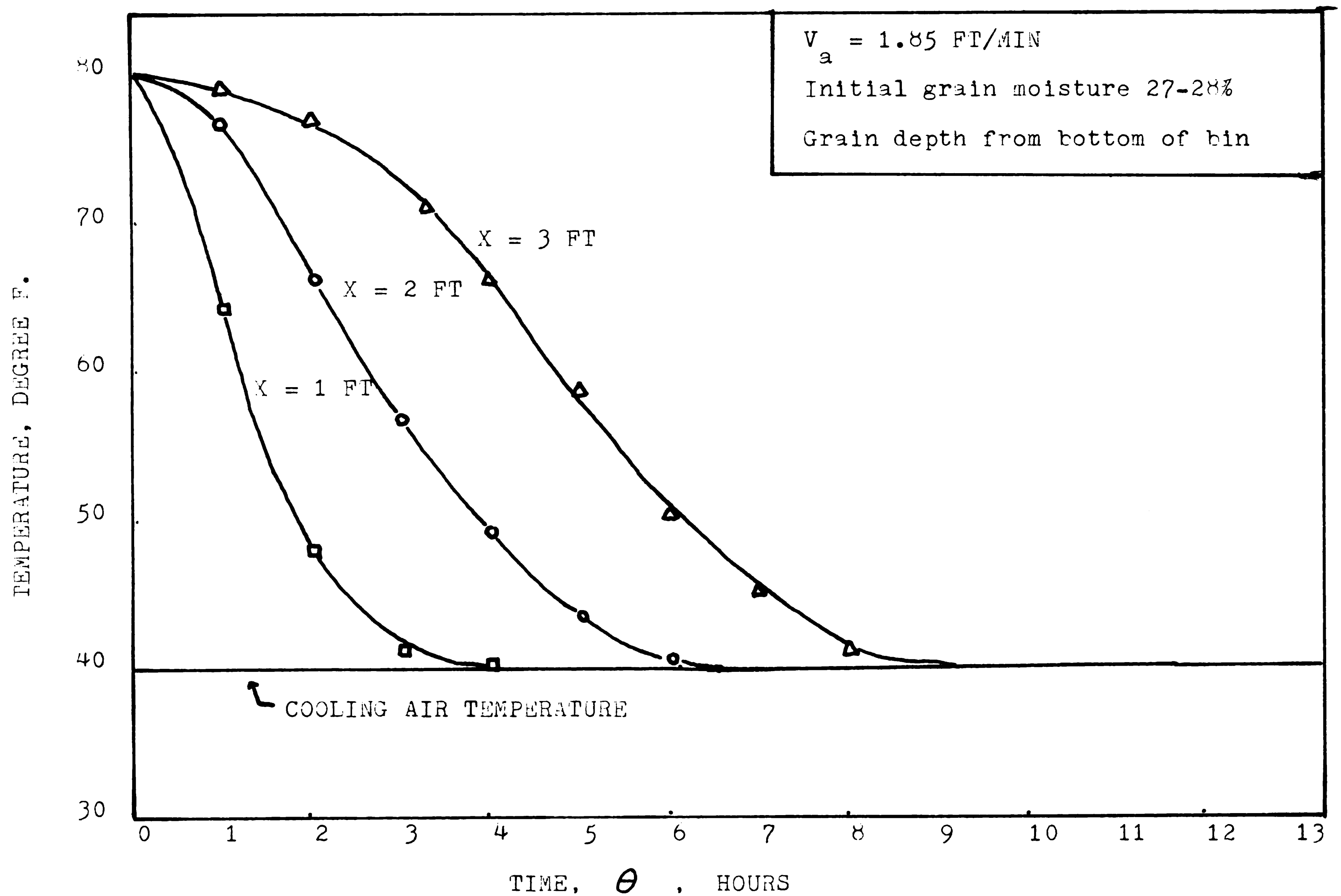

Figure 8b. Experimental Temperature History Curves.

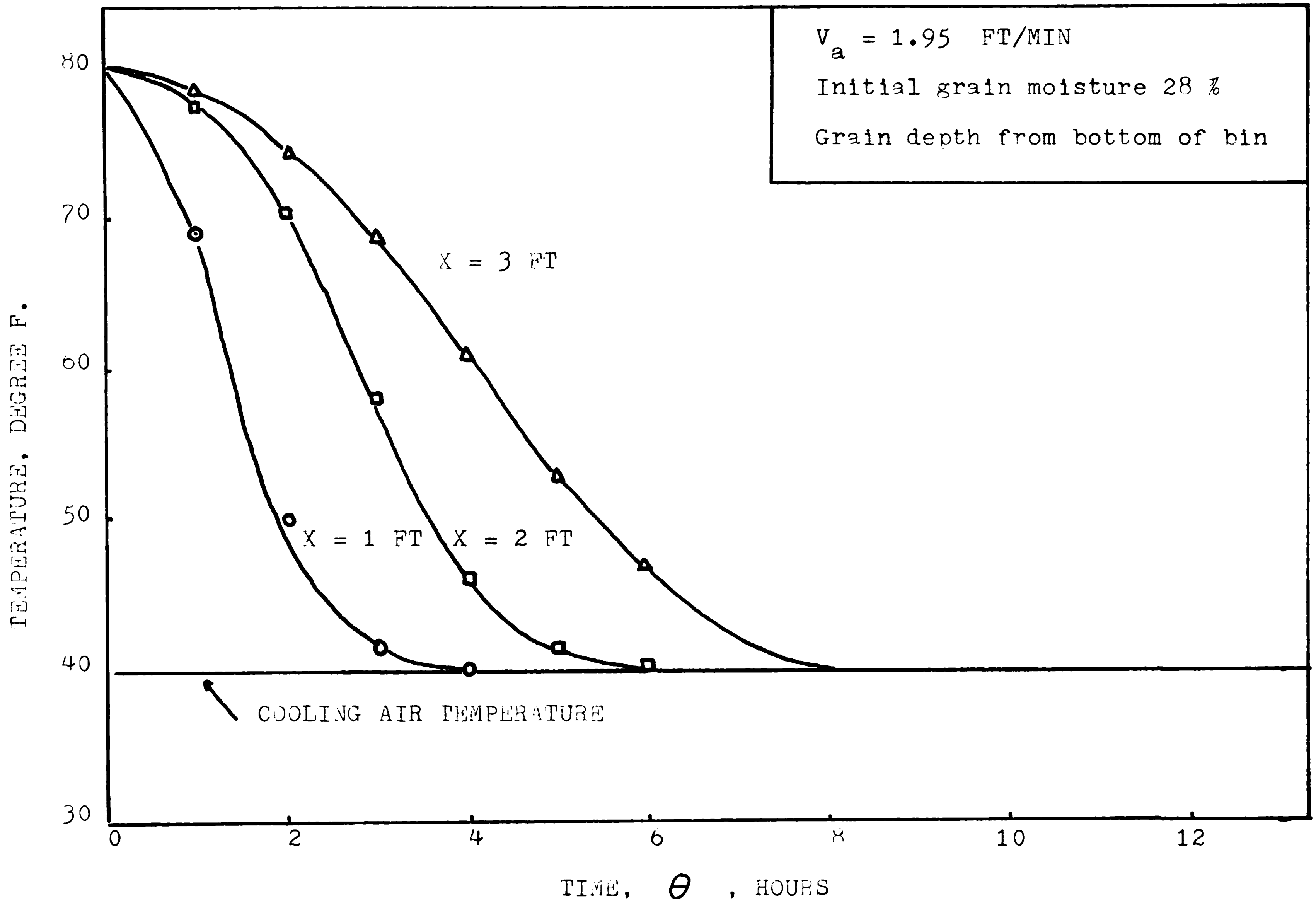

Figure 8c. Experimental Temperature History Curves.

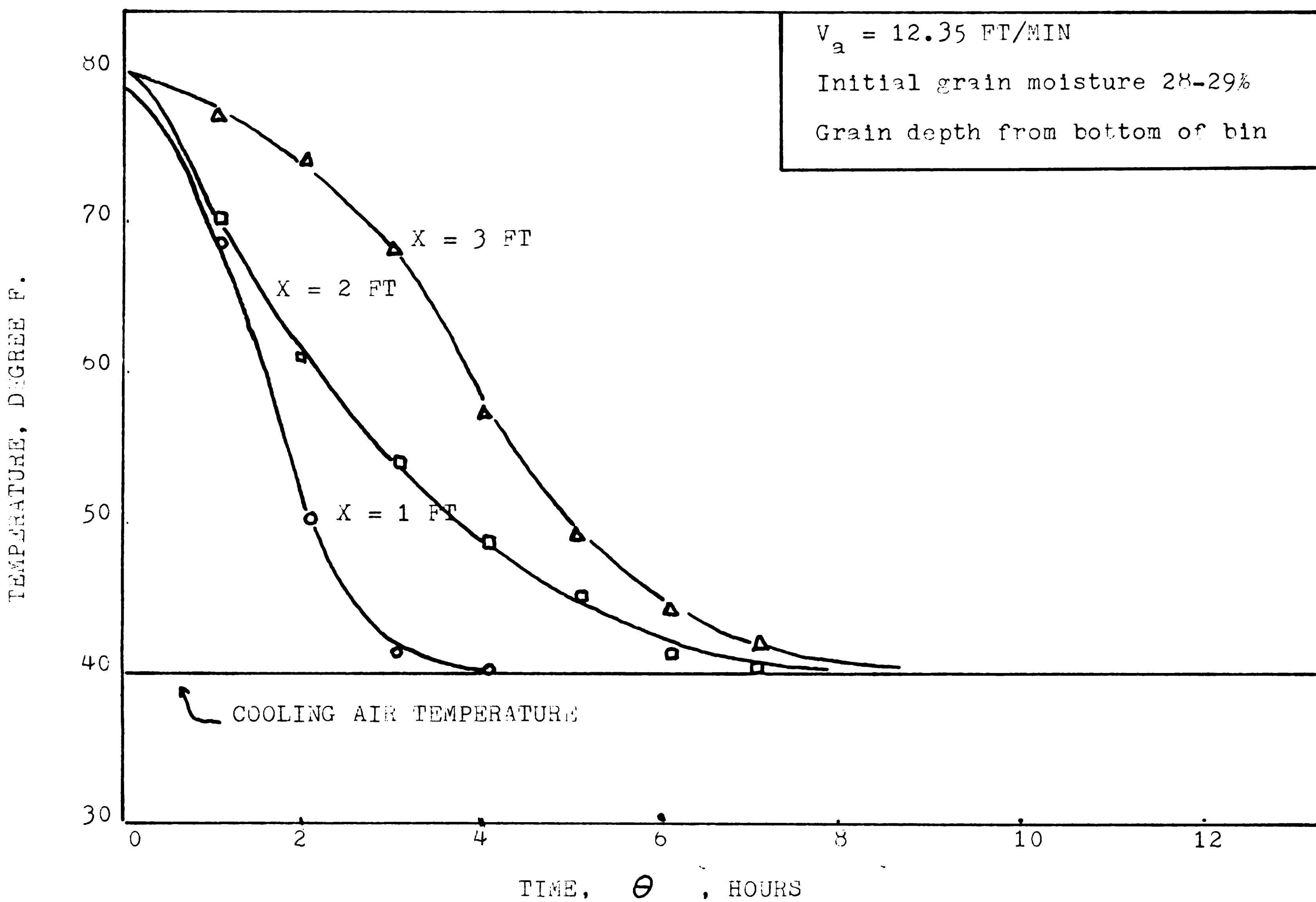

Figure 8d. Experimental Temperature History Curves.

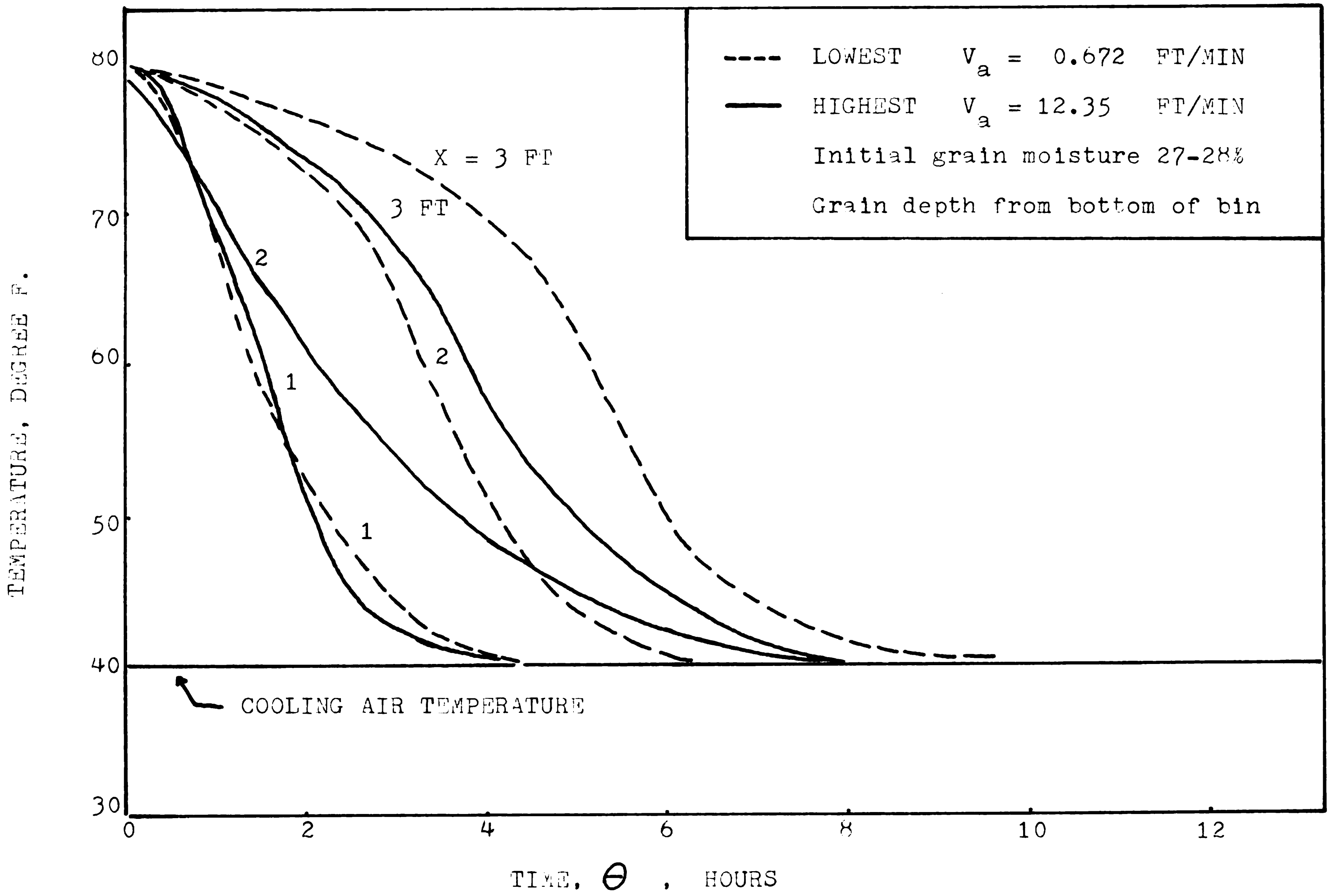

Figure 9. Comparative Plots of Temperature History Curves Between the Highest and Lowest Air Velocities (V_a).

CORN GRAIN
INITIAL GRAIN CONDITIONS:
79-80 F, 28-29% MOISTURE
AIR ENTERING GRAIN:
40 F DRY BULB
37 F DEW POINT
EQUATIONS FOR PREDICTING
COOLING TIME:

$$T_L = 0.48\ Q^{-0.15}$$

$$T_T = 3.22\ Q^{-0.32}$$

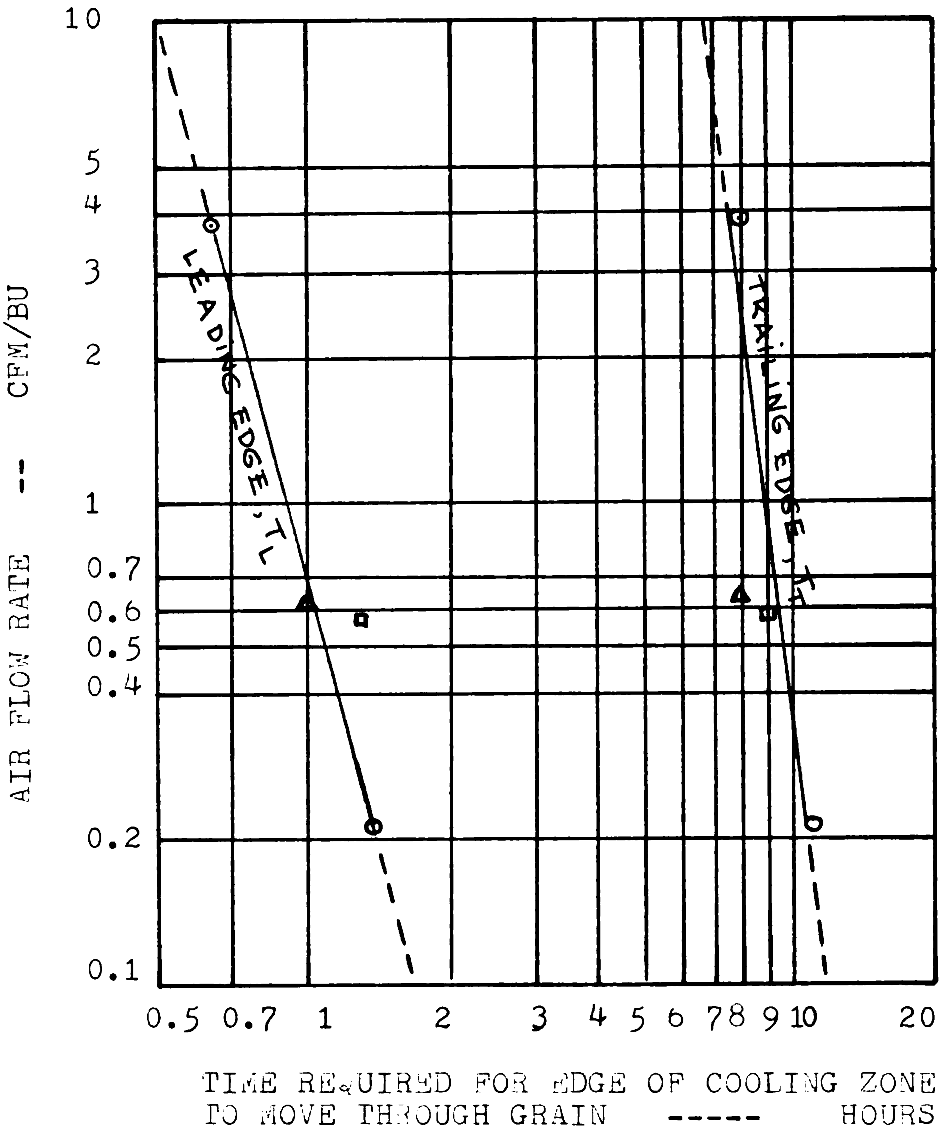

Figure 10. Cooling Time in Relation to Air Flow.

orifice and measure the temperature of this air stream.

The necessity for a uniform air velocity distribution in the bed has already been pointed out. This is very difficult to ensure, particularly for irregular beds. It is probable that the erratic nature of some of the data in Tables 1a, b, c, d may have resulted from a possible non-uniform interstitial air velocity in the stream.

Cooling first occurs where the air enters the grain and proceeds through the grain in the direction of air flow. The thickness of the cooling zone and the speed at which it can progress through the grain mass depends upon some function which describes the cooling rate of grain in relation to air velocity. After the front of the cooling zone has advanced through the grain, the air conditions leaving the grain will follow a definite pattern with time, depending upon the rate of air flow and the rate at which the temperature of the air surrounding the grain is changing.

Cooling times were decreased with increasing air flow for all depths of the packed bed (Figures 8a, b, c, d and 9) and the following relationship between temperature and velocity of the cooling air is presented:

$$T_L = 0.48\ Q^{-0.15}$$

$$T_T = 3.22\ Q^{-0.324}$$

where

T_L = time for leading edge to move through the grain, hours.

T_T = time for trailing edge to move through the grain, hours.

Q = flow rate of air entering the grain, CFM/bu.

The increasing agreement between the curves at low air flow rates is explained by the effect of Reynolds number on the heat transfer coefficient (Bakker and Bickert, 1966). At low Reynolds number, i.e., at low air flow rates, the heat exchange process proceeds with considerable slowness. The air temperature change with time is therefore slowed down and may become negligible at very low values of Reynolds number. A definite correspondence in shape is observed between the highest and lowest curves. This is expected since the equations on which the curves are based are identical. The difference is observed to diminish with decreasing air flow rates, but widens with increasing depths in the column.

The method that has been described here can be used to correlate experimental data, and predicting the cooling time. As the agricultural product situation departs further from the ideal, the accuracy of predicting cooling rates become less precise and finally the ability of the method to correlate cooling data is effected.

2. The effect of mass transfer:

Even though the experimental moisture data (Table 2) indicate only an average moisture loss of 0.4% (wet basis) in each test, the equivalent heat energy required to accomplish the transfer is substantial. This energy will be taken from the air and the product, leading to evaporative cooling.

Cooling a wet product by convection, such as cooling grain by passing chilled air through it, removes some moisture from the product. Assuming that the system is ideally insulated, that is any source of external heat is excluded, the heat for evaporating the moisture and heat for increasing the temperature of the air must come from the product. The moisture content of the product being cooled determines the degree of saturation of the air exhausted from the warm product.
As an example, the equilibrium relative humidity is nearly 100 percent for shelled corn having a moisture content in excess of about 22 percent, wet basis; and air exhausted from the corn will be nearly saturated. The theoretical capacity of air for cooling and removing moisture can be obtained from a table of the properties of moist air or from psychrometric chart. Assuming a value of 0.55 Btu/lb.^{o}F (Shove, 1966) for the specific heat of wet shelled corn, a satisfactory quantity of air for cooling corn from harvest temperatures of 60 to 80 ^{o}F would be one pound of chilled air per pound of shelled corn. Using a specific volume of 12.5 cu.ft/lb of chilled air, the air flow rate for cooling shelled corn in a 24 hours period becomes:

$$\frac{\text{(1 lb chilled air/lb corn) (12.5 cu. ft/lb chilled air)}}{\text{1,440 minutes}}$$

$$= 0.00868 \text{ CFM/lb. corn}$$

or approximately ½ CFM of air per bushel to cool shelled corn from harvest temperatures to 30 ^{o}F to 40 ^{o}F. The moisture content of the corn should be reduced by about one-half of one percent during the cooling period.

Moisture loss from the product during cooling increases the effective N_{Biot} number of the product slightly, because latent heat is absorbed from the product (Bakker and Bickert, 1966). The nature of the product will effect the rate of moisture loss.

All the corn samples used in these tests under the different air flow rates maintained their physical and biological appearances throughout the test. Corn quality is no different than when it was first loaded in the bin.

This study has attempted to cover some fact in the chilling of high moisture corn. It must be well remembered that this particular application of refrigeration is comparatively new and there is still a considerable amount of research to be done on the behaviour of corn when chilled at this low temperature.

At this moment it appears that the greatest application for this method is where a farmer is using the grain for feeding. There are however indications that millers are interested in holding large quantities of grain at low temperature, drawing from store as and when they require it for drying. By this means the miller can keep the drying operation under his own control.

SUMMARY AND CONCLUSIONS

Each year a greater amount of corn comes from the field in shelled form. Technological advances in harvesting, however, have caused problems to farmers and elevator operators because the large amounts of wet shelled corn harvested must be either dried or cooled quickly to prevent spoilage.

Wet, chilled corn can be stored for several weeks (Figure 1) without deterioration. Insulated storage will decrease the time that the refrigeration equipment will need to be operated to maintain the grain at a low temperature.

The following conclusions can be drawn from the study of the experimental temperature history data:

1. The fundamental irregularity in shape of agricultural grains together with the basic anisotropy of the bed constitute unavoidable sources of error in the analysis.
2. For agricultural products, the heating or cooling process is inevitably accompanied by mass transfer.
3. High moisture corns was cooled from 80 degree F to 40 degree F. The moisture content of corn, ambient temperature and airflow rate each affected the safe storage time. Data from tests were used for preparing graphs to show the inter-relationships among these variables.
4. When cool air is forced through a mass of grain, a cooling zone will develop and progress through the grain in the direction of airflow. The thickness of the zone and the speed at which it can progress through the grain mass

depends upon some function which describes the cooling rate of grain in relation to air velocity.

The time required to cool grain in storage is a function of the rate at which air is supplied through the grain. Equations for predicting the time required for a cooling zone to move through corn grain are presented.

5. The effect of evaporative cooling are very beneficial in reducing the time required to move a cooling zone through grain and in reducing the refrigeration load requirements for cooling. Foster (1965) states that the heat to evaporate the moisture comes from the grain and accounts for about half of the cooling. He also found that the air required for cooling the grain is reduced proportionally.

Even though the experimental moisture data (Table 2) indicate only an average moisture reduction of 0.4 % (wet basis) in each test, the moisture loss during cooling could be an advantage if the initial moisture content of the grain is higher than the desired final moisture content. Even if moisture loss is undesirable from the standpoint of excessive loss in weight, it is not considered a problem when grain is stored for a reasonable period of time. Tests have shown that the average moisture content can be re-established after the grain has been cooled by controlling the relative humidity of the entering air at the proper level.

RECOMMENDATIONS

1. From the experience gained, further study should be undertaken to further develop the relationship between cooling time, moisture content ratio, airflow, and temperature of cooling air and relative humidity with grains above 35 percent moisture content, wet basis.
2. With picker sheller grains are harvested at higher moisture content and work should be done on corn above 35 percent moisture content.
   a. Study the resistance to the airflow.
   b. Shrinkage problems.
3. The constants (Equations 3 for leading edge and 4 for trailing edge) developed in this study should be investigated further. While they were the fundamental relationship describing the manner by which the cooling zone will move for optimal airflow, they have not been yet correlated with quality factors in biological material, such as stress cracks in corn. Experimental investigation should be made to determine if any correlation exists between the time required to cool a grain and the quality of the product resulting from the process.
4. The author suggests for the next work to verify the importance of evaporative cooling. If the air temperature is a true indication of grain temperature, then the heat of evaporative cooling (ΔH) must be determined for the various conditions which are present in controlled storage environments for bulk grain.

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APPENDIX:

Table 1a. Experimental Temperature History Data:

Air Temperature = 40 F

V_a = 0.21 CFM/bu = 0.67 ft/min

Initial grain moisture = 27-28 %

Depth of Bed = 4 ft

	THERMOCOUPLE RECORDING (°F)				
TIME (hrs)	X = 0	X = 6"	X = 1'	X = 1'-6"	X = 2' **
0	80.0	80.0	80.0	80.0	80.0
1	40.0	53.0	68.0	73.0	77.0
2	40.0	40.0	52.0	63.0	71.0
3	40.0	40.0	44.0	53.0	65.0
4	40.0	40.0	40.0	46.0	51.0
5	40.0	40.0	40.0	41.0	43.0
6	40.0	40.0	40.0	40.0	40.5
7	40.0	40.0	40.0	40.0	40.0
8	40.0	40.0	40.0	40.0	40.0
9	40.0	40.0	40.0	40.0	40.0
10	40.0	40.0	40.0	40.0	40.0

** average of 5 recordings.

X = 2'-6"	X = 3'	X = 3'-6"
80.0	80.0	80.0
77.5	78.0	78.0
74.0	76.0	77.0
72.0	74.0	74.0
60.0	70.0	72.0
56.0	62.0	69.0
45.0	49.0	56.0
41.0	43.0	54.0
40.0	42.0	43.0
40.0	40.0	40.0
40.0	40.0	40.0

Table 1b. Experimental Temperature History Data:

Air Temperature = 40 F

V_a = 0.58 CFM/bu = 1.85 ft/min

Initial grain moisture = 27-28%

Depth of Bed = 4 ft

THERMOCOUPLE RECORDING (°F)					
TIME (hrs)	X = 0	X = 6"	X = 1'	X = 1'-6"	X = 2' **
0	80.0	80.0	80.0	80.0	80.0
1	42.0	44.0	64.0	70.0	77.0
2	40.0	43.0	48.0	61.5	66.0
3	40.0	40.0	41.0	43.0	57.0
4	40.0	40.0	40.0	41.0	49.0
5	40.0	40.0	40.0	40.0	43.0
6	40.0	40.0	40.0	40.0	40.0
7	40.0	40.0	40.0	40.0	40.0
8	40.0	40.0	40.0	40.0	40.0
9	40.0	40.0	40.0	40.0	40.0

** average of 5 recordings

X = 2'-6"	X = 3'	X = 3'-6"
80.0	80.0	80.0
78.0	79.0	79.5
70.0	77.0	78.0
63.0	71.0	72.0
54.0	66.0	67.0
47.0	58.0	59.0
44.0	50.0	51.5
42.0	45.0	54.5
40.0	41.0	41.0
40.0	40.0	40.0

Table 1c. Experimental Temperature History Data:

Air Temperature = 40 F

V_a = 0.61 CFM/bu = 1.95 ft/min

Initial grain moisture = 28 %

Depth of Bed = 4 ft

THERMOCOUPLE RECORDING (°F)					
TIME (hrs)	X = 0	X = 6"	X = 1'-0"	X = 1'-6"	X = 2'-0" **
0	80.0	80.0	80.0	80.0	80.0
1	54.0	54.0	69.0	76.5	78.0
2	40.0	49.5	50.0	60.5	71.0
3	40.0	40.0	41.0	52.0	58.0
4	40.0	40.0	40.0	40.0	46.0
5	40.0	40.0	40.0	40.0	41.0
6	40.0	40.0	40.0	40.0	40.0
8	40.0	40.0	40.0	40.0	40.0
10	40.0	40.0	40.0	40.0	40.0

** average of 5 recordings

X = 2'-6"	X = 3'	X = 3'-6"
80.0	80.0	80.0
78.0	78.0	78.0
73.0	75.0	78.0
61.5	68.0	72.0
50.0	61.0	61.0
44.0	53.0	53.5
42.0	47.0	49.0
40.0	40.0	40.0
40.0	40.0	40.0

Table 1d. Experimental Temperature History Data:

Air Temperature = 40 F

V_a = 3.86 CFM/bu = 12.35 ft/min

Initial grain moisture = 28-29 %

Depth of Bed = 4 ft

	THERMOCOUPLE RECORDING (^oF)				
TIME (hrs)	X = 0	X = 6"	X = 1'	X = 1'-6"	X = 2' **
0	80.0	80.0	79.5	80.0	80.0
1	40.0	40.0	69.0	70.0	70.0
2	40.0	40.0	50.0	54.0	60.0
3	40.0	40.0	41.0	51.0	54.0
4	40.0	40.0	40.0	48.0	49.0
5	40.0	40.0	40.0	43.0	45.0
6	40.0	40.0	40.0	40.0	41.0
7	40.0	40.0	40.0	40.0	40.0
8	40.0	40.0	40.0	40.0	40.0
9	40.0	40.0	40.0	40.0	40.0

** average of 5 recordings

X = 2'-6"	X = 3'	X = 3'-6"
80.0	80.0	80.0
74.0	77.0	78.0
70.0	74.0	75.0
66.0	68.0	71.0
52.0	57.0	63.0
47.0	49.0	53.0
43.0	44.0	46.0
41.0	42.0	42.0
40.0	40.0	40.0
40.0	40.0	40.0

Table 2. Summary of Laboratory Corn Chilling Tests (Moisture Reduction).

Air flow Rate CFM/bu	Cooling Temp. D.B. F	Air RH*) %	Corn Temperature (Dry Bulb) Initial F	Corn Temperature (Dry Bulb) Final F	Aeration time**) Hrs.	Grain Moisture reduction %
0.21	40.0	37	80.0	40.0	9	0.3
0.58	40.0	42	80.0	40.0	9	0.4
0.61	40.0	51	80.0	40.0	8	0.4
3.86	40.0	54	79.5	40.0	8	0.5

*) Relative humidity of Ambient Air.

**) Time needed when the corn nearest air exhaust was two-thirds cooled.

\- The moisture contents of the corns used in these tests were about 27 to 29 %, wet basis.