LAYER DRYING OF GRAINS IN STORAGE

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY

Anandrao Pandurang Deshmukh

1958

Presented to Dr. Carl W. Hall for his valuable help to me, during my stay in the United States

Dec. 2nd 1958

A P Deshmukh

LAYER DRYING OF GRAINS IN STORAGE

by

Anandrao Pandurang Deshmukh

AN ABSTRACT

Submitted to the School of Advanced Graduate Studies of
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

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Department of Agricultural Engineering

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ANANDRAO PANDURANG DESHMUKH ABSTRACT

The objective was to study the velocity, depth, and relationship of the drying layer to the moisture content ratio, air flow and temperature of drying air for shelled corn and pea beans in a deep bin. Three different air temperatures and four different air flows were used to study the velocity of drying layer and to find the lowest possible air flow for drying pea beans and shelled corn for the controlled conditions in deep bins.

The air flows used were 2, 6, 10, and 14 cfm per bu. and drying temperatures were 58 - 60, 72 - 74, and 86 - 88 deg. F. One inch diameter holes were provided six inches apart along the height of the bin for sampling.

The time required for drying shelled corn is less as compared to pea beans for a given initial and final moisture content. For shelled corn the lowest air flow that can be used for drying a bin of 6 feet is 3.5 cfm per bu. at 58 - 60 deg. F.

The velocity of 15 per cent moisture layer depends on air flow and air temperature. The velocity of 15 per cent moisture content layer is 2 inches per hour at 58-60 deg. F. and 6 cfm per bu. air flow, when the initial moisture content of the shelled corn was 35 per cent.

The depth of drying layer was defined and depends on initial moisture content of the grain, air flow, and air temperature.

The depth of drying layer was 31.2 per cent higher at 88 deg. F. than 74 deg. F., and 33.4 per cent higher at 74 deg. F. than at 60 deg. F. for shelled corn. Thus, at the higher air flow the temperature does not greatly affect depth of drying layer. At a low air flow of 6 cfm per bu. the increase in depth was 23.1 per cent at 88 deg. F. as compared to an increase of 30 per cent at 72 deg. F. over 60 deg. F. for shelled corn. Thus, the temperature difference is quite apparent at low air flows.

The time required to dry a given depth of shelled corn can be calculated from the following formula:

$$\theta = 173.8 - 1.39\,(t) + 8\,(m) + 35(d) - 13(q)$$

θ = time, hours

t = air temperature, deg. F.

$m = \log \dfrac{M - M_e}{M_o - M_e}$

d = depth factor, feet

q = air flow, lb. per sq. ft.

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DEFINITIONS

a	=	constant
b, c	=	coefficients of temperature and moisture content ratio
D	=	depth of grain bin, inches
D'	=	depth of grain dried below 15 per cent moisture content, inches
d	=	depth of drying zone, inches
d'	=	depth factor, feet
f	=	coefficient of depth factor
g	=	coefficient of air flow
M_e	=	equilibrium moisture content of grain, wet basis, per cent
M_o	=	initial moisture content of grain, wet basis
m	=	logarithum of moisture content ratio
Q	=	air flow cfm per bu.
q	=	lb. of air per sq. ft.
t	=	temperature of drying air, deg. F.
V	=	velocity of 15 per cent moisture layer, inches per hour
Θ	=	drying time, hours

INTRODUCTION

The proper drying and storing of agricultural products is an important problem today. Natural field drying which has been used for centuries is no longer practical because of heavy field losses. The value of grain as food to human beings makes the problem one of world wide concern. The request was made to the Food and Agricultural Organization, as a result of discussions at the International Meeting on Infestation of Foodstuffs held in London in August, 1947, to conduct a critical review of the methods of grain drying and storage in use in all parts of the world. This indicates the importance of the problem and is sure evidence of worldwide scope.

In Michigan there continues to be a trend toward fewer but larger farms. Labor scarcity is increasing the rate of farm mechanization on many commercial farms. Mechanization has solved many of the problems of farm operation. With increased production and inadequate drying and storage facilities, the Michigan farmer is facing the difficulties of drying and storage of grain.

The loss of production during harvesting is as high as 15 per cent in sorghum, 30 per cent in seeds of legumes; 8 per cent in storage of potatoes, sorghum 6 per cent, and storage loss as high as 45 per cent has been reported in corn by Hall (1957). Often weather prevents timely completion of harvest. When this happens, the farmer has to be very careful in operating a picker or combine. The harvesting loss of corn in October is 5 per cent as compared to that in November of 8.4 per cent and in December, 18.4 per cent. The estimated loss is $6.00 per acre in October, $10.00 in November, and $22.00 in December.

Too much food value is lost when the crop is dried in the field exposed to the elements of nature. In the United States it has been estimated by Hall (1958) that the losses between harvest and consumption of grain and hay amounts to 25 per cent of the total production, and this loss in fruits and vegetables increases up to 35 per cent. Both harvesting and storage losses can be greatly minimized by adaptation and proper management of sound drying practices. In the United States 10 per cent of the grain produced does not reach the market because of losses during harvesting and storage.

It is very important that the crops should be at proper moisture level in storage. This moisture content is much lower than the moisture content at harvest time. Recent studies have shown that crops harvested at a higher moisture content will have minimum field losses. For corn this moisture content is from 24 to 30 per cent; however, for safe storage of corn the moisture content should be below 13 per cent on wet basis. With higher moisture content the product has a higher rate of respiration and more heat is produced which is more harmful to grain. When a product of high moisture level is stored there is a condensation problem formation of mold growth, and grain insects. Naturally a method of removal of excess moisture is necessary in order to take care of harvesting losses and assure safe storage after harvesting at high moisture levels. Hall (1957) has estimated that approximately 95 per cent of the total losses of both grain and hay could be prevented through proper storage and drying and that a possible saving of 75 per cent of the total losses which occur during harvesting and storage could be realized by combination of early harvest and subsequent drying. This leads, hence, to the importance of artificial drying.

Today, high moisture grain is moved into the storage directly after harvest. In artificially dried hay as much as five times the amount of carotene is preserved as in sun dried hay. By frequent clipping from 40 to 60 per cent more protein can be obtained. A desirable combination would be frequent cutting of forage and subsequent drying. Storing wet hay may lead to spontaneous combustion. Hall (1957) has estimated losses of 20 million dollars from spontaneous combustion in the United States in 1950. Considerable damage occurs to the stored oat crop because excess moisture results in loss of vitality.

For drying grain, fans and dryers are coming into use and the demand for this equipment will continue to increase. The acceptance of the picker-sheller gives assurance against losses of crop, but at the same time it brings the problem of high moisture corn. If real benefits of artificial drying are to be achieved, a fundamental understanding of the drying process and variables involved in drying is necessary. Most of the investigation today has been concerned with finding immediate solutions for the present problems. There is not much work which has been devoted to the theoretical analysis of these problems. As a result the present design practice concerning grain drying and farm processing has remained largely dependent on experience and empirical data. The design of duct and drying installation for specified performance requires a thorough knowledge of the drying profile, fan characteristics, and basic laws pertaining to air flows.

The use of heated air for drying in deep bins has generally been unsatisfactory because of over-drying of the grain which occurs where the heated air enters the grain. This over-drying reduces the value of the crop to the farmer. When the farmer sells the crop on 13 per cent moisture content, wet basis, a moisture content of the grain below 13 per cent results in, the farmer selling dry matter for the price of water. In the drying process, decrease in moisture content is controlled by the drying characteristics of the grain. These characteristics are moisture content of grain, temperature, and relative humidity of drying air. The knowledge of these characteristics is essential in the design and proper management of drying equipment and processes. The amount of heat energy required for the drying operation is essential to the knowledge of the economy and efficiency of the process. During the last few years the drying of crops has been forced to increase the efficiency of operation in order to save the cost of fuel and provide uniformity of drying to the desired moisture content. It is difficult to evaluate the drying efficiency of a drying system by other than the approach of adiabatic heat balance. Usually the amount of heat energy required to vaporize one pound of water from grain is more than the amount of energy required to vaporize one pound of free water. This is due to the resistance offered by the grain body to moisture movement. Very little work has been done to find out how much heat is required for drying various agricultural products.

The pea bean is an important commercial crop in Michigan. In 1956, Michigan produced 5 million 100 lb. bags of pea beans which was 96.1 per cent of all pea beans produced in the United States and 93.3 per cent of the beans of all kinds produced in Michigan. The value of the pea bean in Michigan in 1956 was 33.4 million dollars. Pea beans are stored in bulk, and safe storage moisture content is 15 per cent on wet basis. The climatic conditions during harvesting are such that harvesting is usually carried out with beans above 18 per cent moisture content. For edible condition the beans must be stored at safe moisture content. About 60 per cent of the 1957 beans were stored on the farm and the present trend of storing pea beans in bulk on the farm is increasing. However, relatively few on-the-farm drying systems for handling pea beans are availalbe. Commerical drying installations in use are designed primarily for drying small grains. The need for forced unheated air or supplemental heat for drying pea beans is definitely increasing, and very little information is available that can be used as a basis for design and selection of equipment for drying pea beans. For storage of pea beans, artificial drying is necessary; however, artificial drying is difficult because pea beans crack when heated air is used for rapid drying.

Shelled corn is an important grain crop in the United States. The total area of corn was 65.5 million acres in 1957. The production of this crop in 1957 was 10 per cent higher than that of 1956. In 1957 U.S.A. produced 2330 million bushels of shelled corn and the net value of this crop was 4300 million dollars. Last year 69 per cent of the crop was stored-on-the farm whose net value was 3010 million dollars.

Total area of corn in Michigan was 1.714 million acres in the year of 1957 and the total production of corn was 102 million bushels. More than 36 per cent of the total production of the corn was stored on the farm. The total value of this stored corn was 43 million dollars. Thus, a substantial amount of corn is stored on the farm and, hence, the need for the study of drying and storage of shelled corn is increasing to minimize the storage losses.

The purpose of this work is to develop a more theoretical approach to the problems of grain drying. In order that a deep bin of grain may dry, heat must be transferred from the ambient air to the grain to supply the necessary latent heat for evaporation of the moisture. The moisture must diffuse out from the interior of the grain in liquid or in vapor. It is necessary to know the moisture gradient throughout the bin and air with respect to time.

The work has been established that the higher the moisture content of the grain, the lower the temperature to which it can be safely exposed for a given purpose. Safe temperature is much lower for seed for germination than for grain for milling into flour. No theory has been advanced to explain the variation in the rate of drying with differing air and grain depth conditions and it was therefore decided to study this matter experimentally. This type of relation is found with a number of substances but not much in agricultural products. No correlation has yet been suggested to explain the influence of air temperature and humidity, initial moisture content and air flow, on the rate of drying. Such analysis must be made in terms of either moisture content ratio or vapor pressure and there has been doubt which of these two parameters correctly describes the driving force for drying in the system.

A rigorous analysis has been presented which shows that the moisture content ratio of the grain is the correct physical potential to employ. From the present investigation it appears that the need was to gather data on practical performance of deep layer drying with various air flows and different air temperatures. These data are necessary for the design of drying and storage installations and recommending optimum air flows for the most efficient drying. Time element is a factor in layer drying and hence should be determined with reasonable accuracy. If only drying is wanted, then the minimum air flow rate for different localities and different grains should be established. Very little research work has been done on drying of pea beans and shelled corn in deep bins. More information is necessary for drying so that the drying systems may be properly designed for efficient and uniform drying. The movement of the drying layer has not been defined. The movement of the drying layer may serve as a basis for predicting the time required for drying a particular batch and the hazard due to overdrying and mold growth can be prevented.

Food Situation in India

In accordance with a booklet Indian Agriculture in Brief issued by the Economical and Statistical Adviser, Ministry of Agriculture Government of India (1957), total area of grain crops in India is 272.8 million acres and the annual production of grain crops is 88.7 million tons. The net value of the grain crops is 96.5 thousand million rupees (one rupee is equal to approximately $0.20). To meet various emergencies about 20 to 25 per cent of grains are stored in Central and State Government warehouses;that is about 17 to 22 million tons of grains of 19 to 24 million rupees worth, are stored in these warehouses.

In order to meet successfully the increasing demand, keeping an eye on the increasing population, much more stress has been put on agricultural development in the First and Second Five Year Plans. By the end of the Second Five Year Plan (1961) India hopes to achieve the agricultural production target of 104.5 million tons of grains. When this target will be reached more warehouses will be needed to store grains.

Most of the present storages are not designed and constructed on scientific basis. This leads to the loss of about 20 per cent of total stored grains and fodder. At present government purchases the grain on weight basis and normally moisture content of the grain is not looked into. Obviously, therefore, the farmers try to sell their product as soon as it is harvested. Thus, storage of high moisture content grains leads to losses due to mold and insects. Besides the grains are kept inside the gunny bags of 164.4 pounds of weight, which also adds to the improper ventilation and thus at the end the total losses may exceed even 50 per cent or more. Most of these warehouses are semi-circular in shape and 200 x 100 x 30 feet in size. They have concrete floors, masonary walls, and corrugated sheet metal roof. These warehouses have provided one door only. Inside these warehouses the gunny bags with grain inside are piled one above the other and stored for a period of six to nine months.

This gapping problem of putting an immediate stop to this loss to the national wealth has been receiving a serious consideration in the Ministry of Food and Agriculture. Thus, the principles of grain drying and storage is the only solution for this crying need of Indian Agriculture. By the use of the above principles 80 per cent of the annual losses in storages of grains and fodder can be saved.

From the above discussion it is clear that proper design of ducts and adequate construction of warehouses is needed in India. This will save considerable amount of money and the products. In 1957 India has imported 3.5 million tons of grains, which amounts to 4 per cent of the total annual grain production. Thus proper design of ducts and the bins will not only save the national wealth but also it will suffice the acute need of food.

OBJECTIVES

1. To study drying layer and its velocity and correlate the movement of drying layer, air flow and air temperature.
2. Define the depth of drying layer or zone in terms of initial and equilibrium moisture content of grain.
3. To find the minimum air flow for drying shelled corn and pea beans under the conditions studied.
4. Derive an equation to predict the drying time for a given depth of bin for shelled corn at given air conditions.

REVIEW OF LITERATURE

Drying crops with solar heat is an ancient method. This method has been unchanged, since the crop was first grown, but for the last hundred years crop drying performance has been improved. This method depends on sunshine but many times the sun fails to shine when it is needed to do its part in drying. Then the farmer does little but watch the daily deterioration of his crop in the field while each successive rain or wind makes the situation more hopeless.

This method is still largely used in under-developed countries like India. The use of solar energy offered considerable possibilities for drying agricultural products. Indian farmers are utilizing the solar energy for drying grains, turmeric, tea leaves, coffee beans, pepper, hay, fodder, fruits, vegetables, et cetera. Drying of the above agricultural products is done in thin layers and usually takes 4 to 6 days to dry during good drying season. Sometimes 4 to 6 sunny days are not available for drying and the occurrence of rain or heavy wind storms during the drying period is quite frequent. Thus the farmer has to move the products from the drying yard to a shelter to protect them from rainfall and heavy wind. With intermittent rainfall and sunshine, the operation of drying becomes laborious and time consuming.

For drying grains, the Indian farmer prepares a drying yard on which many times he first threshes and follows with the drying. In preparing the threshing yard he selects a piece of land free from wind obstacles from East and West sides since his winnowing depends on the natural wind velocity. The loose surface soil of this piece of land is scraped off with a shovel and distributed around the edge of the yard. Then the yard is filled with water to a depth of 3 to 4 inches, and allowed to soak for 24 hours. The next day the farmer covers the moist soil with more chaff and rolls it with a heavy roller until the soil is fairly compact. Then he covers the yard with chaff and allows it to dry slowly to avoid severe cracking. The solar energy reaching the earth in India varies from 400 to 600 Btu/hr/ sq.ft. The use of solar collectors is coming into use for drying of agricultural products.

Changing methods in crop harvesting are leading to the new design of crop drying installations. The first drying installation was built in 1850 in England for drying oats. This kiln was circular (Bailey, 1958) in shape and had a conical roof but later this was changed to a square one. The heating of the kiln was with charcoal and wood; later coal stoves used with simple or complex heat exchanger systems. A concrete hay dryer was built at Pennsylvania

State University by Fulmer in 1927. This dryer was unique in its plan and method of operation. The plant depends on artificial heat for operation and is supplied by burning cheap grade hard coal. Short cut hay was placed on a continuous chain conveyor which slowly carried over the inlet vents of the flue to the opposite end of the building, thus giving the alfalfa sufficient time to dry out on its journey from one end of the building to the other. This alfalfa was used as hay meal and was crushed into powder and sold to dairy and poultry farmers. The important feature of this dryer was low cost of construction and use of local materials available.

The Institute of Agricultural Engineers at Oxford developed the first crop dryer and little modifications were made at Purdue University. Aikenhead (1927) used gases of combustion mixing with air blown into the stack of alfalfa and soybeans, and reported that the larger stacks were greatly overdried and dried somewhat in patches. He also reported that the drying was faster in this case as compared with unheated air and gave assurance against losses suffered in the harvest season of 1926. Lehman (1926) built a portable dryer in 1926 to dry beans and indicated that for quick drying and for a minimum loss of grain, forced heated air is more effective. He estimated the drying cost was $5.00 per 100 lb. of water from 37 per cent moisture to 21 per cent moisture content.

After the second World War new mechanical harvesting equipments were devised and as a result, above 90 per cent of wheat, beans, and corn are now machine picked. It is estimated that more than 99 per cent of the 1957 crop was machine picked. Mechanized harvesting operation gives the greatest independence from seasonal labor. A continuous dryer directly coupled to the harvesting machine was developed in Washington State in the year 1951 and a five-pass counter flow conveyor was installed in England in 1955. More conveyors of a single-pass design were installed in Britain in 1957. At present, there are a large number of portable dryers on the farm. Most of them use fuel oil or gas for heating air. The current practice favors direct firing by furnaces burning fuel oil. Hall (1957) has reported that the thermal efficiency of heated air dryers is greatest for direct-type heaters, low air flow, high initial moisture content, high atmospheric temperature and thick columns of grain. He reported that the efficiency of an oil-fired direct heater runs about 34.6 per cent at 7.7 cfm per bu; for coal, about 17.2 per cent at 4.6 cfm per bu, and that the cost of fuel and power was $.05 per bu.

Between 1918 and 1932 fans came into general use and experiments on crop drying began to show the optimum drying air temperature and the use of higher air velocities than had been possible with natural draft. Thus, it enabled the more efficient use of drying installations and accelerated the development of the present day type. Hall (1957) has developed a method for rapidly and accurately determining air flow values in grain drying structures of non-rectangular cross section. Fans are used for drying grain with unheated forced air. At present, fans are mostly used in aeration of grain. Rabe (1952) has shown the primary objects of aeration, the rate of cooling grains and factors deciding the cost of equipment and installations. Hukill (1947) reported on mechanical ventilation of corn with air rate varying 0.5 to 1.2 cfm per bu and derived an equation for the cooling time. The cooling time is inversely proportional to the resistance offered by grain. The power requirement for the fan depends on fan characteristics and pressure loss through the grain. Hukill, Ives, and Hall (1945) have given an analysis of the procedure required to calculate the air pressure required for radial flow.

For shallow bed tests Simmonds (1953) found that most of the grain drying takes place in the falling rate period and none in the constant rate period. Simmonds developed the equations for thin layer drying of wheat on the basis of the total moisture content, the initial moisture content, the equilibrium moisture content of air, and drying time. He showed that the drying rate constant depends on physical properties of grain and the drying conditions. His approach is based on the average moisture content of the whole bin and vapor pressure difference between the vapor pressure of water at the mean grain temperature and vapor pressure of water vapor in drying air.

$$\frac{dw}{d\theta} = KgAm\ (Pg-Pa)$$

Simmons (1953) indicated that the air velocity is not as critical in thin layer drying as it is in deep layer drying. The rate of drying depends solely on the properties of grain at any air temperature. He also found that the rate of drying increases with rising air temperature and that the equilibrium moisture content correspondingly falls. Increasing relative humidity decreases the rate of drying, but the effect is much smaller than the effect of temperature changes. He did not make any effort to compare drying rates. The rate of drying of wheat is inversely proportional to the mean grain diameter over a given range.

Newton's equation of heating or cooling approach is based on the assumption that the surrounding air is at constant temperature and that the temperature difference between the drying air and grain is small. This equation is written as follows:

$$\frac{dt}{d\theta} = -k(t-te)$$

where k is heating or cooling constant, t is temperature in deg. F, in hours at time θ and te is external temperatur in deg.F. Hall (1957) has shown that the equation expresses a relationship between a function and its derivative. By substitution moisture contents (dry basis), for the temperature in the above equation, the equation is changed to moisture content ratio Hall (1957).

$$\frac{M-M_e}{M_o-M_e} = e^{-k\theta}$$

Bailey (1958) has derived an equation for thin layer drying of hops in kilns and shown that drying time is inversely proportional to the difference between vapor pressure of water at the temperature of drying air inlet and vapor pressure of water already present in the atmosphere. This drying time is directly proportional to the loss of water per square foot area per minute and explained by the same equation in terms of air speed in feet per minute leaving the hops. He analyzed the vapor pressure driving force in terms of pressure difference related to water at that inlet air temperature. His work is based on the adiabatic drying and higher air velocities.

Simmonds (1953b) proposed a method for predicting the rate of drying of wheat grain in beds 2 inch to 12 inch deep for air velocities 12 - 130 feet per minute and an average temperature of 70 - 170 deg. F. with accuracies of $\pm$ 10 per cent. In this method, drying took place entirely in the decreasing rate period. The behavior of decreasing drying rate period of wheat was described in terms of its average moisture content and he believed this relationships would be more valuable if the drying rate constant could be simply correlated with air conditions.

He proposed that the mean temperature to be used for predicting the performance of adiabatic dryers in the logarithmic mean temperature between the air temperature and its adiabatic saturation temperature. He showed from a moisture balance equation that the point of maximum rate of drying is proportional to the bed depth, and the rate of drying depends on mass velocity of air. Simmonds (1953) believed that a correlation of the rate constant with temperature would be sufficient for most practical purposes and considered that at any given temperature a certain fraction of molecules present in a system are capable of undergoing chemical reactions, diffusion, viscous flow, et cetera. He developed an equation for the variation of the rate constant with air temperature and worked out a method for predicting drying performance which is based on the drying constant and logarithmic mean temperature of drying air and wet bulb temperature. He suggested that the drying zone could be expressed in terms of drying percentage. Hukill's approach for analysis of deep layer drying: the computed relationship between drying time, grain moisture, and grain depth units have been generalized to make them applicable to the drying problem. In the equation of drying rate he makes use of the drying time unit which is half response time, moisture content ratio, and depth factor.

Henderson (1955) suggested a method for calculating moisture content of the deep bed at any given time. The solution is based on stepwise integration from one layer to the other. He divided the depth into several thin layers and made an assumption of uniform drying of each layer to carry out the procedure. He illustrated a table of calculations which gives the moisture content at any depth with various intervals of time. This method requires more time to calculate the results and is rather laborious. Ives (1957) showed an analysis for traverse time and drying time relationships in parallel and non-linear flow. His analysis is based on the mass balance of water removed per pound of dry matter, and air flow per pound of dry matter times the amount of water per pound of air.

THE INVESTIGATION

Part I

Procedure

This part of the research work consists of studying the effects of filling the bin in six layers at an interval of four days, and study the effectiveness of drying due to sucking drying air through the grain. The good drying weather of three weeks in October, 1956 was made use to dry the shelled corn and following two weeks heated air was used. The heated as well as unheated air was first directed to the wet grain and then through the remainder of the bin. This was done to avoid the over drying of the grain which is observed in the forced heated air drying systems. By making the use of good drying weather in October and with supplemental heat for drying grains it was believed that the drying would be economical and uniform as compared to the present methods of drying grains.

Shelled corn with average moisture content of 25-28 per cent, wet basis, was placed in the quonset-16 building. The total quantity of grain was approximately 2200 bushels. The corn harvested with picker-sheller and was hauled in tractor driven wagon and was transferred to an elevator and dropped inside the bin through the two hatch openings.

The first layer of shelled corn at 28 per cent moisture content covered the duct to a depth of one foot. After filling the first batch the suction or exhaust fan was started and was kept running throughout the entire experiment. Second and third layers of shelled corn were placed at 26.6 moisture content on October 15 and 19, respectively. The fourth layer was placed on October 25, 1956, at 25 per cent moisture content. The fifth layer was placed on October 31 and layer sixth was placed on November 10, 1956 to bring the total height of the bin six feet above the duct.

On the first of November 1956 the heater was started and heated air was sucked through the depth of six feet shelled corn. The temperature of the heated air was maintained at 115 deg. F. until the last three days of the test at which time the temperature was set at 140 deg. F. Samples were taken by means of auger sampler and moisture content of the samples was determined by Tag-Heppenstall electrical resistance moisture meter. The static pressure drop was measured with a tap at the end of the duct opposite the fan.

Apparatus

The quonset-16, 28 feet long with a 4 foot additional workroom a plywood bulkhead forms one end of the bin, was equipped with aduct which was 54 inches wide and 30 inches high. The duct was semi-circular in shape and was covered with 16 mesh screen to avoid the falling the grain inside the duct and making the duct perforated to facilitate the air movement through the grain. The floor of the bin was made of concrete and walls were made of double corrugated sheet metal of galvanized iron. The bin had a sliding door in front as shown in Figure 2. An Aerovent fan, No. 58882, propeller type, with a three horse power motor was used for exhausting the air from the bin. The fan was placed at the rear side of the bin. A Campbell crop dryer, model 11019 with an air flow of 14,000 cfm at 1.5 static pressure was used for heating air using No. 1 fuel oil.

Discussion and Results

With good drying weather of three weeks in October, shelled corn was dried from 28 per cent to 12 to 14 per cent moisture content within four days after drying began when the height of the corn was one foot above the duct. After putting the third layer of shelled corn in, the moisture content of the first or bottom layer was increased 22 per cent. This was due to the fact that the air with high relative came in contact with the bottom layer from the top wet shelled corn. This resulted in the absorption of moisture by the dry grain from the humid air. The moisture gained by the bottom layer was only on the outside surface of the grains and was removed much faster than the moisture content at the center of the kernels.

Fig. 1a. Filling the bin with shelled corn through hatch openings

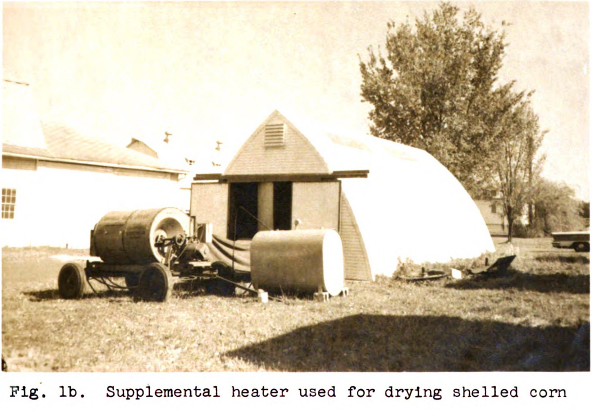

Fig. 1b. Supplemental heater used for drying shelled corn

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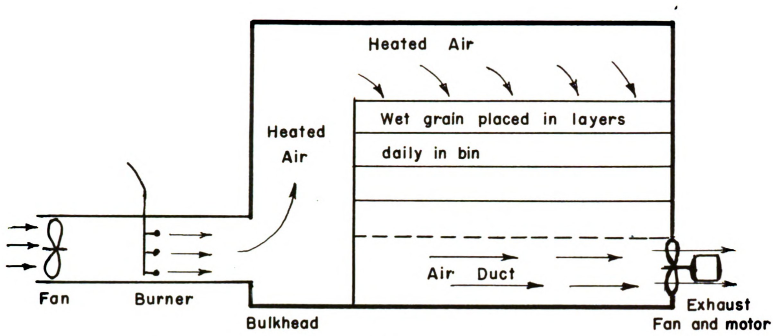

QUONSET BIN

FIG. 2 ARRANGEMENT FOR OBTAINING MORE UNIFORM DRYING OF SHELLED CORN. HEATED AIR DIRECTED TO WETTEST GRAIN FIRST.

As the height of the corn was increased, the drying of the bottom layer was delayed. The moisture content of the bottom layer was as high as 26.6 after adding five to six feet of corn and pulling unheated air through the grain of a high relative humidity during periods of intermittent showers. The moisture content of the bottom layer was increased as much as 6 per cent over a period of 24 hours after the addition of wet corn on the top of the previous layers. During the period of high humidity, the moisture content of the layers was increased with the greatest increase being on the top layer when using unheated air. When heated air was used, there was considerably more uniformity in moisture content of the bin. A variation in moisture content from the top layer to the bottom layer was approximately 3 - 4 per cent when the top layer was dried down to 12 per cent or below. If heated air had been used from the bottom, the variation in moisture content would have been considerably greater. During the sixteen days of heater operation 700 gallons of No. 1 fuel oil were used. During the period of the experiment, the exhaust fan was operated 960 hours, using approximately 2000 kwh of electricity. The estimated cost of drying for fuel and electricity was about six cents per bushel for drying from about 28 per cent moisture content to from 8 - 12 per cent moisture content for 2200 bushels based upon 14 per cent moisture content.

The moisture content in the corner of the bin was approximately 4 per cent higher than that of moisture content above the duct. With heated air, the variation across the bin was only 1 per cent above the grain over the duct.

Conclusions

1. Moisture content of the grain at the bottom layer next to the duct increased as much as 10 per cent when high moisture layer was placed over it and the grains were dried with unheated air.

2. The moisture content of the bottom layer was increased only about 1 per cent when heated air was used for drying the wet layer placed over it. The dry layer just under the wet layer only gained about 2 per cent moisture content when heated air was used for drying by this methos.

3. While operating the fan during rainy weather, the moisture content of all layers increased from 3-5 per cent.

4. The cost of drying was 6.1 cents per bushel for electricity and fuel oil for removing moisture from 25-28 to 10-12 per cent moisture content.

5. By using a heated air unit into the top of the bin down to the grain heating the wet grain first and exhausting the air from the bin provides an excellent means of drying high moisture corn in the fall when the weather conditions are generally unfavorable for forced air drying without over drying part of the grain.

Part II

Apparatus

The experimental apparatus was constructed for the purpose of measuring the velocity of the drying layer in deep bin of grain. The drying bin was, therefore, constructed so that the samples could be taken without disturbing the bed. The general layout is shown in Figure 3.

A refrigerated box of 40 cubic feet capacity was a source of incoming air. The box maintained a reasonably constant temperature and a constant relative humidity. A backward curved centrifugal fan was used to force air from the refrigerated box to the heater box where the air was heated by means of an electrical resistance heater. An 8 inch wooden square pipe was used to connect the fan to the heater box to minimize the frictional loss. A sliding door was used at this entrance of the heater box to control the air flow. The air was heated 14 deg. F. and its relative humidity reduced from 12 - 20 per cent depending upon the incoming temperature,relative humidity of air. On the exit side of this box, another sliding door was provided to check the air flow nearest. The temperature of the air was regulated by means of a bimetallic thermostat located in the

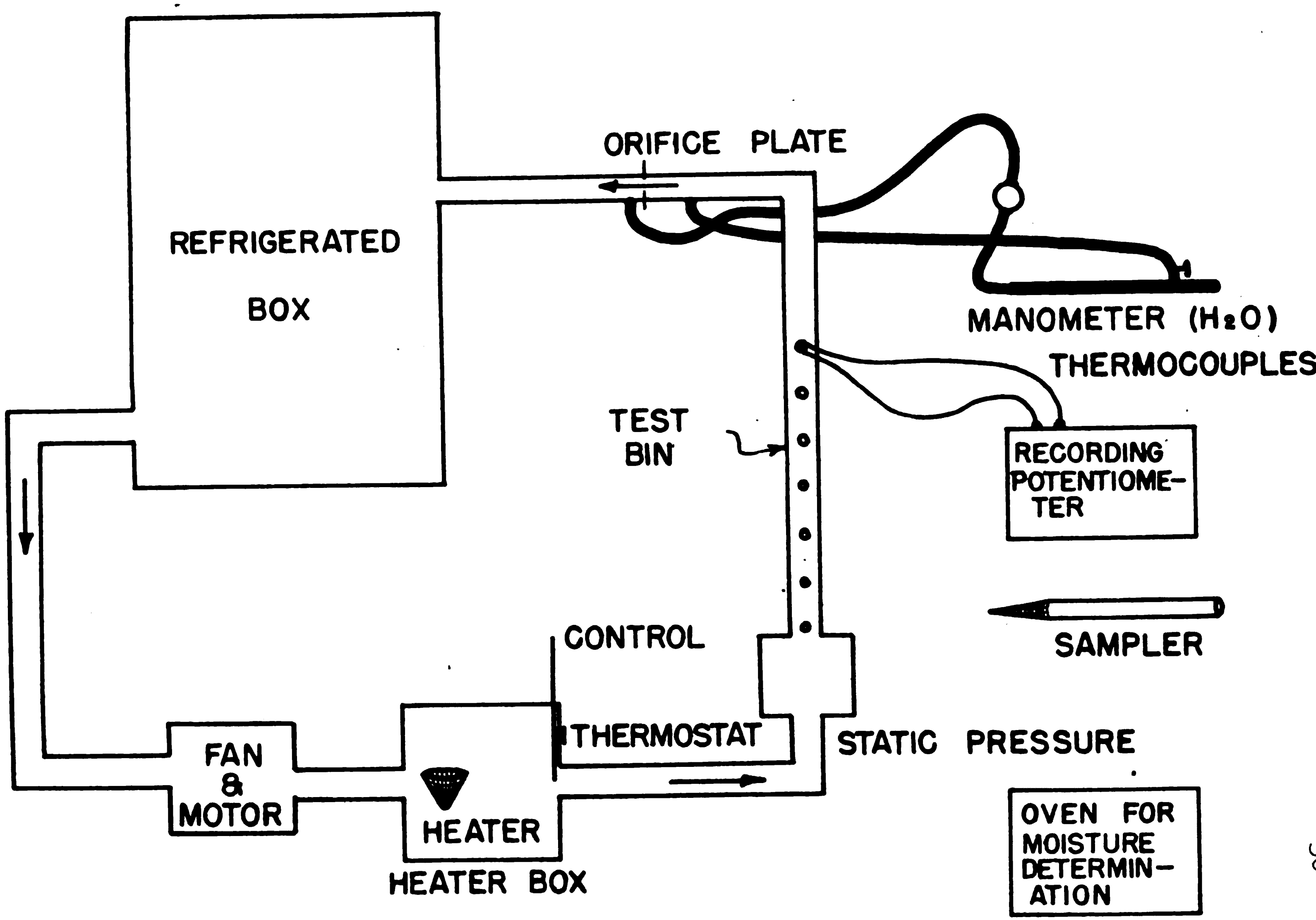

FIG. 3 APPARATUS FOR LAYER DRYING OF GRAIN

heater box. From the heater box, air was forced through a 3 inch insulated steel pipe to the equalizing box to assure uniform air flow through the grain. From this box air traveled through the grain and returned to the cooler.

A round bin was used for this test which was constructed of steel with 4 inch outside diameter, .0625 inch thick and 42 inch height. One inch diameter holes were provided along the height of the bin, 6 inches apart for sampling. The bin was insulated with asbestos for adiabatic drying. A false floor was made with screen wire having 10.5 x 10.5 inch mesh, and 16 gage wire was used to support the grain and established a plenum chamber 12 inch x 12 inch x 12 inch under the perforated floor. The bin was filled to a depth of 42 inches with a full capacity of 0.24 bushel. Air flow was measured by means of an orifice plate with a differential manometer. This orifice plate was located on the exit side of the grain, and the outlet air was moved through the orifice plate back to the cooler where it was cooled and moisture was condensed on the cooling coil. The orifice plate was calibrated from the formula of $Q = 4000\ CA\sqrt{P}$ which was taken from the Buffalo Fan Engineering Book. Dry bulb and wet bulb temperatures were measured and recorded with the thermocouples and recording potentiometer. The pipe joints were sealed with masking tape to insure against air leakage throughout the system. An .025 inch diameter tube sampler was used to obtain uniform samples from the cross section of the test bin. The power required to move air through the grain was taken from a one horse power, 220 volt, 3 phase electrical motor. The static pressure drop was measured with tap and water manometer.

Procedure

Because of the difficulty in obtaining and handling the large quantities of grain necessary to fill a grain bin up to 6-7 feet, a laboratory size test bin was constructed. With this bin, variables such as temperature, air flows, and relative humidity were more accurately and readily controlled than in a regular storage bin. Wet pea beans having moisture content of about 21 per cent on wet basis, which were harvested in the fall of 1956, were stored in 100 pound bags in a 40 deg. F. box. Pea bean bags were obtained from the Michigan Bean Company, Saginaw, Michigan.

Due to wet harvesting conditions in the Fall of 1957, shelled corn was harvested at 35 per cent moisture content, wet basis. The total amount of corn required was 8 bushels. This moisture content was too high to store in a 40 deg. F. box; therefore, it was necessary to store the corn in a zero deg. F. box. Before starting the drying test it was necessary to defrost the frozen grain. The corn was allowed to defrost in 40 deg. F. box for three days in a polyethylene bag to avoid the loss of moisture from the top surface. The corn was well stirred 3-4 times during the defrosting period. The test bin was filled to 42 inches in height and was insulated with 0.5 inch asbestos insulation. The bin was filled by a method called pack filling. This method consisted of pouring the grain into the bin 6-12 inches deep with the use of a funnel and then tapping the bin wall to settle the grain. This was done to measure the loss in volume of the bin during the drying operation. The bin was weighted empty and with grain to an accuracy of 0.125 pound. The bin was then fastened on the equalizing box with four bolts. The pipe was covered with insulation, thermocouples were inserted at proper locations and the bin was capped with 3 inch pipe which carried air to the cooler. All joints were made air tight with masking tape. After making sure everything was properly adjusted, the fan was started. The fan was operated continuously until the drying was completed. The drying was completed when the top layer of the bin was below 12 per cent moisture content, wet basis. Total air flow through the grain was measured by a sharp edged half-inch orifice in a thin plate mounted in a 3 inch pipe. A well-type inclined tube water manometer was used to measure the pressure drop across the orifice plate. Air flows of 2, 6, 10, and 14 cfm per bushel were used for drying the grain, and drying temperatures were 86-88 deg. F., 72-74 deg. F., and 58-60 deg. F. Grain samples were taken at various time intervals depending upon the rate of drying, but at the end of 2, 6, and 10 hours for the first day of drying.

A methód was developed by which a sample could be removed without disturbing the rest of the bed or altering its drying characteristics. The type of grain sampler used in this work is shown in Figure 4a. The sampling unit consists of a 1 inch diameter pipe, of which one end was tapered, and a 4 inch long and 0.25 inch wide slit was made to catch the grain sample. When a sample was to be taken, the insulation was removed from the test bin, the masking tape was taken off from the sampling hole, and the sampling probe was inserted in the grain with the slit up side down. After making sure that the sampler was touching the other side of the bin, it was turned up to get the sample from the entire width. When samples were to be taken, the fan was stopped, the temperatures were recorded with the recording potentiometer, and it was made sure that the desired air flow was coming. In using this technique the moisture distribution in the bin up to 42 inch depth was determined. Moisture determination was made in an air oven heated by electricity at 212 deg. F. for 72 hours. The average weight of the sample was 4-6 gm and approximately 7-8 samples per test were taken. Thus, a series of tests were carried out on a bed 42 inches deep with different air velocities and different air temperatures for pea beans and shelled corn.

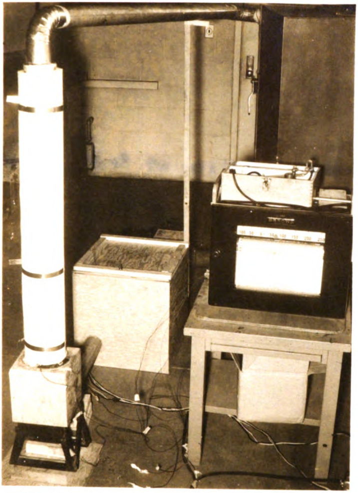

Fig. 4a. General view of the test equipment

Moldy corn Good corn

Fig. 4b. The mold growth on shelled corn

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Discussion and Results

Pea beans. In these experiments three different temperatures and four different air flows were used. Temperaturs were 58 - 60, 72 - 74, and 86 - 88 deg. F. Drying first occurs where the air enters the grain and proceeds through the grain. If the bed of grain is deep enough the air flowing through the bed will become saturated before it leaves, and saturation continues until the zone of vaporization reaches the top of the bin. At this stage the rate of drying decreases and this phenomena is independent of the actual mechanism of drying since it depends only on the moisture carrying capacity of the air. As air moves through the grain it picks up moisture and heat of respiration. Thus, the relative humidity and temperature of drying air increases and when this warm and humid air comes in contact with cold grain condensation takes place, usually on or near the top of the bin.

For the above tests, wet pea beans harvested in Fall of 1956 were stored in 40 deg. F. box to prevent the formation of mold. The condensation was more at low temperatures and low air flow such as 2 cfm per bushel than higher air flows. The condensation took place in upper 6-12 inch layers, and was noticed in less than 40 hours at 2 cfm per bushel air flow. At 6 cfm per bushel air flow condensation took place 12 inches from top and was observed in less than 10 hours. This condensation is a familiar phenomena which is observed during grain drying, with unheated and heated air. During the night air the temperature of the air drops and as a result the air reaches the dew point temperature.

In these tests for drying of pea beans at constant temperature and constant relative humidity, decrease in drying rate towards the end of the process has been observed. This is shown in Figures 21-31. At higher air flows, such as 14 cfm per bu. and 74 deg. F. air temperature, all layers were dried below 12 per cent moisture content and the top layer was only 1.6 per cent higher in moisture conetnt than the bottom layer. This variation was 1.7 per cent moisture at 58-60 deg. F. and 3.2 per cent moisture at 86-88 deg. F. for the same air flow. This indicates that as the temperature of the drying air was increased the difference between the moisture content of the top and bottom layer was increased. It is also evident that for given conditions the effective drying time was shorter with slight increase in air temperature, but this was not evident with air flows between 2 to 6 cfm per bu. At 10 cfm per bu. air flow and at 72 deg. F. air temperature the time required to dry the grain below 12 per cent was 76 hours and the difference between the top and bottom layer was 2.75 per cent moisture content. The time was 85 hours at 58-60 deg. F. and 46 hours at 88 deg. F. with 2.3 per cent difference in moisture content of the top and bottom layers. At 6 cfm per bu the difference was 3.6 at 58-60 deg. F., 4.2 at 72-74 deg. F., and 5.3 per cent moisture content at 86-88 deg. F. air temperatures.

As the temperature of the drying air was increased the uniformity of drying bin was decreased. Using air temperature and high air flow rate, the uniformity of drying was obtained. At 6 cfm per bu. the condensation near the top was observed in less than 10 hours. The drying rate was much faster for the bottom layer in contact with the entering air and the rate was less with the successive layers in the bin. The air flow of 2 cfm is not enough for drying grains in deep layers. For beans mold did not occur at 86 to 88 deg. F. and 2 cfm per bu. air flow because the beans were at a lower moisture content.

At a low air flow of 2 cfm per bu, due to the low drying potential, the drying rate was slow and the total time required to dry the whole bin was longer than the other air flows. In this the condensation was much more predominant and occurred in the top two layers thus the top two layers had the same drying rate. At 2 cfm air flow and 72-74 deg. F. air temperature, it took 32 hours for the bottom layer to dry from 20 per cent moisture content to 12 per cent moisture content, and 200 hours for the top layer.

The lowest air flow for drying pea beans is 6 cfm per bu. at 72-74 deg. F. and 66 per cent relative humidity, as shown in Figure 26. The 2 cfm per bu. is too low an air flow and it results in considerable amount of condensation. For drying 42-inch depth required 8-9 days. It is often obvious that recommended time for drying a bin of 42 inches deep under East Lansing conditions will not always meet the requirements of the other conditions. This point is pertinent because the drying time is selected on the basis of air temperature and at a nearly fixed relative humidity.

For a bin of 6 feet depth the time required to dry will be 16-18 days. The time for drying may be longer if the temperature of the drying air is lower with higher relative humidity. Time element is an important factor in layer drying and, hence, should be determined with reasonable accuracy. If good drying is wanted then the minimum air flow rate for different localities and for different grains should be established. At 6 cfm air flow it took 3.5 days to dry the same bin at 72-74 deg. F., 3 days at 86-88 deg. F. and 6 days at 58-60 deg. F. from 20 per cent moisture content to 12 per cent.

From the above discussion a relation has been established for 15 per cent moisture layer and different air flows. With increased temperature and air flows the velocity of 15 per cent layer increases, as shown in Figure 6, and expressed in the following equation

$$V_1 = V_2 \left(\frac{Q_2}{Q_1} \right)^{-.54}$$

Where

V_1, V_2 = velocity of 15 per cent moisture layer inches per hour

Q_1, Q_2 = air velocities cfm per bu.

One of the major objectives of the work is to define the drying layer or drying zone. For the purpose of the discussion the drying layer is defined on the basis of initial and equilibrium moisture content of grain. The drying layer extends between initial moisture content minus 2 per cent and equilibrium moisture content plus 2 per cent, and also initial moisture content minus 4 per cent to equilibrium moisture content plus 4 per cent moisture content (Table 2). The relationship between air flows and moisture variation within the bin, and the time required to dry the bin is shown in Table 1. This thickness was increased as the air flow was increased for a given condition of air flow. At higher air flows the drying layer has ~~has~~ more depth than at low air flows (Table 2). Also at the higher temperature, the depth of drying layer is more than at lower temperatures (Table 2). This difference was significant even though there was only 14 deg. F. temperature difference in the incoming air used for drying. The movement of the drying layer can be noted from Figures 6 and 7. The lines on Figure 7 indicate the moisture content at various locations in the bin. The distance between moisture contours can be used to visualize the drying layer. It is evident from these figures that the lines become farther apart as the

TABLE 1. Drying pea beans with different air flows.

Air Flow cfm per bu.	Difference between moisture content of top layer and bottom layer, when all layers were less than 12 per cent moisture content.	Time required for the top layer to come to 12 per cent moisture content or below, hour.
At 72 to 74 deg. F. and 58 to 66 per cent relative humidity		
14	1.6	less than 70
10	2.75	76
6	3.0	80
2	4.2	more than 140
At 85 to 88 deg. F. and 32 to 44 per cent relative humidity		
14	3.2	42
10	4.0	46
6	5.3	70
2	6.49	120
At 58 to 60 deg. F. and 58 to 70 per cent relative humidity		
14	1.7	70
10	2.3	85
6	3.6	115
2	3.8	170

TABLE 2. Depth of drying layer, inches, at various air flows and three different temperatures.*

Temp.	Drying Layer	14	10	6	2
85 to 88	M_e + 2% to M_o - 2%	more than 42"	36"		9"
85 to 88	M_e + 4% to M_o - 4%	36"	20"	5" condensation effect	8"
72 to 74	M_e + 2% to M_o - 2%	33"	29"	18 to condensation 30"	15"
72 to 74	M_e + 4% to M_o - 4%	12"	9"	4"	3.6"
58 to 60	M_e + 2% to M_o - 2%	26"	20"	20"	20"
58 to 60	M_e + 4% to M_o - 4%	9"	8"	6"	4"

*Initial moisture content 21 to 22 per cent, w. b.

time increases which means an increase in drying depth. Figure 6 shows the velocity of 15 per cent moisture content layer in the bin. As the air flow was increased the velocity of this layer was increased. The change of velocity of the drying layer is moved from 2 to 6 cfm per bu. air flow after which it decreases.

If we compare the rates of 88 deg. F. and 74 deg. F in Figure 6, it appears that the variation between these two velocities is small as compared to the variation between 74 deg. F. and 60 deg. F. for the same degree of temperature difference of the drying air. After 6 cfm per bu. air flow these lines begin to level off which indicate that the velocity of drying layer becomes a constant.

Figure 5 indicates the amount of water removed per bushel of pea beans at various time intervals. The distance between 2-6, 6-10, or 10-14 cfm per bu. air flow lines decreases with the increased air flows. This also shows that the drying rate does not double with the application of twice the air flow, at the same air temperature and relative humidity. It also gives an indication of average moisture content of the whole bin at a given time and for a given air flow.

Figure 6 gives the velocity of 15 per cent moisture layer at various temperatures. In this analysis 15 per cent moisture layer is used because the safe storage moisture content for pea beans is 15 per cent. At 4 cfm per bu.

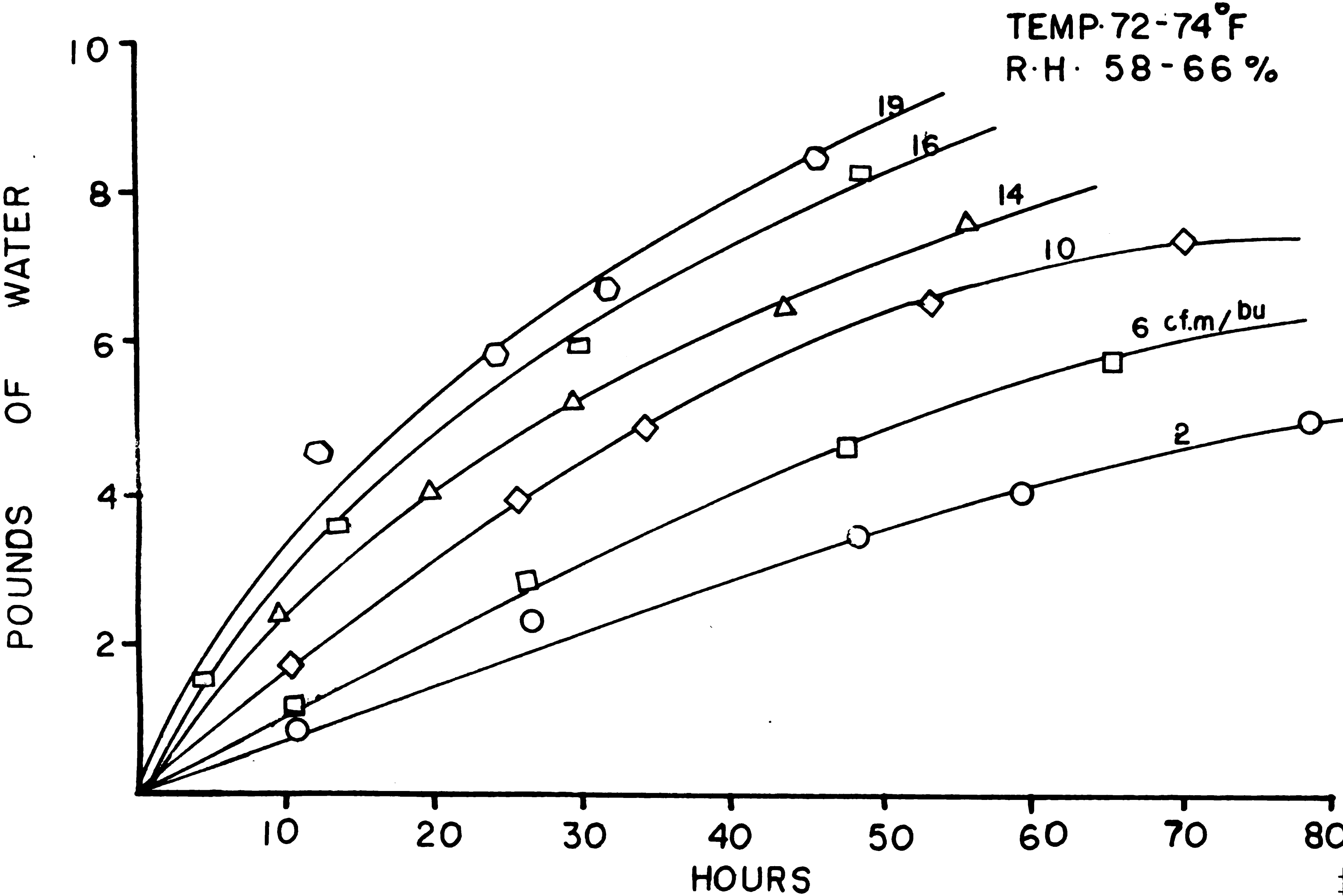
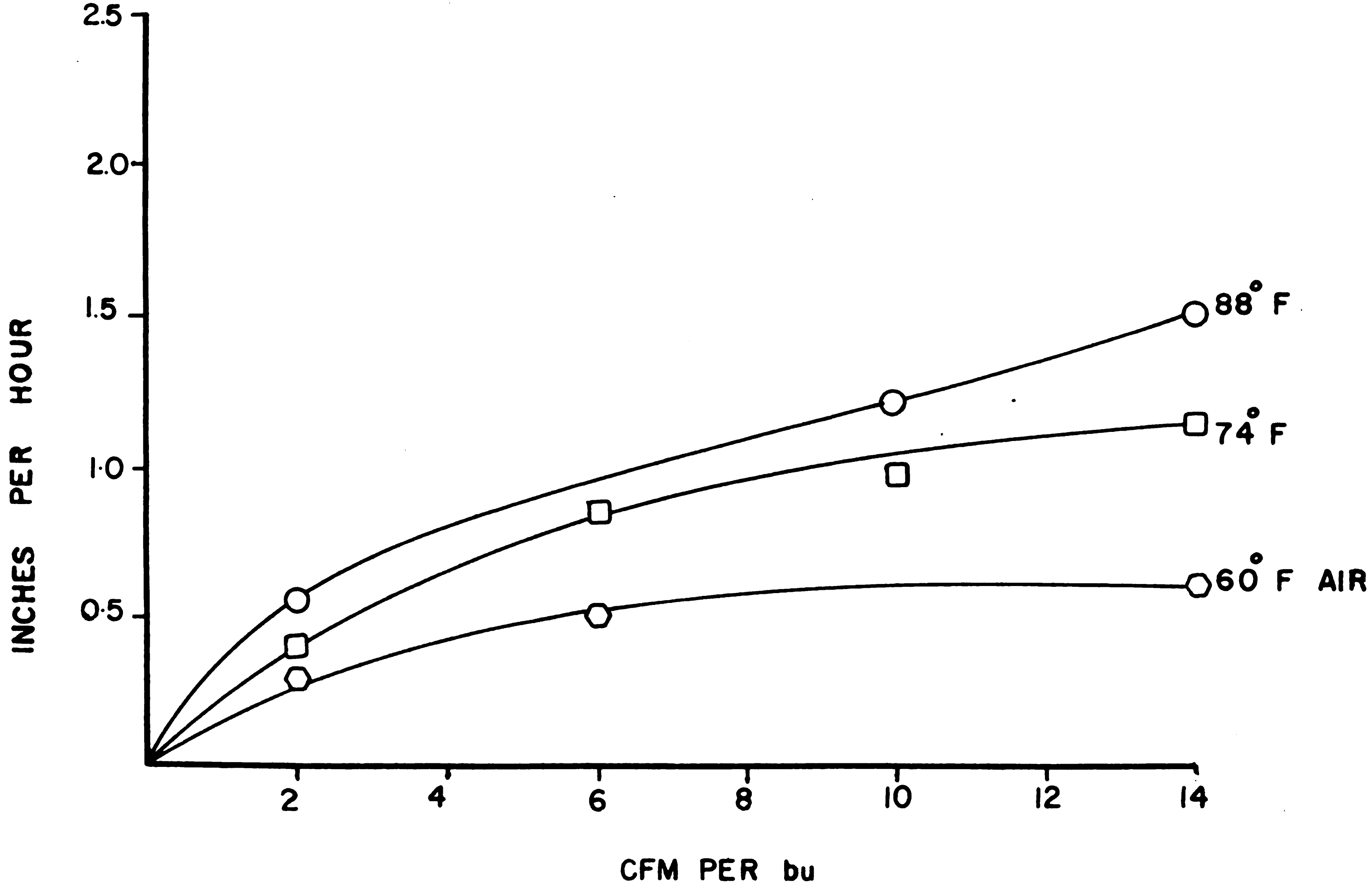


FIG. 5 LOSS OF WATER PER BUSHEL OF PEA BEANS



FIG·6 VELOCITY OF 15 PERCENT MOISTURE LAYER (BEANS) DEPTH OF BIN 3.5'

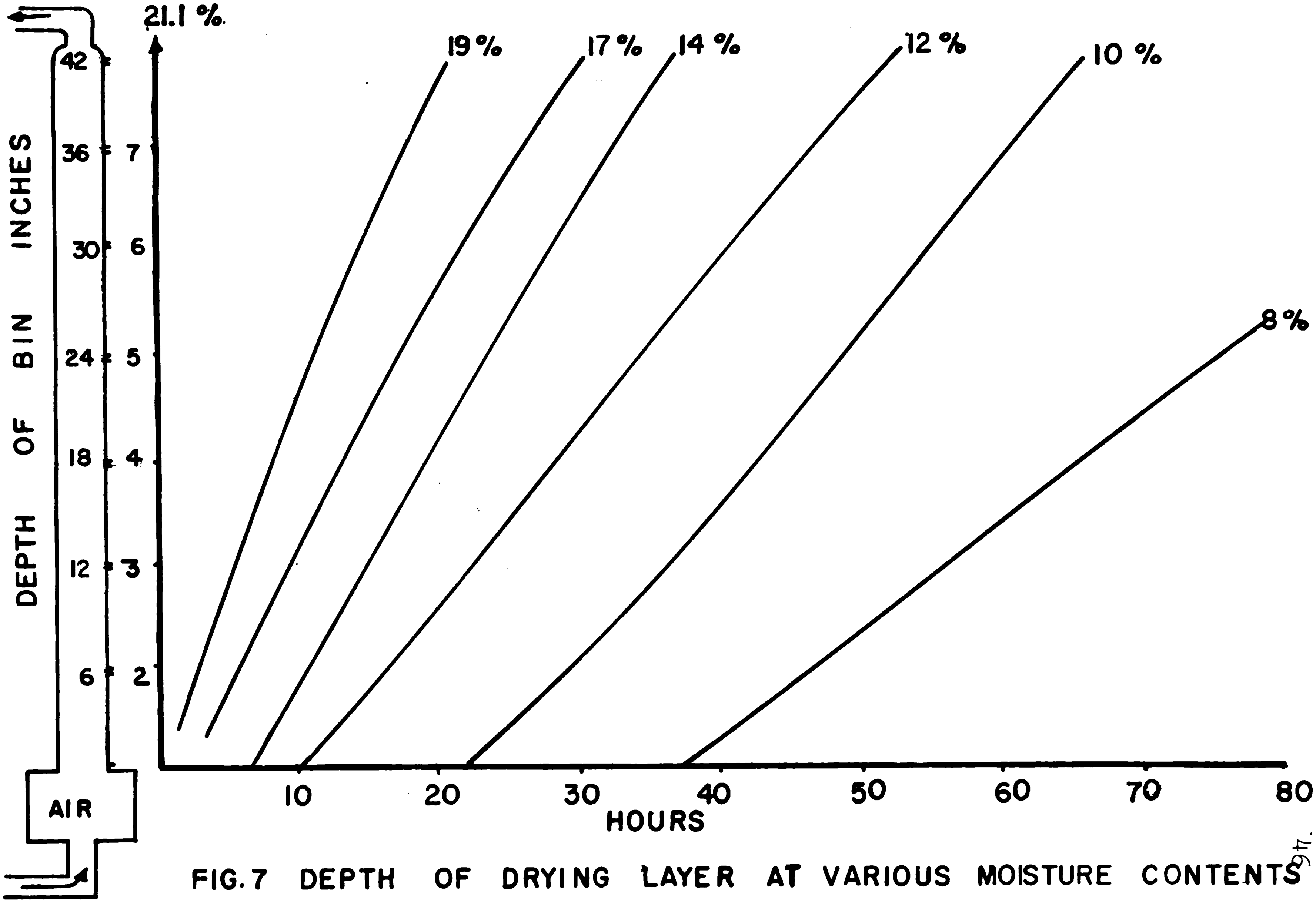


FIG. 7 DEPTH OF DRYING LAYER AT VARIOUS MOISTURE CONTENTS

the velocity of this layer is 0.4 inches per hour at 60 deg. F., 0.65 inches per hour at 74 deg. F., and 0.8 inches per hour at 88 deg. F. The following relationship between temperature and velocity of drying layer is presented:

$$V_1 = V_2 \left(\frac{t_2}{t_1} \right)^{-1.27}$$

t_1, t_2 = temperature in deg. F.

V_1, V_2 = velocity of 15 per cent moisture layer, inches per hour

Thus, with the increase of 14 deg. F. of incoming temperature the change in velocity of this layer was 62.5 per cent from 60 - 74 deg. F., and this increased 22 per cent when the temperature of air was increased from 74 - 88 deg. F. The change in velocity increases up to 6 cfm per bu. at all temperatures and above this air flow the change in velocity decreases gradually. Figure 6 shows the necessary temperature and air flow requirement for drying a given depth of bin within a given time for pea beans.

$$V_1 = V_2 \left(\frac{t_2}{t_1} \right)^{-1.27} \qquad \text{Fig. 6}$$

$$D_1 = D_2 \left(\frac{t_1}{t_2} \right)^{1.12} \qquad \text{Table 1}$$

$$V_1 = V_2 \left(\frac{Q_2}{Q_1} \right)^{-.54} \qquad \text{Fig. 6}$$

$$\frac{V_1}{V_2} = \left(\frac{Q_1}{Q_2} \right)^{-.54}$$

$$(\frac{V_1}{V_2}) = (\frac{Q_1}{Q_2})^{-.84} , (\frac{D_1}{D_2}) = (\frac{Q_1}{Q_2})^{.43} = (\frac{V_1}{V_2})^{.88}$$

$$(\frac{V_1}{V_2}) = (\frac{D_1}{D_2})^{1.17} = (\frac{D_2}{D_1})^{-1.17} = (\frac{V_2}{V_1})^{.88}$$

$$V_1 = V_2 (\frac{D_2}{D_1})^{-1.17}$$

This shows us the relationship between the velocity of 15 per cent layer with respect to the depth of grain. From this the velocity of 15 per cent layer in a deep bin can be determined and the total time requirement to dry a given bin can be calculated.

V_1, V_2 = velocity of 15 per cent moisture layer, inches per hour

D_1, D_2 = depth of dried grain below 15 per cent, inches

Q_1, Q_2 = air flow, cfm per bu.

Shelled corn. Shelled corn used for this work was harvested with an Oliver experimental picker-sheller in the Fall of 1957. The corn was at 35 - 37 per cent moisture content and was stored at zero deg. F. The same procedure, apparatus, air flows, and air temperatures were used for corn as for pea beans.

In general, for drying shelled corn takes less time than pea beans. To dry shelled corn from 30.8 per cent moisture content to 12 per cent wet basis required 41 hours, whereas, to dry pea beans from 22 per cent to 12 per cent required 40 hours. In both cases the air flow was 14 cfm per bu. and temperature drying air was 86-88 deg. F. Table 3 gives the drying time required to dry the top layer below 15 per cent moisture content. The time required to dry the top layer was 18.4 per cent greater for 10 cfm per bu. than 14 cfm per cfm per bu., and was 144 per cent greater at 6 cfm per bu. than for 10 cfm per bu. at 86 - 88 deg. F: air temperature. At 6 cfm per bu. and 86 - 88 deg. F. condensation took place in the upper top 18 inches which makes it longer to dry than expected with 72 - 74 deg. F. air. The drying time to bring the top layer up to 15 per cent was 7.9 per cent more at the 10 cfm per bu. than at 14 cfm per bu. and the drying time was 52.2 per cent more at 6 cfm per bu. than at 10 cfm per bu with 58 - 60 deg. F. air. The drying time to bring the top layer below 15 per cent was 26.4 per cent more for 10 cfm per bu. than 14 cfm per bu. and was 55 per cent higher for 6 cfm per bu. than for 10 cfm per bu.

Condensation did not occur at 14 and 10 cfm per bu. air flows at all temperatures which were used in this work. Maximum condensation occurred with 6 cfm per bu. air flow and maximum amount of condensation was 4.2 per cent increase in moisture content at 58 - 60 deg. F. air temperature and occurred after 20 hours. At 2 cfm the drying rate was low and the extent of condensation was 3.3 per cent increase in

TABLE 3. Drying shelled corn with different air flows.

Air Flow cfm per bu.	Difference between moisture content of top layer and bottom layer, when all layers were less than 15 per cent moisture content.	Time required for the top layer to come to 15 per cent moisture content or below, hours.
At 86 to 88 deg. F. and 40 to 47 per cent relative humidity		
14	3.1	38
10	2.0	45
6	3.5	110
2	mold growth	
At 72 to 74 deg. F. and 50 to 57 per cent relative humidity		
14	3.0	70
10	2.5	92
6	4.7	122
At 58 to 60 deg. F. and 58 to 64 per cent relative humidity		
14	.34	76
10	4.0	120
6	3.7	172
2	3.0	250

moisture content and was noticed less than 10 hours at 58 - 60 deg. F. At 72 - 74 deg. F. condensation increased the moisture content of the top layer by 1.6 per cent.

In drying shelled corn the extent of over drying was noticed. The difference between the moisture content of the top and bottom layer was as high as 4.7 per cent and was noticed at 6 cfm per bu. and 72 - 74 deg. F. This difference was minimum (2 per cent) at 86 - 88 deg. F. and 10 cfm per bu. air flow. At 14 cfm per bu. air flow this difference was constant with various temperatures (Table 3).

At the end of the drying test shrinkage in volume of the bin was noticed. This shrinkage was due to the removal of grain samples and drying of corn. The maximum shrinkage in volume was 27.3 per cent, out of which decrease in volume due to sampling was 2.72 per cent, which occurred at 14 cfm per bu. air flow and 86 - 88 deg. F. While drying the corn offered more resistance to the air flow. The increase in static pressure was 0.18 inch of water for 3.5 foot depth.

At a low air flow of 2 cfm per bu., due to low drying potential, the drying rate was slow and the total time required to dry a bin of 3.5 feet below 15 per cent moisture content was 250 hours.

The initial moisture content of shelled corn was 35 per cent, wet basis, and at 2 cfm per bu. and 86 - 88 deg. F. mold occurred in all the layers except the bottom. The grains had a musty flavor and grain clods were formed. To dry a bin of 3.5 feet below 15 per cent required 250 hours at 2 cfm per bu. and 58 - 60 deg. F. air temperature (Table 3). The time will be more if the air temperature was low or if the relative humidity of drying air was high. For drying a bin of 6 feet deep it will require 496 hours which is 20.30 days. The time is longer than that is recommended (2-3 weeks) for drying shelled corn in Michigan.

The relationships of time of drying, temperature of air, and depth which can be dried to 15 per cent moisture are presented below:

$$V_1 = V_2 \left(\frac{t_1}{t_2}\right)^{.65} \qquad \text{From Fig. 8}$$

$$D_1 = D_2 \left(\frac{Q_1}{Q_2}\right)^{.93} \qquad \text{From Table 3}$$

$$D_1 = D_2 \left(\frac{t_1}{t_2}\right)^{0.63} \qquad \text{From Table 3}$$

$$V_1 = V_2 \left(\frac{Q_2}{Q_1}\right)^{.63}$$

$$= V_2 \left(\frac{D_2'}{D_1'}\right)^{\frac{1}{.93} \times .63}$$

$$= V_2 \left(\frac{D_2'}{D_1'}\right)^{\frac{.63}{.93}}$$

$$V_1 = V_2 \left(\frac{D_2'}{D_1'}\right)^{.678}$$

V_1, V_2 = velocity of 15 per cent moisture, w.b., layer, inches per hour

D_1', D_2' = depth of grain dried below 15 per cent, inches

t_1, t_2 = temperature of drying air, deg. F.

$$V_1 = .10 \left(\frac{72}{42}\right)^{0.678}$$

$$= .145 \text{ in. per hr.}$$

Total time required to dry 6 foot bin of shelled corn with 2 cfm air flow will be as follows:

V_1 = .145 in. per hr., at 2 cfm bu.

D_1 = 72 in.

$$\theta = \frac{72}{.145} = \underline{\underline{496}} \text{ hours} \quad \text{at 58-60 deg. F. air}$$

This drying time is 3 weeks, and under conditions such as higher initial moisture content of the shelled corn or lower temperature or higher relative humidity the time requirement for the bin will be more than 3 weeks. Thus, to be on the safe side the air flow for drying shelled corn should be 3.5 cfm per bu. The air flow of 3.5 cfm per bu. will dry the bin of 6 feet deep in 13.7 days at 58 to 60 deg. F. air temperature.

$$V_1 = (.170) \left(\frac{72}{42}\right)^{.678} \quad \text{for 3.5 cfm per bu.}$$

$$= .218 \text{ inch per hour}$$

$$\theta = \frac{72}{.212} = 330 \text{ hr.} = 13.7 \text{ days}$$

Table 4 shows the depth of drying layer at different air flows and air temperatures. The depth of drying layer is expressed in terms of initial moisture content of the grain (M_o) and equilibrium moisture content of drying air (M_e) for

1. (M_o - 2) per cent moisture content to (M_e + 2) per cent moisture content, and
2. (M_o - 4) per cent moisture content to (M_e + 4) per cent moisture content.

The depth of drying layer was 42 inches or more at all temperatures at 14 cfm per bu. air flow on the basis of (M_o - 2) per cent to (M_e + 2) per cent. The depth of drying layer was 33.2 per cent higher at 88 deg. F. than 72 deg. F. at 6 cfm per bu. air flow and 8 per cent higher at 74 deg. F. than 60 deg. F. air temperature.

Using the depth of drying layer as (M_o - 4) per cent to (M_e+4) per cent, at 14 cfm bu., the depth of drying layer was 31.2 per cent higher at 88 deg. F. than 74 deg. F. and 33.4 per cent higher at 74 deg. F. than 60 deg. F. air temperature. At 6 cfm bu. air flow the depth of drying layer was 23.1 per cent higher at 88 deg. F. and 30 per cent higher at 74 deg. F. than at 60 deg. F. air temperature.

The depth of the drying layer expressed in terms of (M_o - 4) per cent to (M_e + 4) per cent gives the following relationship:

$$d_1 = d_2 \left(\frac{Q_1}{Q_2}\right)^{1.06}$$

TABLE 4. Depth of drying layer, inches, at four air flows and three different temperatures for shelled corn.*

		cfm per bu.			
Temp. of	Drying Layer	14	10	6	2
86-88	M_e + 2% to M_o - 2%	42	42	36	-
72-74	M_e + 2% to M_o - 2%	42	36	27	22
58-60	M_e + 2% to M_o - 2%	42	32	25	20
86-88	M_e + 4% to M_o - 4%	42	22	16	-
72-74	M_e + 4% to M_o - 4%	32	18	13	10
58-60	M_e + 4% to M_o - 4%	24	14	10	8

*Values for an initial moisture content of 35 per cent, w. b.

Q_1, Q_2 = air flow, cfm per bu.

d_1, d_2 = depth of drying layer, inches

From the above equation, for a given depth of drying layer at a particular air flow, the depth of drying layer at any other air flow between 2 to 14 cfm per hour air flows can be calculated.

Statistical Analysis

Sample calculation

$$\text{Moisture content ratio} = \frac{M - M_e}{M_o - M_e}$$

$$M = \log_e \frac{M - M_e}{M_o - M_e}$$

$$\text{Depth factor} = \frac{G}{g} = d \qquad G = 13.6 \text{ lb. total grain}$$

$$g = \frac{\quad x\ 60\ x\ .24\ x \quad t\ x\ \theta}{.01\ x \quad M\ \ x\ H_g}$$

$$= \frac{37\ x\ 60\ x\ .24\ x\ 15\ x\ 24}{.01\ x\ 20\ x\ 1170} = 8.4 \text{ lb.of grain}$$

$$d = \frac{8.4}{13.6} = .614$$

General formula to find the time requirement:

$$\theta = 173.8 - 1.39\ (t) + 8\ (.m) + 35\ (d) - 13(Q)$$

$$= 173.8 - 1.39\ (60) - 8\ (1.3757) + 35\ (.614) - 13(3)$$

$$= 71.8 \text{ hr.}$$

θ = time to dry shelled corn below 15 per cent moisture content, hours

t = temperature of drying air, deg. F.

d = depth factor, feet

q = air flow, pounds per minute per square foot

The following standard statistical analysis, as suggested by Dr. W. Baten, Agricultural Experiment Station Statistician, was used:

1. $$\left[\Sigma tm - \frac{(\Sigma t)(\Sigma m)}{n}\right]b + \left[\Sigma m^2 - \frac{(\Sigma m)^2}{n}\right]c + \left[\Sigma mD - \frac{(\Sigma m)(\Sigma D)}{n}\right]f + \left[\Sigma mq - \frac{(\Sigma m)(\Sigma q)}{n}\right]g = \left[\Sigma m\theta - \frac{(\Sigma m)(\Sigma \theta)}{n}\right]$$

2. $$\left[\Sigma t^2 - \frac{(\Sigma t)^2}{n}\right]b + \left[\Sigma tm - \frac{(\Sigma t)(\Sigma m)}{n}\right]c + \left[\Sigma tD - \frac{(\Sigma t)(\Sigma D)}{n}\right]f + \left[\Sigma qt - \frac{(\Sigma q)(\Sigma t)}{n}\right]g = \overset{G}{\left[\Sigma t\theta - \frac{(\Sigma t)(\Sigma \theta)}{n}\right]}$$

3. $$\left[\Sigma tD - \frac{(\Sigma t)(\Sigma D)}{n}\right]b + \left[\Sigma mD - \frac{(\Sigma m)(\Sigma D)}{n}\right]c + \left[\Sigma D^2 - \frac{(\Sigma D)^2}{n}\right]f + \left[\Sigma Dq - \frac{(\Sigma D)(\Sigma q)}{n}\right]g = \overset{E}{\left[\Sigma D\theta - \frac{(\Sigma D)(\Sigma \theta)}{n}\right]}$$

4. $$\left[\Sigma tq - \frac{(\Sigma t)(\Sigma q)}{n}\right]b + \left[\Sigma mq - \frac{(\Sigma m)(\Sigma q)}{n}\right]c + \left[\Sigma qm - \frac{(\Sigma m)(\Sigma q)}{n}\right]f + \left[\Sigma q^2 - \frac{(\Sigma q)^2}{n}\right]g = \overset{F}{\left[\Sigma q\theta - \frac{(\Sigma q)(\Sigma \theta)}{n}\right]}$$

$$q = \bar{\theta} - b\bar{t} - c\bar{m} - f\bar{d} - gq$$

$$\theta = a + bt + cm + fD + gq + \sigma e$$

Four equations and four unknowns solved simultaneously:

$$2392(b) - 25.7(c) + o(f) - 8.67(g) = -3640$$

$$-25.7(b) + -489(c) + o(f) - .855(g) = -22.36$$

$$-\ 0\ (b) + o\ (c) + 2.027(f) + o(g) = 471$$

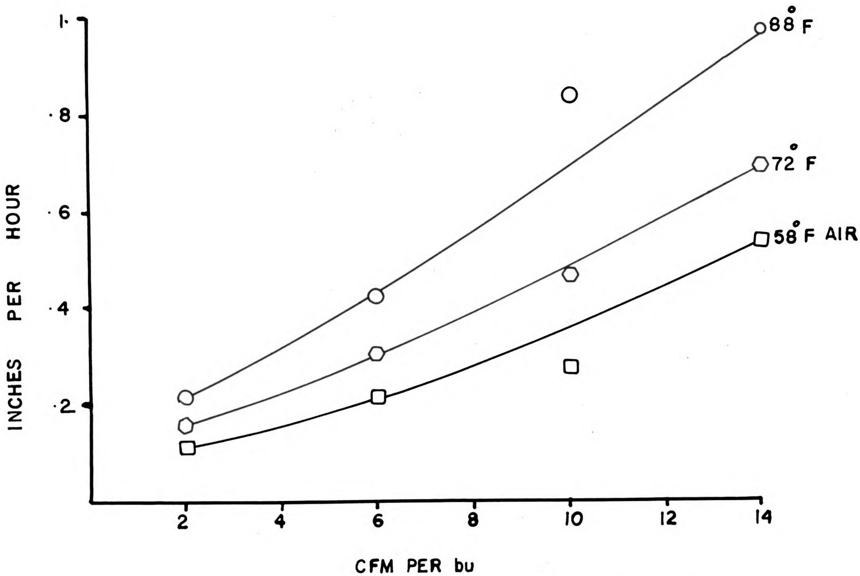
$$.867(b) - .855(c) + o(f) + 8.311(g) = 175.33$$

b = -1.39, f = 35.02, g = -13.0, c = 8.0, a = 173.8

$$\sigma e = \sqrt{\frac{\Sigma t^2 - \frac{(\Sigma t)^2}{n} - b\left[\Sigma t\theta - \frac{(\Sigma t)(\Sigma \theta)}{n}\right] - c[G] - f[E] - g[F]}{n-5}}$$

$= \pm 21.3$

+1.39 (-3640) - q (-22.36) + 35 (1166) + 13 (175.33)



FIG·8 VELOCITY OF 15 PERCENT MOISTURE LAYER IN 3.5′ BIN (S· CORN)

TABLE 5. Relationship of observed and calculated values for drying time.

Temp. deg.F	log. $\frac{M - M_e}{M_o - M_e}$	Depth Factor	Pounds of Air per sq. ft. per minute	Time in Hours	
				Observed	Calculated
t	-m	d'	q	θ_1	θ_2
60	1.2757	0.614	3.0	63	71.8
60	1.2757	1.27	3.0	80	84.
60	1.0000	1.12	2.17	83	104.
60	1,0000	1.96	2.17	120	133.40
60	0.9136	1.22	1.30	116	108.5
60	0.9136	1.93	1.30	144	133.5
60					
60					
74	1.0506	0.325	2.93	34	41.92
74	1.0506	0.69	2.93	53	53.80
74	1.0223	0.282	2.14	54	62.70
74	1.0223	0.638	2.14	73	74.95
74	0.8774	0.486	1.27	74.2	64.92
74	0.08774	1.000	1.27	116	83.14
74					
74					
88	0.7212	0.50	2.84	22	27.18
88	0.7212	0.735	2.84	36	35.25
88	0.7399	0.282	2.10	28	26.18
88	0.7399	0.66	2.10	41	39.31
88	0.8099	0.624	1.22	61	50.83
88	0.8099	1.15	1.22	90	69.24

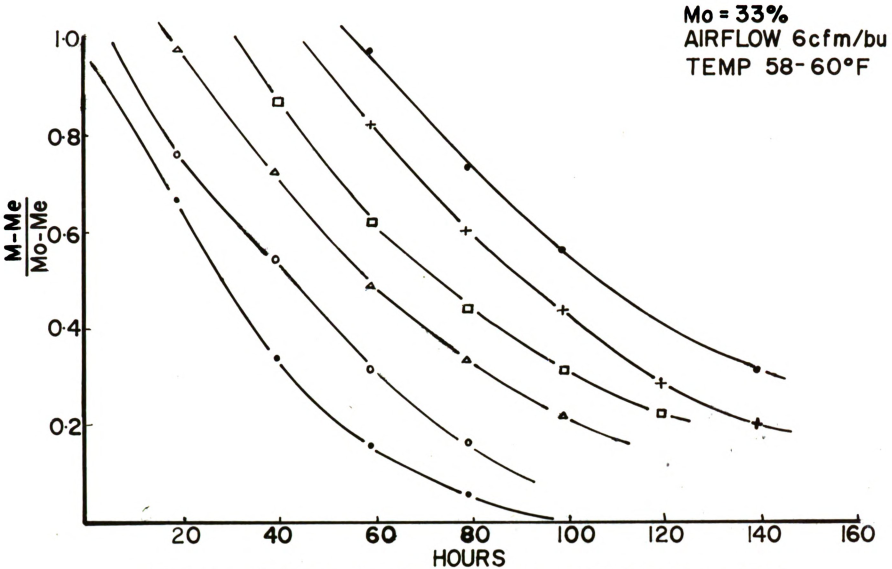


FIG 9 MOISTURE CONTENT RATIO IN DIFFERENT LAYERS

SUMMARY

The effect of air flow rate and temperature for drying pea beans and shelled corn in deep bins was investigated on a laboratory scale.

A refrigerated box of 40 cubic feet was a source of incoming air. The box was maintained at a constant temperature and constant relative humidity. A backward curved centrifugal fan was used to force air from the refrigerated box to the heater box, where the air was heated by electrical resistance heater, 14 deg. F. higher. From heater box air was forced through the grain and back to the refrigerator.

The test bin was constructed of steel with a 4 inch outside diameter and 42 inch height. The bin was insulated with 1.0 inch asbestos insulation to provide adiabatic drying.

Pea beans were dried satisfactory at 6 cfm per bu. air flow at 58-60 deg. F. air temperature. Cracking of pea beans did not occur at all temperatures, 58-88 deg. F., and air flows, 2-14 cfm per bu., applied in this study. The rate of drying of pea bean is slower than that of shelled corn. The velocity of 15 per cent moisture is a good indication of movement of drying zone. By knowing the velocity of the drying layer the total time required to dry a bin can be estimated. At higher air flow, the temperature has much

less effect on drying layer depth than at low air flows. Equal moisture content lines show how the depth of drying layer increases with increase in time units for a given air condition.

From the general formula presented, the total time required to dry a bin of shelled corn can be calculated. Also after certain time of drying, the depth of grain below 15 per cent moisture content can be predicted. At the higher temperatures with 2 cfm per bu. air flow, mold growth occurred on shelled corn. For drying shelled corn 3.5 cfm per bu. is the lowest air flow that can be used. The velocity of 15 per cent moisture layer is expressed in terms of inches per hour movement. This velocity remains fairly constant at all temperatures considered at 14 cfm per bu air flow. The drying of shelled corn was more uniform at lower temperatures.

CONCLUSIONS

Pea Beans

1. For drying of pea beans with unheated air minimum air flow is 6 cfm per bu. within the temperature range of 60 - 88 deg. F.; 2 cfm per bu. air flow is low which takes longer time to dry for a given bin of 6 feet depth.
2. The velocity of 15 per cent moisture layer for pea bean is expressed in terms of temperature of drying air for air flows 2 - 14 cfm per bu. and relative humidity 36-70 per cent.

$$V_1 = V_2 \left(\frac{t_2}{t_1}\right)^{-1.27}$$

3. The depth of drying layer for pea bean increases with increased temperature, for a given air flow. This can be expressed as follows:

$$d_1 = d_2 \left(\frac{t_1}{t_2}\right)^{0.91}$$

4. The velocity of 15 per cent moisture layer for pea beans is related in terms of air flow, within the range of air temperature studied

$$V_1 = V_2 \left(\frac{Q_2}{Q_1}\right)^{-.54}$$

Shelled Corn

5. The time required to dry a given depth of bin can be calculated by the following formula:

$$V_1 = V_2 \left(\frac{D_2}{D_1}\right)^{.658}$$

$$\theta = \frac{D_2}{V_2}$$

V_1, V_2 are the velocities inches per hour of 15 per cent moisture layer at depths D_1 and D_2 in inches. This formula works all temperatures between 60 to 88 deg. F. and at 6 cfm to 14 cfm per bu. air flow.

6. The lowest acceptable air flow for drying shelled corn without mold damage under Michigan conditions is 3.5 cfm per bu. over the temperature range considered.

7. The depth of drying layer is expressed in terms of air flow as follows:

$$d_1 = d_2 \left(\frac{t_2}{t_1}\right)^{.7}$$

This formula applies from 2-14 cfm per bu. air flows and 50-60 deg. F. air temperatures.

8. The velocity of the 15 per cent moisture layer can be expressed in terms of drying air temperature deg. F.

$$V_1 = V_2 \left(\frac{t_1}{t_2}\right)^{.65}$$

V = velocity of 15 per cent moisture layer, inches per hour. This equation applies within the range of 60-88 deg. F. air and 2-14 cfm per bu. air flow. This equation can be used to determine the time to dry a given depth of grain.

9. The time, Θ, hours, is related to the moisture content ratio, m, temperature, t, deg. F., air flow, q, pound of dry air per square foot per minute and the depth factor, d, of grain. These variables are related by the following general formula:

$$\Theta = 173.8 - 1.39(t) + 8.63(m) + 35.02(d) - 13(q)$$

From this equation the time required to dry a given bin of shelled corn can be calculated.

SUGGESTIONS FOR FUTURE STUDY

1. From the experience gained, further studies should be undertaken to further develop the relationship between drying time, moisture content ratio, air flow, and temperature of drying air and relative humidity with gains above 40 per cent moisture content, wet basis.
2. With picker-sheller grains are harvested at higher moisture content and work should be done on corn above 40 per cent moisture content.
   a. Study the resistance to the air flow
   b. Shrinkage problems
   c. Pressure drop
3. Additional studies of drying grains in fluidized bed by agitation should be carried on for getting sufficient basic data.
4. Consideration should be given to develop the theory involved beyond the given limitations.
5. Further efforts should be directed toward the development of equipment and procedure for measurement of moisture contents and temperature at various locations in a single kernel.
6. Determine the effect of drying on size and shape of grains at different moisture content.

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APPENDIX

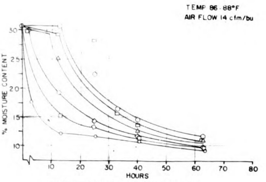

FIG 10 LAYER DRYING OF SHELLED CORN

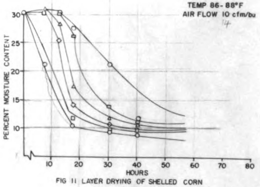

FIG 11 LAYER DRYING OF SHELLED CORN

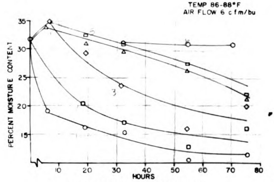

FIG 12 LAYER DRYING OF SHELLED CORN

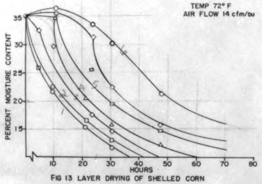

FIG 13 LAYER DRYING OF SHELLED CORN

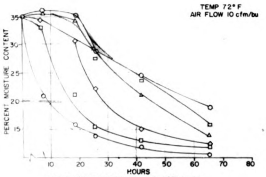

FIG 14 LAYER DRYING OF SHELLED CORN

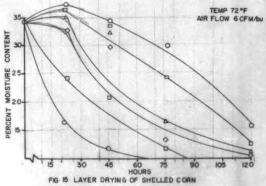

FIG 15 LAYER DRYING OF SHELLED CORN

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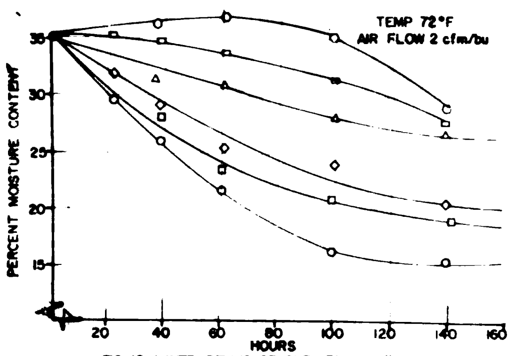

FIG 16 LAYER DRYING OF SHELLED CORN

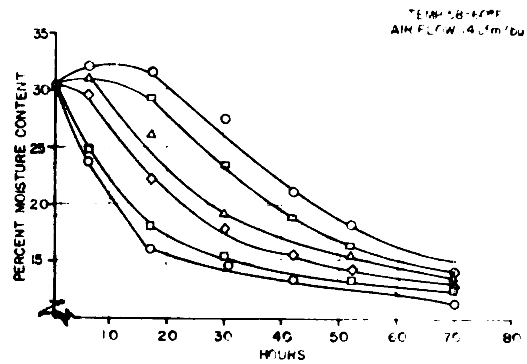

FIG 17 LAYER DRYING OF SHELLED CORN

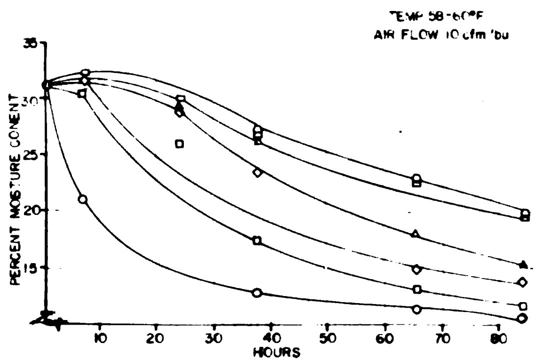

FIG 18 LAYER DRYING OF SHELLED CORN

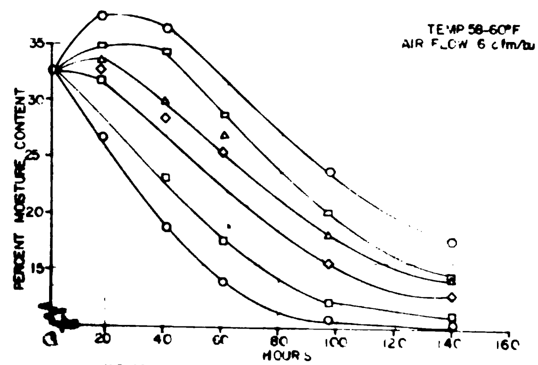

FIG 19 LAYER DRYING OF SHELLED CORN

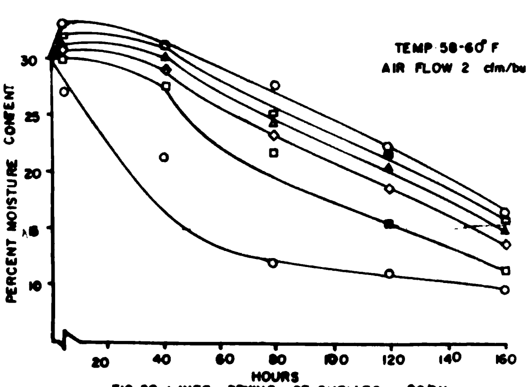

FIG 20 LAYER DRYING OF SHELLED CORN

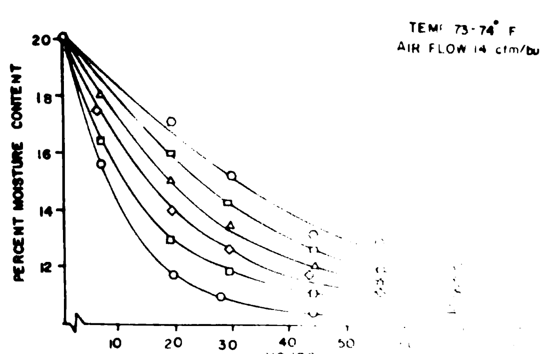

FIG 21 LAYER DRYING OF PEA BEAN

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w b.

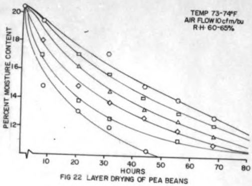

FIG 22 LAYER DRYING OF PEA BEANS

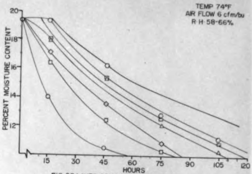

FIG 23 LAYER DRYING OF PEA BEANS

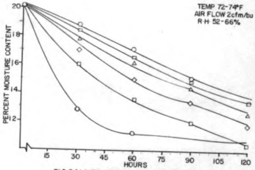

FIG 24 LAYER DRYING OF PEA BEANS

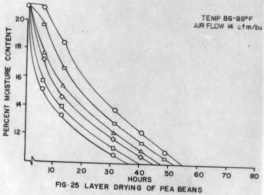

FIG 25 LAYER DRYING OF PEA BEANS

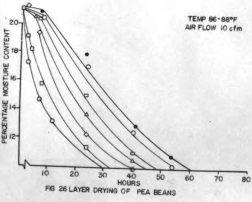

FIG 26 LAYER DRYING OF PEA BEANS

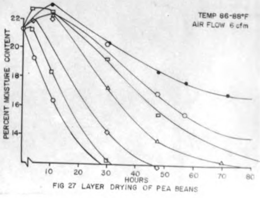

FIG 27 LAYER DRYING OF PEA BEANS

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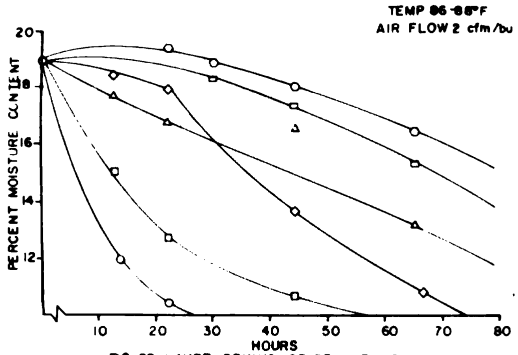

FIG 28 LAYER DRYING OF PEA BEANS

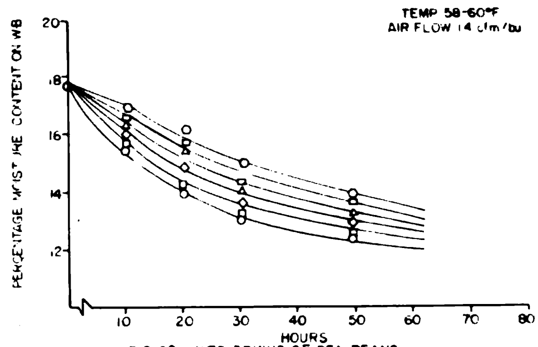

FIG 29 LAYER DRYING OF PEA BEANS

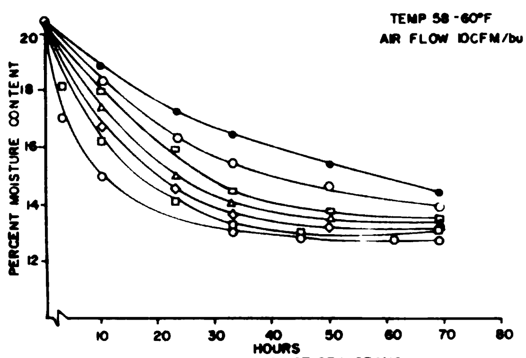

FIG 30 LAYER DRYING OF PEA BEANS

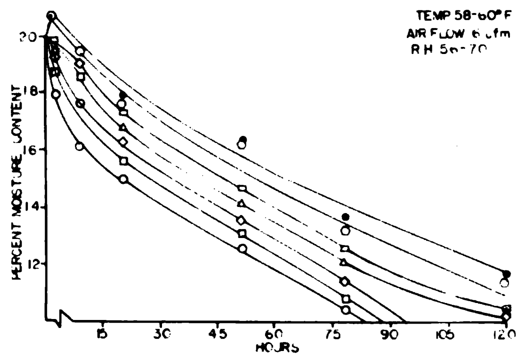

FIG 31 LAYER DRYING OF PEA BEANS

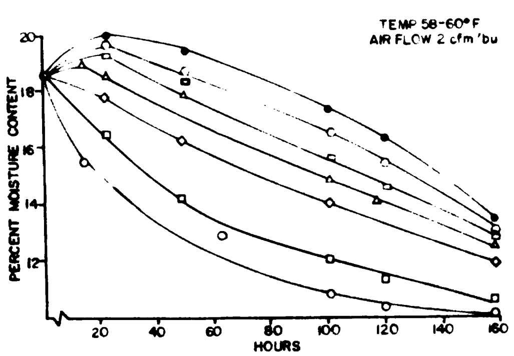

FIG 32 LAYER DRYING OF PEA BEANS

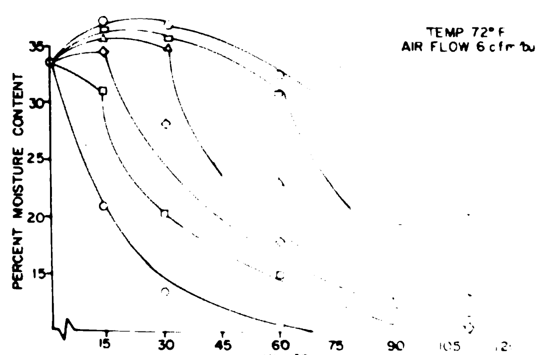

FIG 15 LAYER DRYING OF SHELLED CORN

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