

AIR DISTRIBUTION DUCTS FOR VENTILATING HIGH-MOISTURE WHEAT
IN FARM TYPE STORAGE STRUCTURES

by

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INTRODUCTION

Food storage has the indispensable function of making an economy of any sort possible. The demand for food is continuous - but production is seasonal. Hence the preservation and storage of food crops are of utmost importance.

Certain economic aspects of food storage more closely concern the producer. One is the effect on market price. Since production is seasonal, storage facilities must be available to permit crops to be marketed over an extended period. The alternative is a disastrous over-supply for a few weeks, with resultant low prices. On the other hand, a price rise during storage is not always a net gain. Storage expenses must be considered. Also, delayed marketing can result in a reduction of grade. This means a lower price, and cash loss to the producer. Such a loss is suffered largely in net income, since the costs of production and marketing are relatively independent of a change in grade after harvest.

Wheat is the second most important food crop in the world. A considerable portion of it is stored on farms before being marketed. The storage period may consist of a few weeks, or may extend to a year or more. Inadequate storage and conditioning facilities, or their complete absence, contribute to an enormous annual loss in the income from grain, and to a loss in quality for consumption or processing. Exact statistics are not available; but losses of wheat stored on farms in the United States have been estimated as high as 15 per cent. Such losses vary with years, crops, and geographical areas.

STORAGE OF WHEAT

Indices of Quality or Condition

Almost everyone experienced with the handling of grain can classify it as to general condition by its appearance and odor. For marketing purposes, however, numerical grades for each kind of grain have been established by the grain standards of the U. S. Department of Agriculture (7). They, together with the individual grade factors, including moisture content, test weight, damaged kernels, foreign material, and odor, reflect the quality or condition of grain. The grade factor most indicative of the condition of grain is kernel damage caused by fungus growth or excessive heating.

More sensitive indices of quality and condition of the grain are germination and fat acidity.¹ In extensive storage experiments on wheat, Kelley, et al. (34), found good agreement between these two indices and damaged kernels. However, loss of germination and increase in fat acidity were found valuable in indicating incipient deterioration not apparent from the grade factors.

Agents of Deterioration

All storage losses are theoretically preventable; that is, they can be greatly reduced or eliminated entirely if owners and handlers are sufficiently concerned. One reason for them is that they are insidious, the damage being done usually before the owner is aware of danger. Obviously, the first step in preventing storage losses is to acquire an understanding of how, why, and under what circumstances they are likely to occur.

¹Fat acidity represents the amount of free fatty acids in the wheat. It is determined chemically by the number of milligrams of potassium hydroxide required to neutralize the free fatty acids in 100 grams of wheat. (32)

Agents contributing to the loss and deterioration of stored grain are listed by Oxley (45) as due to rodents, insects, living processes in the grain (respiration), microorganisms, and enzymes. All except those due to rodents are greatly dependent on moisture content of the grain and the temperature conditions which prevail.

Rodents. Damage to the grain and the storage structure by rodents can be avoided if construction excludes them. The foundation, floor, and lower part of the walls are most subject to rat and mouse damage. Not only may an appreciable quantity of grain be consumed and damaged (partially eaten kernels), but also a rat odor is imparted and excreta is mixed with grain. This makes it unfit for human consumption.

Insects. Stored-grain insects can be classed according to the type of damage to the grain. One class includes insects of the boring type, such as the rice weevil, granary weevil, and the lesser grain borer. In the second class are insects of the nonboring type, such as the saw-tooth grain beetle and the rust-red flour beetle. The nonboring insects, called "bran bugs", feed only on broken kernels and bran. They do not attack whole kernels. (Barre and Sammet, 5)

Damage by insects to stored wheat may consist of one or more of the following:

1. Consumption of grain and accumulation of refuse from feeding in the kernels.
2. Contribution to excessive heating of the grain.
3. Contribute to the accumulation of moisture in parts of stored grain.
4. Impart an insect or "weevily" odor.

4

Insect damage in kernels is caused by the boring type of insects. Although the damage is chiefly mechanical, most of the boring insects leave considerable refuse in the kernel which cannot be removed or separated. Whereas, the so-called bran bugs are not harmful to the grain directly, they do contribute to the "weevily" odor caused by heavy infestation. (Barre and Sammet, 5)

In the absence of prevention or control measures, stored-grain insects are likely to develop rapidly where conditions are favorable. Gray (20) has calculated that the progeny of a single pair of confused flour beetles, a typical member of this group, would exceed a million in 150 days. A study made by Walkden (64) revealed that the damage caused by insects to wheat during five months' storage on south-central Kansas farms, ranged up to 14 per cent. Test weight of the grain was reduced over 13 per cent in some cases, and market discounts amounted to as much as 30 cents per bushel when No. 1 wheat was selling for \$1.98 per bushel.

Dry grain in bulk storage that is apparently in good condition may suddenly become hot. Usually, in such cases, heating of the grain is caused by presence of insects. An excellent discussion of the causes of spontaneous heating is given by Oxley (46). He points out that the metabolism of the grain itself produces heat, but that with grain moistures below 15 per cent¹, the amount of heat produced from this source is negligible. In all cases investigated, he found that when dry grain heated, insect infestations were the cause; and the source of heat was the metabolism of the insects. Only a few insects are necessary to initiate spontaneous heating.

¹The moisture contents indicated are calculated by the wet basis method.

If grain heats because of insect infestation, its temperature does not rise above 108°F. However, heat produced by insects may result in translocation of water vapor from the hot to the cool areas of the grain. This inaugurates damp grain heating with its characteristic higher temperatures (up to approximately 150°F). Since temperatures of 100 degrees or above are not favorable for the development of weevils, they move into cooler grain, and thereby enlarge the hot spots. (Oxley, 46)

Cotton, et al. (12) state that temperature is the most important single factor affecting the prevalence of stored-grain insects. However, the modifying effect of moisture is so great that both factors must be considered. Most of these insects are thought to be of subtropical origin and do not hibernate. They have not developed resistance to low temperatures or the ability to thrive in dry grain.

Subject to certain upper limits, rate of development and reproductive capacity of all grain-infesting insects increases as the temperature rises. A grain temperature of 70°F is considered to be the danger point. At favorable moisture levels, the optimum breeding temperature appears to be about 80°F. Grain beetles, such as the red flour beetle and the saw-toothed grain beetle, do not lay eggs at temperatures below 60°F (12). Anderson (1) noted that neither the rice weevil nor the granary weevil mated when temperature fell below 53.6° to 55.4°F. Richards (49) placed the lower limit of oviposition of these weevils at 49.1°F. Hatching and development of larvae at temperatures between 55 and 60 degrees were extremely slow.

The insect pests of stored grain are dependent upon their food supply for the moisture requirements to carry on their life processes. Hence, grain moisture is important to their life economy. Where grain moisture content is low, insects can obtain water only by breaking down the food supply or the

food reserves of the body. The ability of different insects to do this varies. At normal temperatures, rice and granary weevils rarely breed in grain with a moisture content below 11 per cent. They are unable to breed in grain with a moisture content below nine per cent, and the adults soon die. (Cotton, et al., 12)

Living Processes in the Grain. Any normal, sound kernel of grain is a living organism, and all living organisms respire - a process, in grain, accompanied by the production of carbon dioxide and the liberation of energy in the form of heat. Bailey and Gurjar (4) explain that this release of carbon dioxide and heat is occasioned by the biological oxidation of dextrose and similar sugars, chiefly in the germ or embryo of the kernel.

Moisture is one of the determining factors in grain respiration. It establishes the comparative rate of diffusion between the several kernel structures. Any gain in moisture content of the kernel, accordingly increases the rate of diffusion and, simultaneously, the rate of respiration. The increase is gradual and fairly uniform until the moisture exceeds 14.5 per cent, in the case of plump spring wheat, when it is markedly accelerated (4). The period of dampness - that is, the length of time excess moisture has been present in the grain - bears a relation to rate of respiration.

Density of the wheat kernel generally parallels gluten content. Gluten possesses the property of imbibing more water than starch; hence, varying percentages of gluten result in varying degrees of viscosity at the same moisture level. The relative viscosity affects rate of diffusion and this, in turn, directly affects rate of respiration. Thus soft, starch wheats respire more rapidly than hard, vitreous wheats containing the same percentage of moisture. (Bailey and Gurjar, 4)

Plumpness of the wheat kernel affects rate of respiration as shown by contrasting plump and shriveled grain. Bailey and Gurjar (4) found that shriveled wheat respired two to three times as much as did plump wheat at moisture contents above 14 per cent. Below 14 per cent moisture, the difference was not very significant. The acceleration of respiration in high-moisture, shriveled wheat was attributed to the greater ratio of germ to endosperm, and hence, the larger percentage of enzyme to substrate as compared with plump wheat.

The temperature at which grain is stored affects the rate of diastatic action, and thus, varies the quantity of substrate available to the respiratory enzymes. Observations on wheat with a 15 per cent moisture content indicate that increasing temperature accelerates the rate of respiration until 131°F is reached. The rate at this temperature is 25 times that at 95 degrees. As temperature rises, the diastatic action upon starch increases. A point is reached, however, at which the enzyme activity diminishes. (Bailey and Gurjar, 4)

When the respiration rate of bulk-stored grain is increased by raising moisture or temperature levels, the process becomes self-accelerating. The greater respiration rate results in an increased liberation of heat. The additional heat raises the grain temperature which, in turn, increases the respiration process.

Microorganisms. Concurrent with the build-up of grain respiration is the increasing activity of microorganisms. The principal microorganisms affecting wheat in storage are fungi of the mold type. The molds are characterized by the formation of a network of filaments or threads which are visible usually to the unaided eye. The nature of damage in moldy grain is fairly obvious. The germ is first to be affected, as is reflected by loss of viability. With

advanced development, the waste products from the metabolic process impart a musty odor to the grain and impair its quality. A part of the kernel affected by mold is consumed, with consequent loss in dry matter. Most fungi will not grow at a relative humidity below 70 per cent (Milner, et al, 41). This corresponds to a moisture content of about 13.5 to 14 per cent in wheat.

Actually, biological activity (respiration) of the grain itself may be regarded as of secondary importance. It is now generally agreed that microorganisms are the primary cause of heating and deterioration of high-moisture grain in storage. Through the use of specially devised techniques, Milner, et al. (41) have been able to quantitatively separate the respiration due to fungi on grain and that due to the grain itself. They found that as moisture content of the grain is raised, the respiration of the fungi increased at a much greater rate than that of the grain. For example at 16 per cent moisture, respiration due to molds was about 30 times that due to the grain, though the respiration of the two were about equal at lower moisture levels.

In the absence of insects, Carter and Young (9) have shown that heat damage of high moisture wheat in storage can be entirely accounted for by the energy released in the respiration of the fungi on the kernels.

Enzymes. In addition to the destructive work of microorganisms, grain deterioration may be greatly increased by enzyme activity. Enzymes are special proteins that are built up in living plant and animal tissue for the purpose of accelerating the chemical reactions necessary to life.

Two aspects of enzyme activity affect stored wheat. One, mentioned previously, is its contribution to the respiration process that occurs in the living portion of the kernel constituting the germ. The other is its contribution to the chemical breakdown of the non-living portion of the kernel.

Both of these processes are oxidative and result in the production of heat, carbon dioxide and water. The immediate effect on the grain is consumption of dry matter and loss in dry weight. (Barre and Sammet, 5)

An important distinction between enzymes and microorganisms is that enzymes are a part of the tissue and cannot be separated, whereas microorganism activity can be suppressed. If only enzymes are active, the process is described as "autolysis." Where both enzymes and microorganisms are active, the deterioration is described as "decay." Even after death of the tissue, many enzymes continue to function and cause tissue disintegration. (Barre and Sammet, 5)

Moisture Limit for Safe Storage

The moisture content at which wheat can be stored without excessive damage from the destructive agents described depends on the locality in which it is grown and stored, and the length of the storage period. Milner (40) indicates that the critical moisture level for growth of fungi on wheat is about 14.5 per cent at normal temperatures. This is for sound grain. He found that immature, frosted, shriveled, or otherwise damaged kernels may support mold growth at a lower moisture content. Also, respiration of the grain, chemical changes in the kernel embryo, and enzyme activity proceed at lower moisture levels. These factors must be considered. In general, wheat with a moisture content above 13 per cent cannot be safely stored for long periods. An 11 to 12 per cent moisture value is more desirable if the grain is to be in storage more than a year. Such limiting moisture contents apply to the wettest portions and not to the average moisture of the entire bulk of grain.

Throughout the principal winter wheat-growing areas, harvesting takes place during the warmest months of the year. Losses due to increased kernel

respiration and fungi are promoted by the high temperatures likely to prevail during the earlier part of the storage period. "Sick" wheat conditions have been reported in hard red winter wheat with moisture contents no higher than 12 per cent. Carter and Young (8) produced sick wheat artificially in soft winter wheat with a moisture content of 12.2 per cent in 279 days at a temperature of 104°F. Increases in fat acidity and loss of germination were observed in less time and at lower temperatures. Such observations support the generalization that when wheat is to be stored for more than a few months, or in areas and situations where it is likely to be subjected to high temperatures, the safe moisture limit is considerably less than where the opposite conditions prevail.

Observations of Long-Term Storage Effects

Fifield and Robertson (14) reported milling and baking tests of Marquis and Kanred wheat stored for 14 to 22 years in dry, unheated rooms at Ft. Collins, Colorado. The grain was in good condition when it went into storage. They found no consistent effect on the protein content of the grain. Ash content of the flour increased with storage, possibly due to brittleness of the bran causing it to pulverize and be carried into the flour during milling. There was an increase in fat acidity with values indicating deterioration, but it was possible to make satisfactory bread from the wheat. Thiamin content did not change materially. The Marquis wheat germinated 91.5 per cent after 11 years and 22 per cent after 22 years storage. The Kanred germinated 90 per cent after 9 years, but only 4 per cent after 21 years.

The milling and baking results of a sample of Turkey wheat stored for 11 years were reported by Swanson (57). It represented 800 bushels harvested in 1927 and stored in a farm bin in Norton County, Kansas. During the storage

period, the wheat had never been turned, ventilated, fumigated, or moved in any manner. When taken from the bin in 1938, it showed no evidence of damage from insects or other causes, and contained 11 per cent moisture. Samples planted in soil in a greenhouse germinated 53 per cent. The wheat milled satisfactorily and produced a good loaf of bread. The quality compared favorably with that of other wheat grown in the same region in 1938.

Swanson (58) studied a small lot of Turkey wheat that had been kept 25 years in a covered tin pail located in a granary loft. The grain was free of insects and in first-class condition, but failed to show life in a single kernel when subjected to a germination test. It behaved almost as normal wheat in milling; however, it produced an inferior loaf of bread in baking tests. He noted that the characteristics of the flour in baking, the texture of the baked loaf, and the properties of the gluten were somewhat identical to those observed in wheat injured in storage when moisture was high and excessive heating occurred. In the latter case, aging processes take place in a comparatively short time and usually in connection with fungi growth. However, the end results were similar when measured by properties of the flour.

Saunders, et al. (50) reported that air-dried wheat was stored for six years in the cool climate of Ottawa, Canada, without loss of baking value.

It would seem, from these isolated, but significant cases, that sound wheat can be stored safely for several years without serious deterioration in milling and baking quality provided it is kept dry, cool, and free of insects.

Sources of High-Moisture Grain

New Grain. Quite often, newly harvested grain is not dry enough for long-term, bulk-type storage. The damp grain may result from harvesting before the grain has dried sufficiently after kernel development, or it may

be caused by dew or rain. There are some grains, such as rice, which must be harvested at very high moisture contents (20 to 25 per cent) in order to secure maximum yield and quality (Kramer, 37). Other grains, including wheat, can be harvested at moisture levels suitable for storage during most years. Climate and the prevailing weather conditions are major factors. About one Kansas harvest in five is prolonged by extreme dampness.

Research has disclosed advantages which sufficiently justify earlier, higher moisture harvests of wheat regardless of weather. Investigators (6)(31) have shown that farmers incur appreciable losses by delaying harvest until the grain is dry. They found that wheat stands in the field about a week in a mature state before it will become dry enough for safe storage - providing weather conditions are ideal. Precipitation and night-time dampness not only lengthen this desiccation period, but tend to shorten the effective harvest day. Each day the crop stands in the field following maturity, additional grain shattering takes place, secondary weed or legume growth is more troublesome, and the risk of lodged grain becomes greater. It was proved that every time wheat is dried to 14 per cent moisture content, then rewet and dried, it will have a lower test weight. This results in market grade reduction. It has been proposed also as a contributing factor in the development of sick wheat.

Method of Harvest. Moisture trouble may originate, primarily, due to the labor-saving machines employed to harvest a crop. Adoption of the grain combine introduced the present era of moisture difficulties in harvesting small grains. With the old binder or header method of harvesting, wheat was usually dry enough when threshed to store safely. It has been observed that the overall grain losses from a properly adjusted combine are least when harvesting about 18 per cent wheat (Johnson and Hurst, 31). Thus, the machine is not

limited in operation by higher than normal grain moistures when the farmer is in a hurry to complete harvest.

Moisture Migration. Low temperature not only has a desirable effect on the insect, respiration, and fungi problems, but it is extremely valuable in retarding a process of moisture migration in the stored grain. When grain has been in a bin during the warm summer months and is held there through the winter, appreciable differences in temperature occur in various parts of the grain mass. As the colder winter weather approaches, grain near the walls and roof of the bin gets cooler. However, the center mass of the grain will remain relatively warm for some time in large bins. Tests conducted by the National Bureau of Standards indicate that for wheat with a moisture content of 12.5 to 14 per cent, the thermal-conductivity varies from 0.89 to 0.98 Btu per degree F per hour per square foot per inch thickness (Kelly, 32). This means that wheat as an insulator is about as effective as sawdust, and will resist transfer of heat to the bin wall. Temperature differences throughout the grain cause corresponding vapor pressure differences. In addition, convection currents are initiated because air from the cool grain displaces the less-dense air in the warm grain. As a result, there is a slow, but continuous migration of moisture from the grain in the warmest area (high vapor pressure) to that which is cool (lower vapor pressure). The increase in moisture usually occurs at the top surface. It can be of sufficient magnitude to cause damp grain heating and mold in the upper 12 to 15 inches of grain.

Obviously, moisture migration can be avoided if the entire mass of grain is maintained at a uniform temperature. In small bins, 1000 bushels or less, it may not be a serious problem because the smaller quantity of grain cools quicker with the advent of cold weather.

Moisture-Tight Storage Structures. A moisture problem in stored grain is created whenever water from an external source enters the bin. Rain and snow may leak or be blown through small openings in the walls and roof, or around the door. Poor surface drainage of the ground around a bin may cause water to run into the structure. Lack of a vapor barrier in the bin floor can result in accumulated moisture in the bottom layers of grain.

Occasionally, snow is carried into a bin which is apparently rain-tight. The wind may deposit it in ventilation openings or blow it through cracks under the eaves of the building. The circular steel bins are especially bad in this respect. During the earlier part of winter, snow which has been deposited on the grain surface may melt rapidly because grain temperatures are still high, and the air space above the grain is warmed by radiation from the sun-heated roof. Kelly (33) observed snow melting on the surface of grain in steel bins when outside, dry bulb temperature was -2°F .

Another source of trouble from snow can occur when drifts against the south side of a bin begin to melt sooner than snow farther away. The trapped water may run into the joint between the side walls and bin floor on the older steel bins.

MOISTURE PROPERTIES OF WHEAT

Since grain moisture and the activity of destructive agents are closely related, consideration must be given to factors affecting the amount of moisture retained by the grain.

Equilibrium Moisture Content

Equilibrium moisture content of hygroscopic materials, which includes all grains, is important because of its direct relationship to storage and

drying problems. The water in a hygroscopic material of a certain moisture content produces a water vapor pressure, P , which is less than the saturated water vapor pressure of pure water, P_g , at the same temperature as the material. The ratio of these pressures, P/P_g is the equilibrium relative humidity for that particular moisture content and the temperature of the material. The equilibrium moisture curve is a graphic expression of the relationship between the moisture content of a material (ordinate) and the relative humidity of the ambient space (abscissa). Temperature affects the curve somewhat, an increase in temperature causing a slight reduction in moisture content for a fixed relative humidity. (Henderson, 22)

Henderson (22) found that the equilibrium moisture content curves for a number of materials have the following mathematical characteristic:

$$\frac{\ln(1 - rh)}{-cT} = Mn \quad 1.$$

$$\text{or} \quad 1 - rh = e^{-cTM^n} \quad 2.$$

where: rh = equilibrium relative humidity expressed as a decimal.

M = equilibrium moisture content, dry basis, per cent.

T = temperature, degrees R.

c, n = constants.

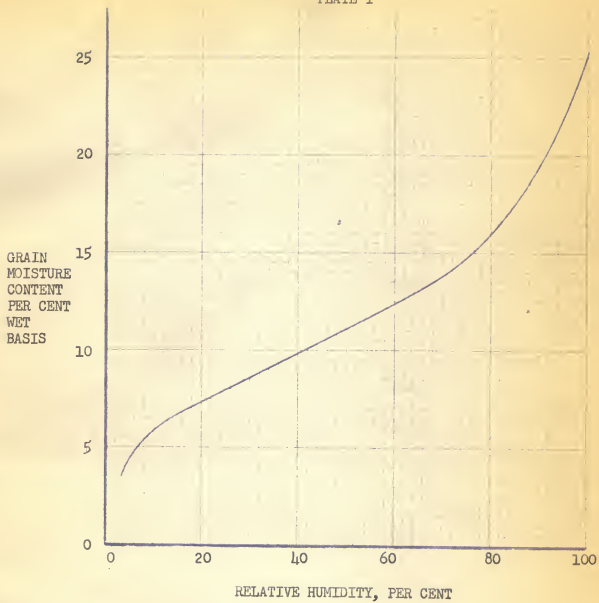
Therefore, equilibrium moisture data can be reported in terms of the constants c and n . For wheat, c is given as 5.59×10^{-7} and n is 3.03.

The equilibrium moisture properties of a grain are significant. If the relative humidity of the air in contact with that grain is higher than the equilibrium relative humidity of the grain at its current moisture content, the grain will increase in moisture content, the moisture content of the air

EXPLANATION OF PLATE I

An equilibrium moisture curve for hard, red winter wheat. Data by Coleman and Fellows (10).

PLATE I



relative humidity being the value approached. An air relative humidity lower than the equilibrium will cause the moisture content to decrease.

Heat Required to Vaporize Moisture

The water contained in a hygroscopic material is bound within the material in some chemical or physical manner, or in a combination of these. It is an intimate part of the material, but does not materially change the physical or chemical properties. According to Henderson (22) the predominant fixing mechanism is adsorption. The molecules of the material attract and physically hold the water molecules. Thus, the binding is assumed to be a surface phenomenon, although moisture of solution, hydration, chemical combination, and capillarity may also be present in limited amount.

"Adsorption" refers to the phenomena associated with the retention and concentration of molecules on solid surfaces. It occurs on the surface of a solid substance because of the existence of certain surface forces. When a gas or vapor is exposed to the solid, the gas molecules become distributed between the gas phase and the adsorbed phase. Concentration of the gas in the adsorbed phase proceeds until a condition of equilibrium is reached. The amount of gas or vapor adsorbed depends on the nature of the gas and solid, temperature, and pressure of the gas or vapor.

Biochemical changes occur so slowly in grain containing up to 14 per cent moisture that it is difficult to detect respiration of the living cells. Johnson and Dale (30) cite research which explains this on the basis of the theory of bound water, i.e., water which is so bound to the grain colloids, particularly proteinaceous substances, that it cannot serve as a solvent and medium in which biochemical changes can occur in the living cell. They also note that such water does not freeze at temperatures below the freezing point

of free water. At a moisture content of 15.6 per cent, over 90 per cent of the total water in wheat is reported as bound water. Free and bound water are present in about equal quantities as the moisture content approaches 30 per cent.

Grain-drying processes, which usually lower the moisture content to 13 per cent or below, apparently involve the removal of both free and bound, or adsorbed water.

The heat required for a phase change may be predicted from thermodynamic considerations. Othmer (42) devised a method using vapor pressures at different temperatures and based upon the Clapeyron equation. This equation is developed and applied in chemists' thermodynamic texts and may be expressed in the form:

$$dP/dT = L/(V-v)T \quad 3.$$

where: P = vapor pressure.

T = absolute temperature.

L = heat of vaporization at average temperature, T.

V = specific volume of saturated vapor.

v = specific volume of saturated liquid.

If the vapor is assumed to behave as an ideal gas and the volume of the liquid is neglected, the equation becomes:

$$dP/dT = LP/RT^2 \quad 4.$$

where R is the gas constant.

This form is known as the Clausius-Clapeyron equation. The method of Othmer makes use of the preceding equation to predict the heat of vaporization of one liquid if the heat of vaporization of another liquid is known at

the same temperature, and vapor-pressure data for both liquids are available.

The equation developed is:

$$\log P = L/L' \log P' + C \quad 5.$$

where: P = vapor pressure of one liquid.

P' = vapor pressure of second liquid.

L = heat of vaporization of first liquid.

L' = heat of vaporization of second liquid.

C = constant of integration.

It is evident from the above equations that if the vapor pressures are plotted on a log-log chart, the slope of the resulting line will be equal to the ratio of the heats of vaporization. This method was used by Gallaher (18) to predict heat of vaporization in wheat. The most convenient reference liquid is free water since abundant data for it is available in steam tables.

The preceding method of predicting heat of vaporization is based on equilibrium vapor-pressure data. During a drying process, equilibrium conditions do not prevail. In fact, it is the non-equilibrium condition, with respect to vapor pressures of moisture in grain and that in the drying air which provides the drying potential. This limits the application of the Clausius-Chapeyron equation. While drying, grain kernels may have a certain mean moisture content measured by weighing, but this is not necessarily the moisture content at the regions where vaporization is actually occurring. The wheat kernel is composed of a somewhat dense material which offers resistance to movement of moisture from the interior to the surface. Moreover, the particle is non-uniform in shape, and heterogenous in physical and chemical properties. (Johnson and Dale, 30)

Calculations of the latent heat of vaporization have been investigated. Although explicit numerical results are possible, further study appears advisable because of some inconsistencies between calculated and observed values.

Table 1. Heat of vaporization of moisture in wheat in BTU per pound of water.

Moisture Content, Per Cent Wet Basis:	Values Calculated	Values Calculated	Values Determined
	From Henderson(22): Equilibrium Equation	By Gallaher (18) Using Vapor Pressure: Data of Gay (19)	Experimentally By Johnson and Dale (30)
18	1030	1020	985
16.7	1040	1025	995
15.2	1050	1035	1010
13.8	1060	1055	1040
12.25	1070	1100	1080
10.75	1080	1220	1125
9.1	1090	1460	1180

Table 2. Heat of vaporization of moisture in wheat in BTU per pound at various temperatures of evaporation. Data by Thompson and Shedd (63).

Moisture Content, Per Cent Wet Basis:	Temperature in Degrees F					
	32	50	70	100	150	
15	1110	1100	1090	1070	1040	
14	1130	1120	1110	1090	1060	
13	1160	1150	1140	1120	1090	
12	1200	1190	1175	1155	1120	
11	1250	1240	1225	1200	1170	
Free Water	1075	1065	1055	1037	1008	

Johnson and Dale (30), following experimental observation, concluded that the heat requirement for vaporization is essentially dependent on kernel

moisture content only. If this is true, the moisture gradient, though necessarily present during drying, would have but little influence on the heat of vaporization at a given average kernel moisture content. Drying temperature and initial moisture would not be significant.

On the other hand, Thompson and Shedd (63), using the Othmer method, took into consideration both temperature of evaporation and initial grain moisture. The results of their tests and calculations are reported in Table 2.

One general conclusion can be made as a result of reviewing previous research. As kernel moisture decreases, the heat of vaporization of moisture in wheat increases, approaching a value of perhaps 1.2 times that for free water when the kernel contains about 9 per cent moisture.

The Drying Process

In a simple batch drier, grain is placed in a bin and air is directed through it until the desired moisture content is reached. With this type drier, grain at the air intake side dries most rapidly, and that where the air leaves takes longest to dry. It has been observed that drying takes place, generally, in a narrow layer of grain at the intake side, and this layer may be dried almost to completion before other layers have lost appreciable moisture. The layer of grain in which most of the drying is taking place is referred to as the "zone of drying." The zone of drying progresses through the grain in the direction of air movement until it has passed all grain and drying is complete.

When evaporation of grain moisture occurs, heat must be absorbed. There are two possible sources for the heat - the sensible heat of the grain and the sensible heat of the air. Sound, healthy grain will not be hot enough at the

start to supply enough heat for the complete drying process, and so the air must furnish practically all of it. For this reason, air will undergo a drop in temperature as it passes through the grain if any drying has taken place. Other conditions known, this temperature drop can be used to measure the amount of drying actually done.

As air enters damp grain in a drying bin, some moisture is evaporated. The air suffers a reduction in temperature and an increase in relative humidity. As the air continues through the grain, moisture will evaporate less rapidly in successive layers because of the lower temperature and higher humidity. Eventually, its humidity will be high enough and temperature low enough that no more drying can occur. The total heat of the air would be the same as at the start, but some of its sensible heat would have been used to supply heat for vaporization which is now contained in the air as latent heat. Essentially, this approximates a process of constant total heat. Since total heat of air is a function of wet-bulb temperature, it is simplest to describe the process as one approaching adiabatic saturation. Under steady flow conditions in a batch type drier, the wet-bulb temperature of the air exhausted from the grain is nearly equal to the wet-bulb temperature of the air entering the bin. This relation is modified, of course, if there are excessive losses of heat by conduction or radiation. It is further modified because grain moisture requires more heat for vaporization than does free water.

The drying rate varies from layer to layer and from time to time in a batch or bulk grain drier. The change in moisture content of grain in a given layer and at a given time depends on the characteristics of the grain and the air employed for drying. Several factors combine to determine the drying progress. They are:

1. The drying rate at full exposure for the kind of grain.

2. The initial air temperature (dry bulb).
3. The wet-bulb temperature of the air.
4. Depth of grain through which the air passes.
5. Volume of air passed through the grain.

Exposed Drying Rate. The drying rate of fully exposed grain is a function of the air temperature and humidity, and the grain moisture content. It is affected very little by air velocity. With a given temperature, humidity, and moisture content, each grain dries at some characteristic rate. Smaller grains generally dry faster than larger ones, and the characteristic rate for each grain varies also with previous treatment.¹

With fixed air conditions, the rate of moisture loss is proportional to the difference between the existing moisture content of the grain, and the moisture content which it would have at equilibrium with the air. At a given moisture content and at a given wet-bulb temperature, there will be a dry-bulb temperature at which the grain and air are in equilibrium. Under these conditions, the rate of moisture loss at full exposure appears to be approximately in proportion to the difference between the dry-bulb temperature of the air and the dry-bulb temperature which the grain would have at equilibrium. As air moves upward through grain of uniform moisture content, the wet-bulb temperature of the air remains constant but the dry-bulb temperature drops, approaching a temperature at which the air and grain are in equilibrium. At any point along its path the rate of evaporation appears to be nearly proportional to the amount by which the dry-bulb exceeds its final equilibrium temperature. With these two assumptions, both of which are approximations, it

¹For example, grain which has been dried once and then rewetted will dry somewhat more rapidly than naturally wet grain (27).

is possible to follow the course of drying air through grain, and compute the rate of evaporation at any point and also the moisture content at any time after drying starts. (Barre and Sammet, 5; Hukill, 27)

Air Temperature - Dry-bulb and Wet-bulb. It is obvious from the previous discussion that raising the dry-bulb temperature of the air results in a reduction of time required for drying. Since grain drying is nearly an adiabatic process, the maximum total heat available from the air is the sensible heat represented by a drop in temperature from the initial dry-bulb to the wet-bulb. At grain moisture contents below 25 per cent, wet basis, even less heat is available because the dry-bulb cannot drop to equal the wet-bulb temperature unless the air is exhausted from the grain at 100 per cent relative humidity. Initial dry-bulb and wet-bulb temperatures in combination determine the relative humidity which in turn fixes the final moisture content which the grain approaches.

Depth of Grain. The depth of grain through which the air passes, together with the velocity of the air, determines how long each particle of air stays in the grain. In general, the longer the air takes in passing through the grain, the more completely its available sensible heat is used for evaporation and the more the difference in drying rate between bottom and top layers. (Hukill, 27)

Volume of Air. If air is supplied in large volume, its condition changes proportionately less in passing through a given thickness of grain than if supplied in small volume. Tests indicate that under conditions of given initial temperature, humidity, and grain moisture content, the factors of depth of grain and rate of air flow in cubic feet per minute per square foot of floor area may be combined into a single factor of pounds of air per minute

per unit weight of dry grain and handled independently of grain depth or air velocity. For example, if air is passed through grain at the rate of 1/2 pound per minute per 500 pounds of dry grain, the moisture changes in the bottom, top, or intermediate layers will be the same regardless of whether the grain is in a deep column of small cross section, or in a shallow depth of large cross section. (Hakill, 27)

METHODS OF CONDITIONING HIGH-MOISTURE WHEAT

In the farm storage of wheat, several methods have been employed to remove excess moisture and heat. They include moving or turning, natural ventilation, and mechanical ventilation.

Turning

Turning grain (moving it from one bin to another) to prevent heating and deterioration is a common practice in terminal and country elevators. This may be done conveniently where grain can be drawn by gravity from one bin into an elevator pit and elevated to another bin without any hand work. It requires one empty bin. Most farms are not equipped to move grain economically from one bin to another; but this practice has been carried on experimentally in farm type bins to determine what benefits will result. Kelly, et al. (34) found that turning does not make any important reduction in the average temperature or the average moisture content of a bin of grain. However, when moisture content is uneven, turning is often effective in arresting heating and deterioration by mixing the damp grain with the dry.

In grain bins containing hot spots due to insect infestation, turning scatters these insects throughout the bin, causing universal infestation of the grain.

Natural Ventilation

A large amount of experimental work has been done in testing the storage of damp grain in bins provided with various designs of ventilators that depend upon the wind to force air through the bin. The practice has never gained widespread acceptance because of the inherent limitations. Swanson and Fenton (59) conducted one of the first investigations on practical methods of conditioning high-moisture wheat in 1929-1931. Their natural ventilation systems demonstrated the value of aeration in drying and cooling damp grain. But they concluded that when grain moisture was high and the weather hot, no system of natural ventilation would solve the storage problem.

Other investigations (32)(33)(34) of natural ventilation systems have since been undertaken, but no satisfactory design has evolved. There is currently a renewed interest in the possibility of using this method to cool stored grain during the winter in order to control moisture migration.

Mechanical Ventilation

Mechanical ventilation of stored grain involves the use of a power-driven fan or blower to create a positive movement of air through the grain. The method is gaining in popularity since most farms now have electrical service. Either heated or unheated air may be forced through the grain. Usually, air is blown through the grain from bottom to top; however, the process may be reversed and the air sucked downward through the grain.

MINIMUM AIR FLOW REQUIREMENTS

Mechanical ventilation with unheated air may be used for drying grain and offers certain advantages over heated air. This method is usually less

expensive, requires less supervision, and presents less fire hazard than drying with heated air. However, the effectiveness of unheated air drying is dependent on weather conditions.

In addition to the uncontrollable weather factor, the moisture ranges through which grain is to be dried and the rate at which the drying air is supplied are important factors influencing the effectiveness of unheated air drying. The air-flow rate used greatly affects both the equipment required and the operating cost. For example, increasing the rate of air flow from two to four cfm per bu. through the same depth of grain will increase the power required about six fold, while the drying rate can only be doubled. Thus it becomes important to establish the minimum rate of air flow which can be expected to dry the grain without objectionable quality deterioration during the drying process. Actually, the controlling factor is the maximum length of time the grain can be held with excess moisture before drying is completed.

Agricultural authorities differ in the air flow rates required for drying wheat. In general, three cubic feet of air per minute (cfm) per bushel should be supplied when grain moisture is 18 to 20 per cent. With grain moisture in the range of 16 to 18 per cent, two cfm per bushel is considered sufficient. Below 16 per cent, one cfm per bushel will be adequate under most circumstances.

Air flow rates of 1/10 cfm per bushel and less are sufficient for cooling dry grain in order to avoid moisture migration.

RESISTANCE OF WHEAT TO AIR PASSAGE

The void space in wheat has been reported as 43 per cent (Zink, 65). In the design of a mechanical ventilating system for drying high-moisture wheat, reliable data on the resistance to passage of air is essential. Factors

affecting air flow, including moisture content, density, presence of cracked grain and foreign material must be given consideration. Some information has been published on pressure-flow relationships under conditions of parallel flow. (Henderson, 24; Kelly, 32; Shedd, 51; Stirniman, Bodnar and Bates, 56) Unfortunately, each investigator has chosen a different method of reporting data and the results are somewhat difficult to interpret. None of the data were presented in a form suitable for use by the layman.

Factors Affecting Air Flow

Moisture Content. The density of high moisture grain is less and the resistance pressure less for a given rate of air flow than for the same grain after it has been dried to a lower moisture content. However, in a batch drying operation, shrinkage of the kernels tends to loosen the fill as the grain dries. This loosening offsets any increase in pressure requirements that would be expected as a result of reduced moisture content.

Density. There is no record of how the density of wheat used in the laboratory resistance to air passage measurements compares with the density of wheat in a full-scale farm bin as normally filled. Shedd (52) did observe, however, that vibration of his test bin while filling, changed the density from 49.8 to 51.8 pounds per cubic foot for wheat with 11.3 per cent moisture. This increased the ventilation pressure requirements by 30 per cent. Kelly (32) reported that changes in density affected air flow characteristics by as much as 10 per cent in his tests.

Cracked Grain and Foreign Material. Foreign material mixed with wheat tends to increase the resistance to air flow if the foreign material is finer than the whole kernels, and to reduce the resistance if it is coarser than the grain. Kelly (32) noted that the rate of air flow through wheat containing

two per cent of fine chaff was approximately 25 per cent less than through clean wheat, under similar conditions of pressure and grain depth. The other investigators also observed such effects.

Pressure Ventilation vs. Suction Ventilation. The test apparatus of Shedd's (52) provided a good means of comparing the effect of forcing vs. drawing air through grain. Checking on the basis of pounds of air flow per unit time, he found that drawing the air resulted in about two per cent reduction in weight of air moved. It would be safe to assume that any apparent saving in power by drawing rather than forcing the air will be offset by reduction in weight of air delivered.

All test data available were measured when forcing air through the grain.

Size of Bin. The theory has been advanced that air will have a tendency to flow up along the bin-wall surface rather than pass evenly through the mass of grain. Each of the investigators cited made attempts to isolate any effects of bin-wall surface area on rate of air flow. All of them concluded that the effect of wall surface is negligible.

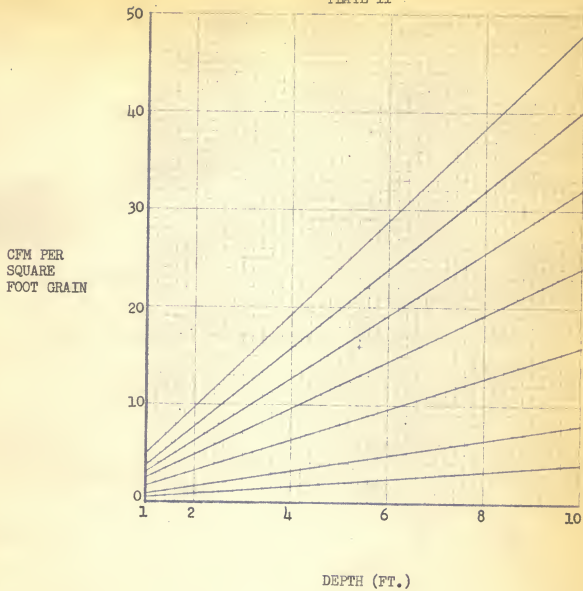
Units of Pressure and Flow

Air flow rates are most commonly stated in terms of cfm per bushel. Pressure requirements for ventilation are given in inches of water. But resistance of grain to air passage is best specified in terms of pressure loss per foot depth of grain (inches water) for a given air flow in cfm per square foot of grain. Thus, when applying such data, air flow in cfm per bushel must be converted to cfm per square foot of grain before a pressure loss value can be obtained. There is some misunderstanding in connection with this conversion and why it is necessary. However, consideration must be given to the fact that a bushel of wheat represents no particular physical dimensions. Such a

EXPLANATION OF PLATE II

Chart for converting air flow in cfm per bushel to cfm per square foot. Curves are shown for air flows of from 0.5 to 6 cfm per bushel for depths of grain up to 10 feet.

PLATE II



quantity of grain can be of shallow depth and large cross section or in a deep column of small cross section. Obviously, there could be no correlation between the pressures required to force air through a quantity of grain unless they are specified in terms of a unit cross section and a unit depth. Once the value of cfm per bushel is converted to cfm per square foot and a total pressure figure established for a given depth of grain, the information can be presented in curve form. Charts have been prepared to facilitate this conversion and the ensuing determination of pressure requirements for ventilating different depths of wheat at various rates of air flow. They are included as Plates II, III, and IV.

Pressure-Flow Relationship Equations for Parallel Air Flow

Stirniman, et al. (56), Kelly (32), Henderson (24), and Shedd (52) have published data on the pressure losses encountered in forcing air through certain grains. The data were obtained from experimental observations with each investigator employing different test apparatus. A comparative study of their results reveals both minor and major discrepancies, depending on the magnitude of air flow. Considering the variables involved in measurements of this type, the data can be depended on to give a close approximation only of the pressure losses which might be encountered in practice.

Shedd's (51)(52) work appears to be the most complete, and the positive displacement type air pump used in his tests lends itself to good accuracy. For the rather narrow range of air flows used in unheated air grain drying, the pressure-flow relationship which he established experimentally can be expressed within limits by the formula:

$$Q = xP^V \quad 6.$$

where: Q = air flow in cfm per square foot of grain.

P = pressure loss per foot depth of grain in
inches of water.

x = the value of Z when $P = 1$.

y = the slope of the pressure-flow relationship
curve for a given grain.

In the case of wheat, x is 32 and y is 0.80. The formula fits the experimental pressure flow relationship curve (Plate III.) quite well within the range of 10 to 40 cfm per square foot. Below or above these values deviation can be expected.

To express the relationship throughout a greater range of air flows with good accuracy, Hukill and Ives (28) suggest a more involved equation of the form:

$$P = cQ^2 / \ln(1 + kQ) \quad 7.$$

where: P = pressure loss per foot depth of grain in
inches of water

Q = air flow in cfm per square foot of grain.

c = constant = 0.00092 for wheat.

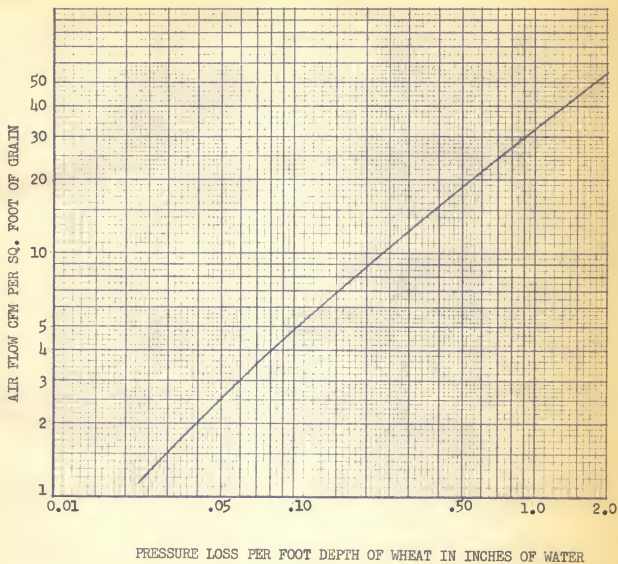
k = constant = 0.050 for wheat.

There is no experimental evidence to indicate the validity of this equation if extrapolated to values above or below Shedd's data. It is interesting to note that as the value of Q in Equation 7 increases without limit, the relationship between P and Q approaches $P = KQ^2$. As Q decreases toward zero, the relationship approaches $P = KQ$.

EXPLANATION OF PLATE III

Pressure-flow relationship for ventilating wheat
under conditions of parallel flow. Data by Shedd (51).

PLATE III



The Problem of Non-Parallel Air Flow

All measurements on the resistance of wheat to air flow have been made under conditions of parallel flow. The investigators employed small cylindrical or rectangular bins with perforated floors. Air was introduced uniformly throughout the cross section of the grain mass, and therefore, the air-flow paths in the grain were essentially parallel.

From the practical standpoint, perforated floors are installed in a few of the circular steel bins for grain drying purposes. The performance of such a system in ventilating wheat can be satisfactorily predicted from Shedd's (52) data provided the perforations in the floor are sufficient to allow air to enter the grain freely. The research conducted by Henderson (24) on the resistance to air flow of perforated steel sheets covered with oats would indicate that about 10 per cent opening should be the minimum for wheat, depending on the size, shape, and distribution of the openings. Perforated steel sheets sold for use as flooring in drying bins usually have about twice that percentage of opening.

Although perforated flooring is the most efficient means of distributing air in a grain ventilation system, it has several inherent disadvantages. It involves a greater investment, is difficult to suspend, and hard to clean when emptying the bin. Cracked kernels of wheat fall through the perforations and collect in the plenum below where they serve as a breeding place for insects. It is for these reasons that the cheaper, more flexible, duct type distribution system is most commonly used in farm storage bins for grain drying purposes.

Pressure requirements for ventilating a bin of wheat with a duct system are not so easily predicted since parallel air flow does not exist in the

areas adjacent to the ducts. Ducts are spaced three to four feet apart and air flow away from them is divergent. Parallel flow characteristics are not realized until the air has fanned out over the entire horizontal cross section of the bin. This will be at some certain height above the bin floor depending on duct design, duct spacing, rate of air flow, and depth of grain. It is obvious that there will be stagnation areas in the grain with a duct distribution system, i.e., areas near the floor and mid-way between the ducts where air movement is very slow as compared with other locations. Also, if the air escape opening in the ducts is equivalent to 20 per cent of the floor area, for example, the velocity of the air at a point where it leaves the ducts and first enters the grain will be about five times greater than at a point in the grain where parallel flow conditions exist.

Thus, with a duct type air distribution system, pressure losses will be proportionately greater in the bottom layers of grain. Up to the time of this study, there was no published report of any attempt to evaluate these losses. Hall (21), and Hukill and Ives (28) have devised methods of analyzing radial air flow characteristics from a single duct in non-rectangular cross section bins. But their procedure is of little value in the case of multiple duct ventilation systems in rectangular structures.

A STUDY OF AIR DISTRIBUTION DUCTS

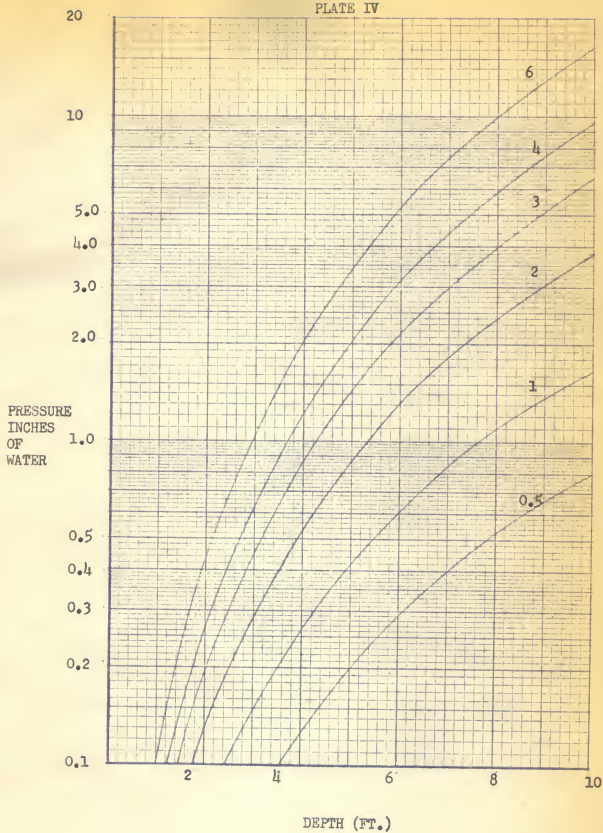
Objectives

Moisture is the most important single factor affecting deterioration of wheat in storage. The moisture content of stored wheat can be reduced if the grain is ventilated adequately with dry air. Through research and practical experience, minimum air flow requirements for drying wheat are established.

EXPLANATION OF PLATE IV

Pressure-air flow relationship for ventilating wheat
at rates of from 0.5 to 6 cfm per bushel for grain depths
up to 10 feet. Data by Shedd (51).

PLATE IV



Under certain ideal conditions of parallel flow, the pressures required to ventilate the grain at these rates have been determined. A majority of the farm grain drying installations consist of duct type air distribution systems. Design of these systems involve pressure-air flow relationships which had not been investigated.

The objectives of this study were:

1. To duplicate previous investigations on the resistance of wheat to air passage and compare the results with existing pressure-flow data.
2. To determine, in relation to the floor area of storage bins, the minimum concentrated air escape area necessary for efficient ventilation of wheat in farm type storage structures.
3. To compare the pressure-flow characteristics of various types of air distribution ducts commonly used for grain ventilation.

Experimental Apparatus

Test Bin. The dimensions of the wooden test bin employed in the study were considerably larger than those of bins used in previous investigations. The grain chamber was four feet square and 10 feet high. The air plenum located directly below the grain chamber was four feet square and two feet in depth. Stirniman, et al. (56) used a circular metal bin two feet in diameter with a maximum depth of 12 feet. Kelly's (32) bin was a cylindrical metal tube 18 inches in diameter and eight feet high. Henderson (23) had a circular metal bin $8\frac{1}{2}$ inches in diameter and eight feet high. Shedd (52) employed an

EXPLANATION OF PLATE V

An overall view of the test apparatus used in the study. Inside dimensions of the bin are four feet by four feet. The plenum is two feet in depth and the grain chamber ten feet in depth. The pressure taps on the right side extend to the center of the bin. The two smaller doors on the front were for removing grain and directly below them is the plenum door. The bin was constructed in three sections to facilitate handling.



eight inch circular metal tube nine feet in height. The major reason for the larger bin in this case was to facilitate testing of full-size specimens of the various air duct designs. Density of grain placed in a large test bin also more nearly approaches the density of the same grain in an actual farm bin.

In order to accomplish the first and second objectives of the investigation, a special type floor was installed between the grain chamber and plenum of the test bin. A layer of 1/8 inch hardware cloth served as the previous flooring. It was suspended over one inch by six inch wood joists spaced six inches apart. Air from the plenum passed between the joists, through the hardware cloth, and into the grain. To vary the per cent of air opening to the grain, small panels were used to seal off the individual spaces between the joists so that air could not pass. These were added or removed by opening a small air-tight door in the side of the plenum. Since they were located below the hardware cloth which supported the grain, changes were made without disturbing any wheat in the grain chamber.

The 1/8 inch hardware cloth had about 73 per cent free opening.¹ The floor joists supporting the hardware cloth restricted 15 per cent of the total floor area. The net result was a total actual air opening of 62 per cent of the floor area. By use of the removable panels which fit between the joists, the air entrance area was varied in amount by 1/8 intervals. Thus, data on air flow were recorded for 62, 54.25, 46.5, 38.75, 31, 23.25, 15.5, and 7.75 per cent concentrated air opening in terms of total floor area. By "concentrated" opening, it is meant that the openings were not uniformly distributed

¹This was measured by photographing the hardware cloth, printing an enlarged photo (25X) of it, and then using a planimeter to establish the open and restricted area.

over the entire floor, but are all located in small portions of the floor. This corresponds to a duct type air distribution system.

For testing the air ducts, the hardware cloth was replaced with a solid plywood panel floor. The ducts rested on this and the air was introduced at one end of them, as would be the case with an actual farm installation. The bin is shown in Plate V.

Air Source. Numerous types of air moving devices have been employed in past investigations of this nature. Stirniman, et al. (56) and Kelly (32) used centrifugal type blowers, Shedd (52) a single-action, positive displacement, pneumatic pump, and Henderson (23) used compressed air at reduced pressures. In the case of the latter two methods, steady flow conditions were possible for only short periods of time - depending on rate of air flow.

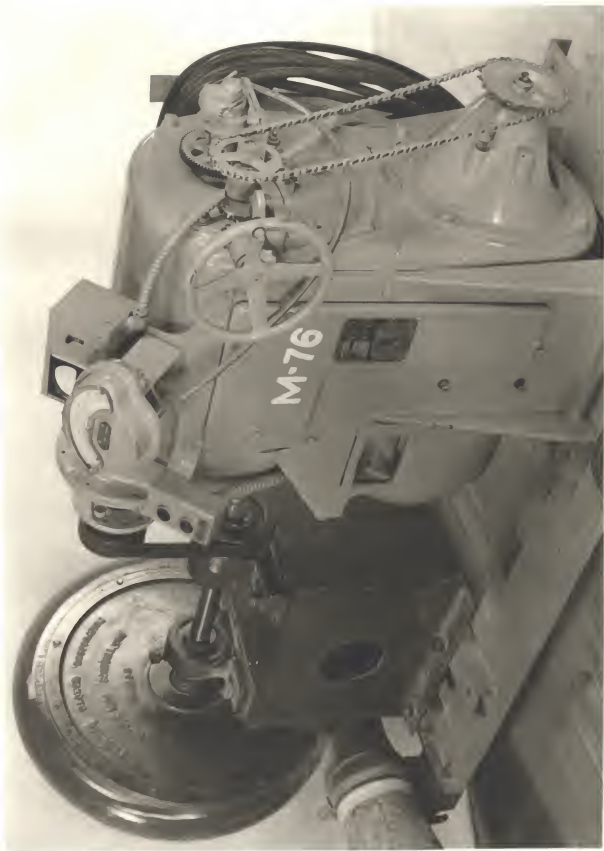
A comparatively large volume of air, under steady-flow conditions and over a wide range of pressures, was desirable for this study. Due to the method of air flow measurement, higher pressures were necessary than would be encountered in grain ventilation alone. A No. 5, Type F, high-pressure, centrifugal blower furnished by the American Blower Company was utilized. It was capable of delivering up to 1200 cfm while developing a pressure of 30 inches of water. The blower was powered by a $7\frac{1}{2}$ horsepower electric motor through a Reeve's variable-speed drive. A combination of blower speed regulation and restriction of air inlet to blower served to adjust rate of air flow. The blower could be operated at speeds ranging from 600 to 3500 rpm. The unit is shown in Plate VI.

Air Flow Measurement. A four inch diameter, A. S. M. E. long-radius nozzle was employed to measure rate of air flow. It was installed, according to standard specifications (15), in the nine foot section of 12 inch diameter

EXPLANATION OF PLATE VI

A view of the high pressure blower used to force air through the grain, along with the 7-1/2 horsepower, variable speed, electric drive.

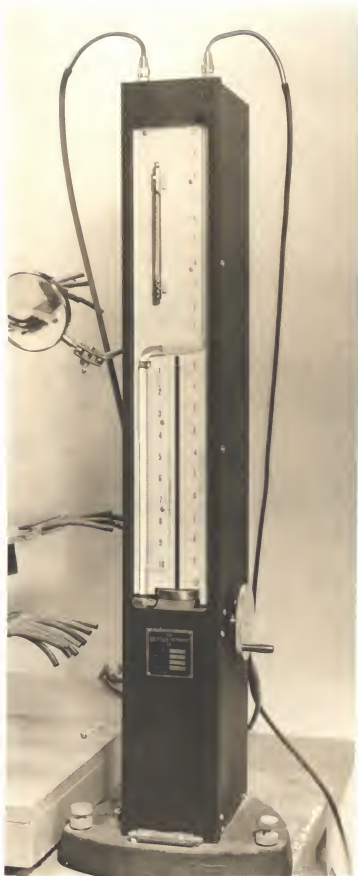
PLATE VI



EXPLANATION OF PLATE VII

Meriam water manometer employed to measure velocity pressure of nozzle. It has a range of ten inches and is accurate to 0.001 inch of water.

PLATE VII



light-metal pipe which was used to deliver air from the blower to the bin plenum. A combined pitot-static tube served as a means of measuring air velocities through the nozzle.

Based on the Bernoulli theorem, the net pressure (velocity head) indicated by the pitot tube is very nearly

$$h_a = v^2/2g \quad \delta.$$

where: h_a = velocity head measured in feet of air.

g = acceleration due to gravity in feet per second per second = 32.2.

v = air velocity in feet per second.

Since velocity head is measured more conveniently in inches of water, a conversion is necessary to make the relationship useful.

$$h_a = h_w \times \frac{D_w}{D_a} \times \frac{1}{T_s/T_a \times P_b/P_s}$$

where: h_a = velocity head measured in feet of air.

h_w = velocity head measured in inches of water.

D_w = density of water in pounds per cubic foot at temperature $T_s = 62.4$.

D_a = density of air in pounds per cubic foot at temperature T_s and pressure $P_s = 0.0807$.

T_s = standard temperature for conversion in degrees R = 492

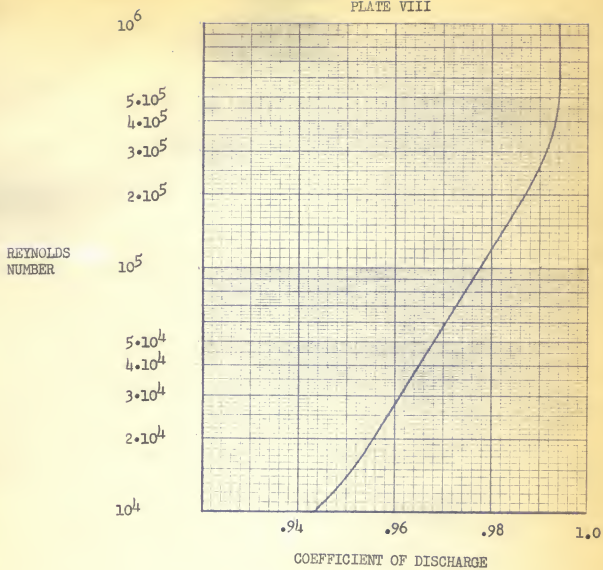
T_a = temperature in degrees R of air passing through nozzle at time of velocity measurement.

P_b = barometric pressure in inches of Hg existing at time of velocity measurement.

EXPLANATION OF PLATE VIII

Curve showing the relationship of discharge coefficient to Reynolds Number for the A. S. M. E. long-radius nozzle employed to measure air flow. Data from Flow Measurement (47).

PLATE VIII



P_b = standard barometric pressure in inches Hg =
29.92.

Substituting the given numerical values into Equation 9., and reducing to its simplest form

$$h_a = 3.92 \times \frac{h_w \times T_a}{P_b} \quad 10.$$

Combining Equations 8 and 9

$$\begin{aligned} V^2/64.4 &= 3.92 \times \frac{h_w \times T_a}{P_b} \\ V^2 &= 64.4(3.92 \times h_w \times T_a/P_b) \\ V &= 15.885 (h_w \times T_a/P_b)^{\frac{1}{2}} \end{aligned} \quad 11.$$

Since air flow is equal to the product of the velocity and cross-sectional area of the nozzle

$$Q = 15.885 AC(h_w \times T_a/P_b)^{\frac{1}{2}} \quad 12.$$

Where: Q = air flow in cubic feet per second.
 A = cross-sectional area of nozzle in square feet.
 C = discharge coefficient which varies with
Reynolds number.

The relationship of the discharge coefficient to Reynolds number is given in Plate VIII. Reynolds number can be determined by

$$R = Vdu/v \quad 13.$$

Where: R = Reynolds number, dimensionless.
 V = average velocity of fluid stream in
feet per second.
 d = nozzle diameter in feet.

u = specific weight of fluid in pounds per cubic feet.

v = fluid viscosity in pounds per foot second.

Pressure Measurement. A Meriam water manometer was used to indicate the velocity head at the nozzle for flow measurement purposes. It has a ten-inch range and was accurate to 0.001 inch. It is pictured in Plate VII.

An inclined, multiple tube, well type manometer was constructed to indicate pressures in the bin plenum and at various locations in the grain. It consisted of ten glass tubes, 40 inches in length, inclined at a ten to one (horizontal to vertical) slope, ten tubes at a five to one slope, and ten tubes at a two to one slope. Scale ranges for each slope were four, eight, and 20 inches respectively and the scale accuracy was 0.01, 0.02, and 0.05 inch of water. When the test bin was filled to a ten-foot depth, a total of 16 different pressures were recorded at one time. Thus, 18 glass bottles (800 c.c.) served adequately as manometer wells. Since increasing the area of the well results in a greater accuracy for the same size manometer tube, the bottles were supported on their sides and filled one-half full of distilled water. Each bottle could be raised or lowered independently for adjusting the liquid level to zero on the scale. All of the bottles could be used in conjunction with tubes at any of the three slopes, and were switched from tubes of one slope to those of another as the need arose. A picture of the complete unit is included as part of Plate IX. The Meriam instrument which has been described was used for calibrating the inclined manometer tubes.

Atmospheric or barometric pressure was recorded from a mercury barometer located near the test apparatus.

Grain. Newly-harvested wheat of the 1955 crop was obtained for the tests. It had a 14 per cent moisture content, contained less than one per

EXPLANATION OF PLATE IX

Well-type, inclined water manometer constructed to measure pressures in grain. Tubes are arranged at slopes of ten to one (horizontal to slope), five to one, and two to one, allowing an accuracy of 0.01, 0.02, and 0.05 inch of water, respectively.

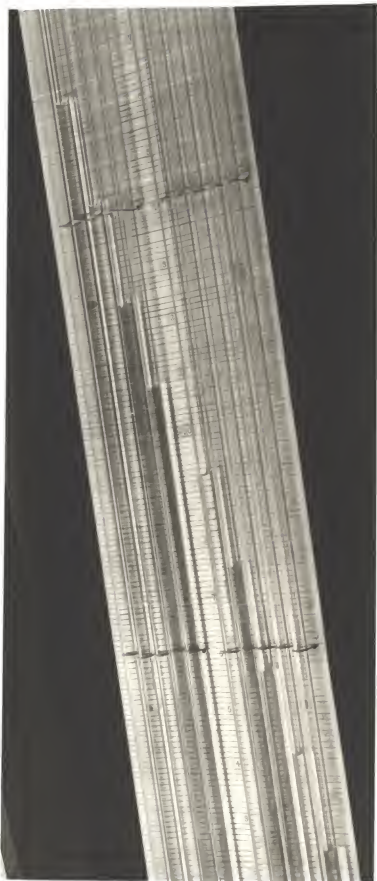
PLATE IX



EXPLANATION OF PLATE X

A close-up of the manometer tubes and scale arranged at the ten to one slope. Each scale division is equivalent to 0.01 inch of water.

PLATE I



cent foreign materials, and had about two per cent of the kernels broken or damaged.

Grain Handling. An auxiliary bin was constructed to hold the grain when it was not in the test unit. A four-inch diameter, auger conveyor served to transfer the grain from one bin to the other.

Test Procedure

1st Test. This test was designed to fulfill the first and second objectives of the study. Wheat was put in the bin in a manner which insured no unusual packing or accumulations of foreign materials. It was kept uniformly distributed at all times. Air flow rates of from one-half to ten cfm per bushel were used with grain depths of from two to ten feet in one-foot increments. Pressures in the grain were measured at one, two, four, six, 12, 18, and 24 inches above the floor and at one-foot intervals for depths exceeding 24 inches. Air opening in the hardware cloth floor was varied from 7.75 to 62 per cent.

The bin was filled up to a depth of six feet a second time and data were recorded at various points in order to substantiate data from the first fill.

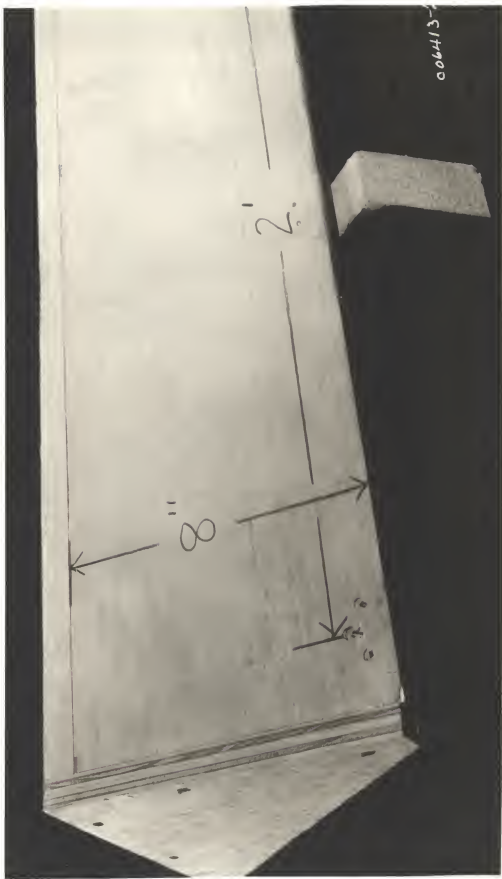
2nd Test. A check was made to determine the effect of putting the bottom layer of wheat in the bin in such a manner as to make more kernels fit into the openings of the hardware cloth. After the bottom six-inch layer of grain was in place, the bin was filled as in Test 1. Only the plenum pressures required to maintain air flow rates of from one-half to ten cfm per bushel were recorded for air openings of 7.75 to 31 per cent of the floor area.

3rd Test. The bin was filled by dropping the wheat from a point 10 feet above the floor and directly over the center of the bin. The grain piled in a cone and was leveled without tramping at four, six, eight, and ten foot

EXPLANATION OF PLATE XI

The triangular, wood duct raised $3\text{-}\frac{5}{8}$ inches above floor.

PLATE XI



EXPLANATION OF PLATE XII

The triangular, steel duct raised seven inches above
the floor.

PLATE XII



EXPLANATION OF PLATE XIII

The trianguler, steel duct enclosed with fly screen.

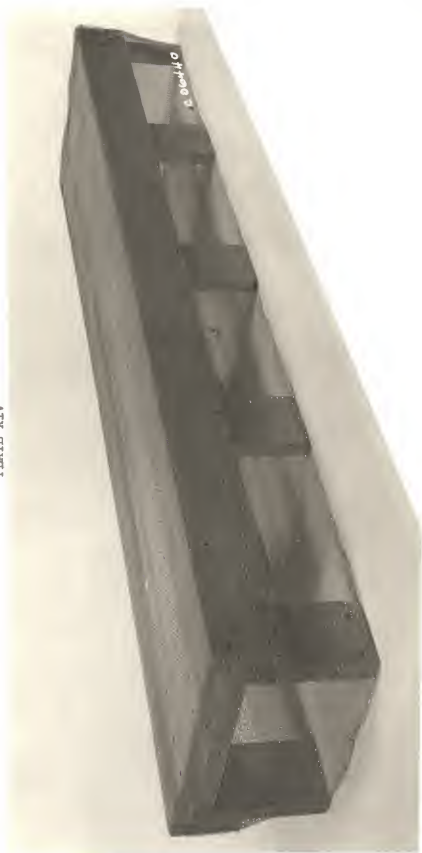
PLATE XIII



EXPLANATION OF PLATE XIV

Rectangular, wood frame duct covered with $1/8$ inch hardware cloth.

PLATE XIV



EXPLANATION OF PLATE XV

Semi-circular, steel frame duct covered with fly
screen.

PLATE XV



EXPLANATION OF PLATE XVI

- Fig. 1. Enlarged close-up photo of fly screen showing relative size and distribution of openings.
- Fig. 2. Enlarged close-up photo of 1/8 inch hardware cloth.
- Fig. 3. Enlarged close-up photo of perforated steel sheet.

PLATE XVI

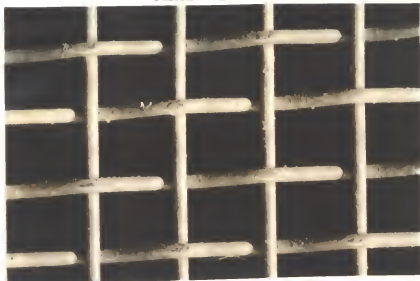


Fig. 1. Fly screen.



Fig. 2. Hardware cloth.

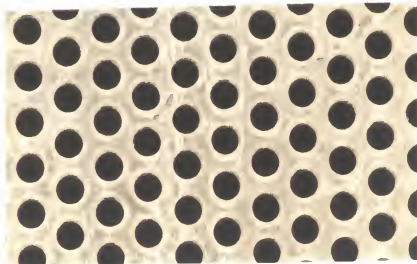


Fig. 3. Perforated steel sheet.

depths. Plenum pressure data were recorded for various air flow rates, and air openings of 7.75 and 15.5 per cent.

4th Test. The 3rd Test was repeated up to a grain depth of six feet to substantiate the data. The grain was tramped thoroughly at that level in order to note the effects. This is the depth at which most farmers would first walk on grain to level it in an actual bin.

5th Test. The 1/8 inch hardware cloth was replaced with fly screen and the procedure of the 1st Test repeated. The fly screen had 66 per cent free opening. This made possible variations in air openings in steps of seven per cent, i.e., 7, 14, 21, per cent. The major reason for this test was to compare the effects of different sizes and arrangements of air openings or perforations.

6th Test. The procedure of the 5th Test was repeated with a perforated steel sheet substituted for the fly screen. The sheet had 36 per cent opening consisting of small, uniformly distributed, circular holes.

7th Through 13th Test. A solid plywood floor was placed in the bin and the grain chamber sealed from the plenum. Then the pressure-flow characteristics of full-scale specimens of various air ducts four feet in length were checked. Provision was made for introducing air into one end of the ducts as would be the case in an actual ventilation system. The bin was filled by dropping the grain from a point ten feet above the floor, and leveling at two-foot increments where measurements were recorded. This method of filling approaches the procedure used by a farmer in filling his bins; however, the grain in the test bin was not tramped. The ducts tested were as follows:

7th Test. A triangular wooden duct raised 3-5/8 inches above the floor.

Air opening was 15 per cent of floor area (Plate XI).

- 8th Test. A triangular steel duct raised seven inches above the floor. Air opening was 29 per cent (Plate XII).
- 9th Test. Same triangular steel duct raised nine inches above floor. Air opening was 37.5 per cent.
- 10th Test. Same triangular steel duct used in 8th Test raised seven inches above the floor but enclosed with fly screen. Air opening was 19 per cent (Plate XIII).
- 11th Test. A rectangular, wood frame duct covered with 1/8 inch hardware cloth. Air opening was 21 per cent (Plate XIV).
- 12th Test. A semi-circular, steel frame duct covered with 1/8 inch hardware cloth. Air opening was 27.5 per cent (Plate XV).
- 13th Test. Same semi-circular, steel frame duct covered with fly screen. Air opening was 25 per cent.
- 14th Test. This was a repetition of the 13th Test, except that the grain was thoroughly tramped while the bin filled. The purpose was to note any effects due to walking on the grain when leveling the surface.
- 15th Test. The wheat was cleaned and test 6 repeated.

RESULTS OF TESTS

The results of the various tests are shown in curve form. Since practical ventilation rates for drying wheat are in the range of one to two cfm per bushel, data for those air flows are shown. In some cases it is desirable to see the effects of a greater air flow. Thus, where pertinent, curves for four cfm per bushel have been included for comparison.

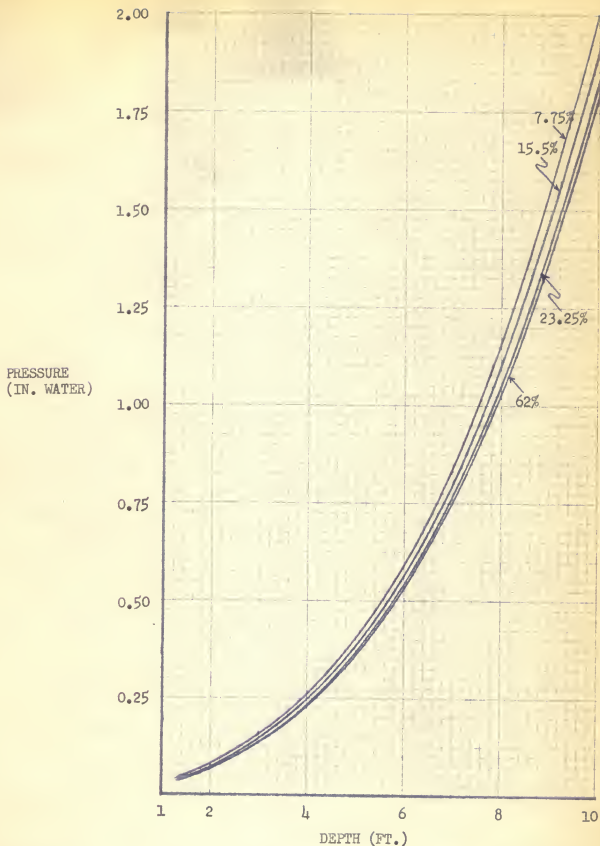


Fig. 1. A comparison of the pressures required to ventilate wheat at depths up to 10 feet with 1 cfm per bushel for various air entrance areas.

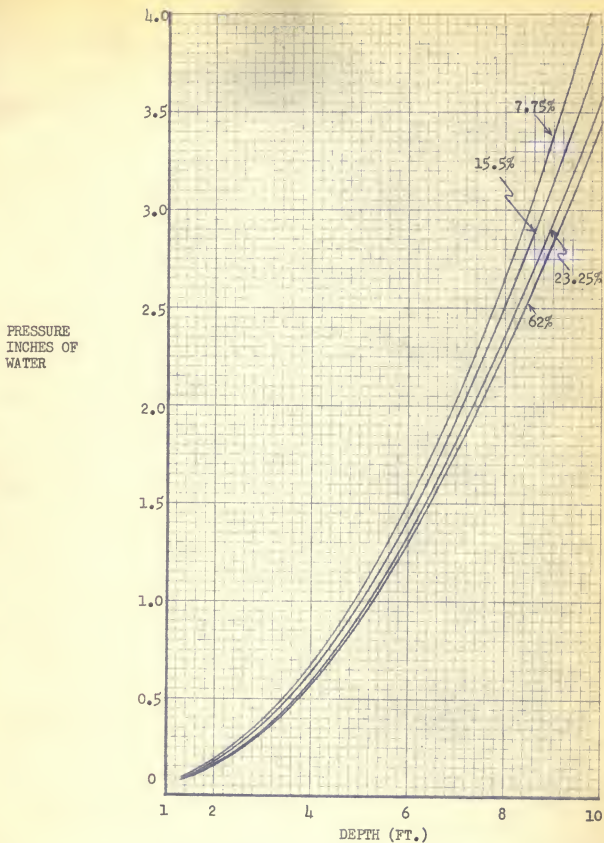


Fig. 2. A comparison of the pressures required to ventilate wheat at depths up to 10 feet with 2 cfm per bushel for various air entrance areas.

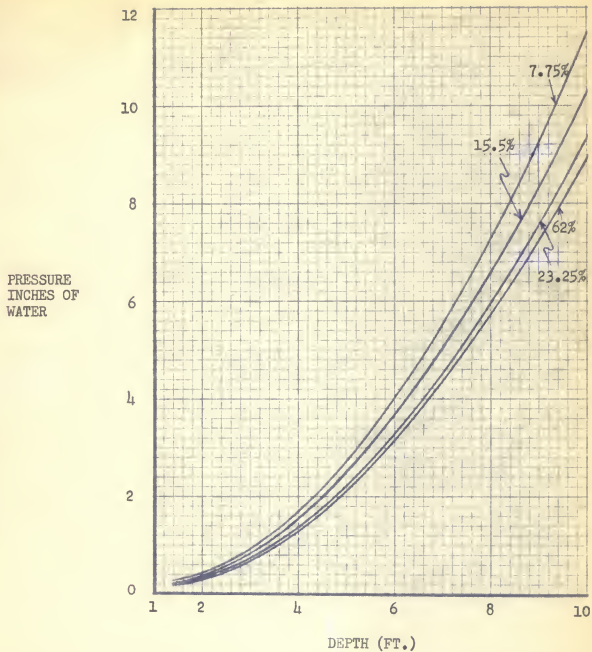


Fig. 3. A comparison of the pressures required to ventilate wheat at depths up to 10 feet with 4 cfm per bushel for various air entrance areas.

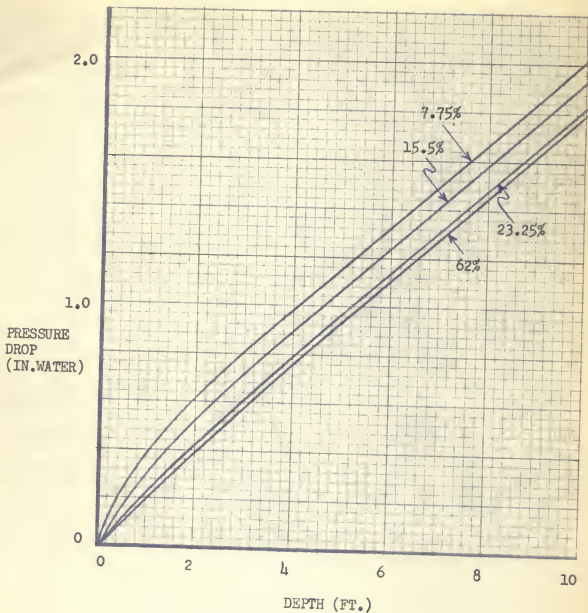


Fig. 4. These curves show distribution of the total pressure loss, from bottom to top, through 10 feet of wheat when ventilating at the rate of 1 cfm per bushel with various air entrance areas.

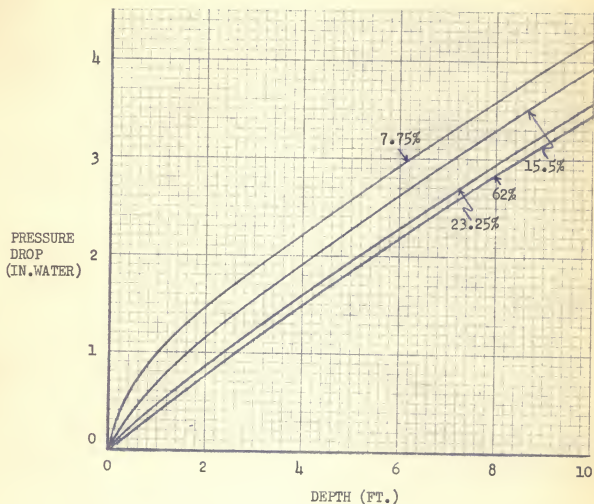


Fig. 5. These curves show distribution of the total pressure loss, from bottom to top, through 10 feet of wheat when ventilating at the rate of 2 cfm per bushel with various air entrance areas.

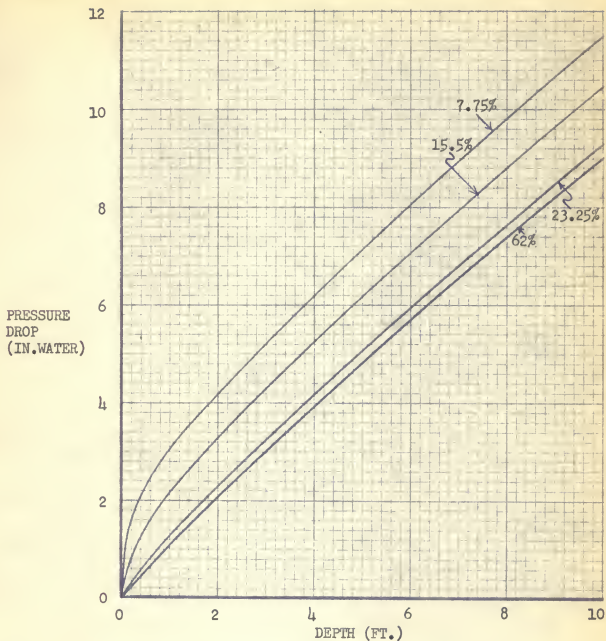


Fig. 6. These curves show distribution of the total pressure loss, from bottom to top, through 10 feet of wheat when ventilating at the rate of 4 cfm per bushel with various air entrance areas.

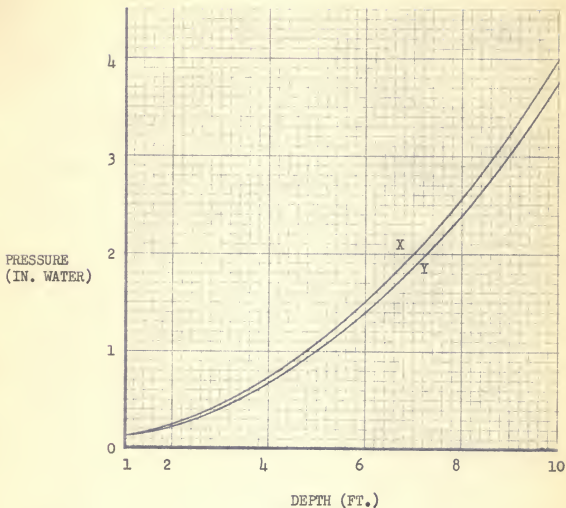


Fig. 7. A comparison of the pressure requirements for ventilating wheat at depths up to 10 feet using $1/8$ inch hardware cloth, X, and fly screen, Y, as the pervious section of the floor. Rate of ventilation is 2 cfm per bushel and an equivalent of 14 and 15.5 per cent, respectively, of the total floor area is exposed for a concentrated air entrance to the grain.

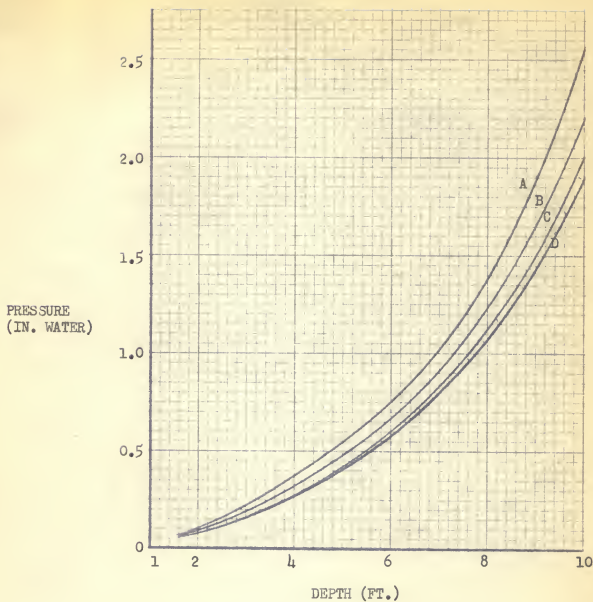


Fig. 8. A comparison of the pressure requirements for ventilating wheat at the rate of 1 cfm per bushel up to a depth of 10 feet with various ducts spaced $\frac{1}{4}$ feet apart. Curve A is for the triangular wood duct raised $3\text{-}\frac{5}{8}$ inches above the floor. Curve B is for the triangular steel duct raised 7 inches above the floor. Curve C is for the triangular steel duct raised $9\text{-}\frac{1}{2}$ inches above the floor. Curve D is for the semi-circular, fly screen covered duct. Curves for the triangular steel duct raised 7 inches with a screen enclosure, the rectangular duct covered with $\frac{1}{8}$ inch hardware cloth, and the semi-circular duct covered with $\frac{1}{8}$ inch hardware cloth fall between curves C and D, with the triangular steel duct approaching C and the latter two approaching D.

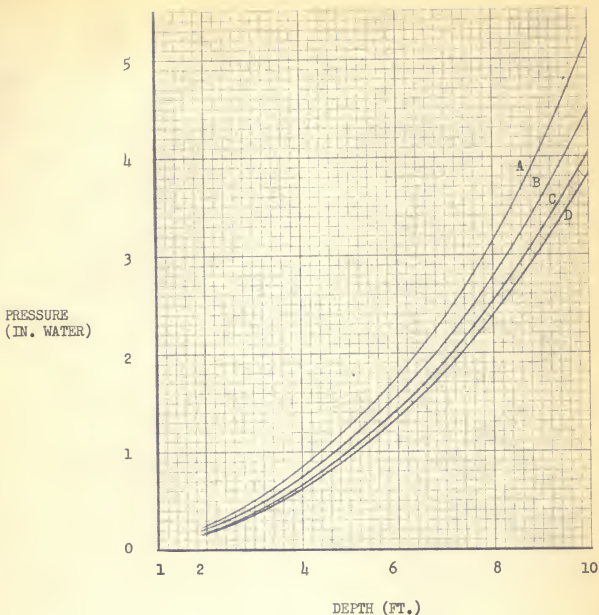


Fig. 9. A comparison of the pressure requirements for ventilating wheat at the rate of 2 cfm per bushel up to a depth of 10 feet with various ducts spaced 4 feet apart. Curve A is for the triangular wood duct raised $3\frac{5}{8}$ inches above the floor. Curve B is for the triangular steel duct raised 7 inches above the floor. Curve C is for the triangular steel duct raised $9\frac{1}{2}$ inches above the floor. Curve D is for the semi-circular, fly screen covered duct. Curves for the triangular steel duct raised 7 inches with a screen enclosure, the rectangular duct covered with $\frac{1}{8}$ inch hardware cloth, and the semi-circular duct covered with $\frac{1}{8}$ inch hardware cloth fall between curves C and D, with the triangular steel duct approaching C and the latter two approaching D.

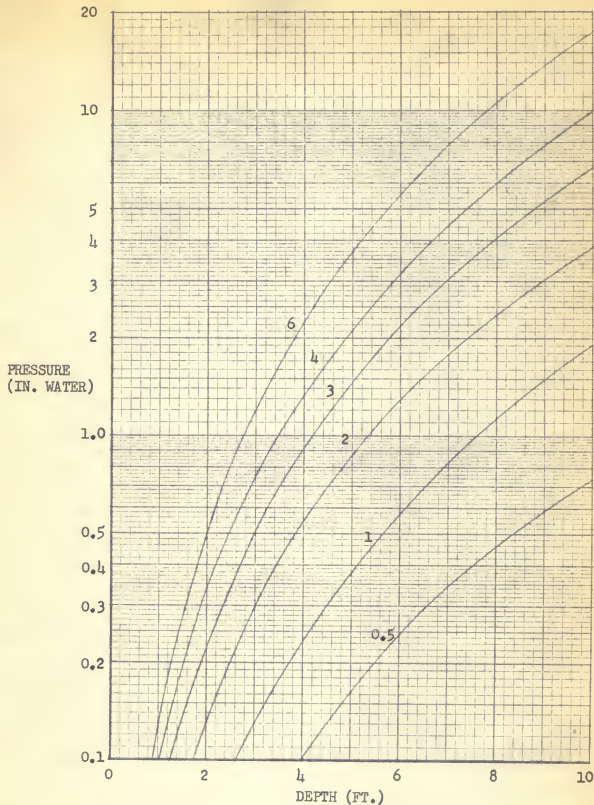


Fig. 10. Pressure requirements for ventilating wheat with the semi-circular, fly screen covered ducts spaced 4 feet apart. Curves are for air flow rates of from 0.5 to 6 cfm per bushel of grain for depths up to 10 feet.

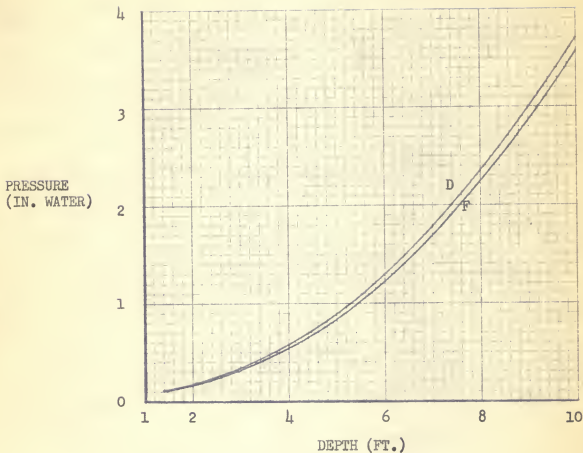


Fig. 11. A comparison of the pressure requirements for ventilating wheat at depths up to 10 feet using the semi-circular, fly screen covered duct, D, and the perforated steel sheet flooring, F. Rate of air flow is 2 cfm per bushel. Air entrance areas are equivalent to 25 per cent of the floor area (concentrated) and 36 per cent of the floor area (uniformly distributed), respectively.

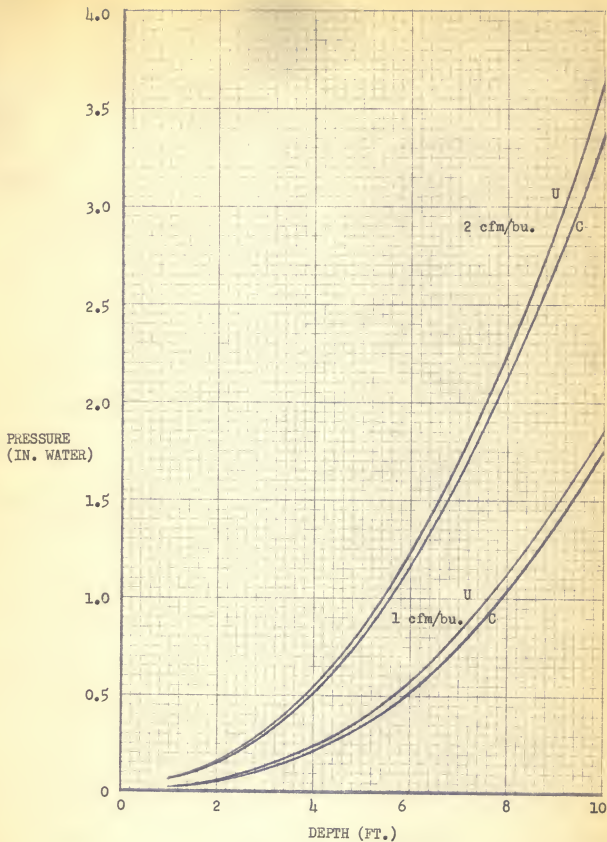


Fig. 12. These curves show the pressure-flow relationships of uncleaned, U, and cleaned, C, wheat when ventilated through the perforated steel sheet flooring (air entrance 36 per cent uniformly distributed).

An examination of the curves shown in Figures 1, 2, and 3 will give some idea of the pressure-flow relationships for ventilating wheat at depths up to ten feet with one, two, and four cfm per bushel. Percentage wise, there is little to be gained by increasing the concentrated air entrance area above 20 to 25 per cent of the floor area with air flows of two cfm per bushel or less. The curves for uniformly distributed air entrance areas of 62 per cent checked very closely with Shedd's (51) data (Plate IV).

The curves shown in Figures 4, 5, and 6 illustrate the distribution of total pressure losses through wheat with various air entrance areas. It is obvious that, for air flows of four cfm per bushel or less, parallel flow conditions were attained about one foot above the floor. With a uniformly distributed air entrance area of 62 per cent, the pressure loss through the bottom foot of grain very nearly equals the pressure loss through any other one-foot layer. But with concentrated air entrance areas, increased pressure requirements are necessary to overcome the difficulty encountered by the air in establishing parallel flow conditions. Once the air has reached parallel flow status, its pressure loss through the remainder of the grain will be identical regardless of size, shape, and distribution of entrance openings.

Figure 7 gives a comparison of the pressure-flow characteristics of 1/8 inch hardware cloth and fly screen. Even though the hardware cloth has a greater percentage of opening (73 to 66), the size of its openings are such that many kernels of wheat lodge in them. This tends to decrease its effectiveness. On the other hand, the openings in fly screen are too small for kernels to "plug."

A comparison of the performance of the various air distribution ducts is given in Figures 8 and 9. The triangular wood duct (15 per cent opening) was

relatively the poorest because of insufficient opening and an inadequate cross sectional area for conveying air. At two cfm per bushel, its ventilation pressure requirements were about 30 per cent greater than those of the semi-circular, steel frame duct covered with fly screen (25 per cent opening). The triangular steel duct raised seven inches above the floor (29 per cent opening) and raised $9\frac{1}{2}$ inches ($37\frac{1}{2}$ per cent opening) required about 14 per cent and four per cent, respectively, greater pressures than the steel semi-circular, fly screen covered duct. The triangular steel duct raised seven inches and enclosed with fly screen (19 per cent opening) exhibited characteristics slightly better than when it was raised $9\frac{1}{2}$ inches without screen. The rectangular wood duct covered with $1/8$ inch hardware cloth (21 per cent opening), the semi-circular, steel frame duct covered with $1/8$ inch hardware cloth (27.5 per cent opening), and the semi-circular, steel frame duct covered with fly screen all performed about the same - with the latter being slightly the best.

Data from the semi-circular, steel frame duct covered with fly screen were used to plot curves showing the pressures required to ventilate wheat at various air flows for depths up to 10 feet. A comparison of this chart, included as Figure 10, with that plotted from Shedd's (51) data (Plate IV) will show that the lower air flow curves indicate less pressure required, under similar conditions, than does Shedd. The higher air flow curves indicate a greater pressure requirement than Shedd's. With this type duct air distribution system, not all of the air passes through the full depth of grain. Much of the air will leave through the top of the duct which is several inches above the floor. This accounts for the reduced pressures at low air flows. However, as ventilation rate is increased, the losses due to divergent air flow away from the duct become more prominent and increased pressures over those of Shedd are indicated.

Examination of Figure 11 indicates that for air flow rates of two cfm per bushel or less, the pressure-flow characteristics of perforated flooring with 36 per cent uniformly distributed opening, is little better than those of the semi-circular, steel frame duct covered with fly screen spaced four feet.

The effect of cleaning wheat with respect to ventilation is shown in Figure 12. The clean grain required slightly less pressure for ventilation under similar conditions. Curves showing the effect of tramping the grain were not included since, under normal conditions, tramping did not change the pressure-flow characteristics appreciably. Only after an unusually large amount of tramping were the pressure requirements increased by about five per cent for similar conditions of air flow and grain depth.

SUMMARY AND CONCLUSIONS

A considerable portion of the wheat crop is stored on the farm before it is marketed. Due to inadequate storage and conditioning facilities, enormous losses of the grain occur during this storage period. Agents contributing to loss and deterioration of the grain include rodents, insects, living processes in the grain (respiration), microorganisms, and enzymes. All except the losses due to rodents are greatly dependent on moisture content of the grain and the temperature conditions which prevail. Past observations indicate that wheat can be stored for several years without serious deterioration provided it is kept dry, and free of rodents and insects.

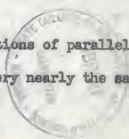
The problem of combatting rodents and insects is now simplified. Modern construction materials and methods will eliminate rats and mice. Fumigants have been developed for prevention and control of stored-grain insects. But the moisture problem is somewhat difficult. The safe moisture limit for storing wheat is about 11 to 13 per cent, depending on climate, length of

storage period, and the time of year the grain is to be stored. But occasionally, the farmer is faced with the problem of preserving the quality of wheat which has a moisture content exceeding 13 per cent. Generally, this will be newly-harvested grain, but it can also be old wheat in storage which has accumulated moisture in certain areas due to moisture migration processes, insect infestation, or rain and snow entering the bin.

Research and experience have born out the fact that turning the grain will not solve the moisture problem. Neither can systems of natural ventilation be depended on to dry grain before it deteriorates. But forcing unheated air through damp wheat by mechanical means can dry it soon enough to prevent spoilage under climatic conditions encountered throughout most of the winter wheat-growing areas.

In order to design ventilation systems suitable for drying stored wheat, some knowledge of its pressure-air flow characteristics is necessary. Several investigators have conducted experiments in an effort to determine these relationships. However, they limited their studies to ventilation systems in which conditions of parallel air flow exist throughout the mass of grain. Thus the data cannot be used to predict accurately the pressures required to ventilate wheat with a duct type air distribution system, since both divergent and parallel air flow conditions occur. The objectives of this study were to check the existing data on the pressure-flow characteristics of wheat, determine the minimum amount of concentrated air entrance area necessary for efficient ventilation of wheat, and to compare the pressure-flow relationship of several types of ducts commonly employed to distribute air in grain drying installations.

The data obtained from the experiment, where conditions of parallel flow of air through the entire mass of grain existed, were very nearly the same as



data by Shedd (51). For air flows of two cfm per bushel or less, and grain depths not exceeding ten feet, a uniformly distributed air entrance area equivalent to about ten per cent of the floor area is necessary for ventilating wheat. Uniformly distributed air entrances equivalent to more than 20% of the floor area would be difficult to justify.

In the case of non-parallel flow air distribution systems, 20 to 30 per cent opening, in terms of floor area, is necessary, depending on duct design. The wood or steel frame type ducts covered with fly screen exhibit the best pressure-flow characteristics. If the solid top, triangular ducts are used, they should be enclosed with fly screen in order to reduce pressure losses at the point where air leaves the duct and enters the grain. A well-designed duct system based on 25 per cent air entrance area with ducts four feet apart will compare very favorably with perforated floor ventilation systems.

Cleaning grain will reduce the pressures required to ventilate it slightly, though wheat harvested with a properly adjusted combine is not trashy enough to present a problem. The amount of tramping which grain normally undergoes in a farm bin will have very little effect on ventilation pressures.

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AIR DISTRIBUTION DUCTS FOR VENTILATING HIGH-MOISTURE WHEAT
IN FARM TYPE STORAGE STRUCTURES

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Wheat is a food crop. The demand for it is continuous, but production is seasonal. Hence, storage of the crop in such a way as to maintain maximum nutritive value is of utmost importance. A considerable portion of it is held by farmers before being marketed. The inadequate storage and conditioning facilities which exist on many farms are responsible for an enormous annual loss in the income from wheat, and to a loss in quality for consumption or processing.

All storage losses are theoretically preventable; that is, they can be greatly reduced or eliminated entirely if owners and handlers are sufficiently concerned. One reason for them is that they are insidious, the damage being done usually before the owner is aware of danger. Agents contributing to the loss and deterioration of stored grain include rodents, insects, living processes in the grain (respiration), microorganisms, and enzymes. Modern construction materials and methods will exclude rodents. Fumigants can be employed to prevent insect infestation. But the activity of the remaining destructive agents is dependent on the moisture content of the grain and the temperature conditions which prevail.

The safe moisture limit for storing wheat is from 11 to 13 per cent, wet basis, depending on climate, length of storage period, and the time of year the grain is to be stored. But occasionally, the farmer is faced with the problem of preserving the quality of wheat which has a moisture content exceeding 13 per cent. Generally, this will be newly-harvested grain; however, it may be old wheat in storage which has accumulated moisture in certain areas due to moisture migration, insect infestation, or rain and snow entering the bin.

All grain is hygroscopic. It can be dried in the presence of air which has a relative humidity below the equilibrium relative humidity of the grain at its existing moisture content and temperature. Since bulk-stored wheat has approximately 43 per cent void space, drying can be accomplished by circulating low relative humidity air through it. The drying process approaches one of adiabatic saturation of the air, but is modified because grain moisture requires more heat for vaporization than does free water.

Use of an electrically powered fan or blower has proved to be the most effective method of ventilating stored grain. In order to design the air distribution system, reliable data on the resistance of wheat to air passage is essential. Several investigators have conducted experiments in an effort to establish such information. However, their studies were limited to ventilation systems from which conditions of parallel air flow exist throughout the mass of grain. The data cannot be used to predict accurately the pressures required to ventilate wheat with a duct type air distribution system, since both divergent and parallel air flow conditions occur.

The objectives of this study were to check existing data on the pressure-air flow characteristics of wheat, to determine the minimum amount of concentrated air entrance area necessary for efficient ventilation of wheat, and to compare the pressure-flow relationship of several types of ducts commonly employed to distribute air in grain drying installations. Special equipment was assembled in order to accomplish these objectives.

The data obtained from the experiments for conditions of parallel air flow through the entire mass of grain were very nearly the same as that published by one farmer investigator. For air flow rates of two cubic feet per minute (cfm) per bushel or less, and grain depths not exceeding ten feet, a uniformly distributed air entrance area equivalent to about ten per cent of

the floor area is necessary for ventilating wheat efficiently. Uniformly distributed air entrances equivalent to more than 20 per cent of the bin floor area would be difficult to justify for practical grain drying installations.

In the case of non-parallel flow distribution systems, air entrance areas equivalent to from 20 to 30 per cent of the bin floor area are necessary, depending on duct design and spacing. The wood or steel frame type ducts covered with fly screen exhibit the best pressure-air flow characteristics. If the solid top, triangular ducts are used, they should be enclosed with fly screen to reduce pressure losses at the point where air leaves the duct and enters the grain. A well-designed duct system based on 25 per cent air entrance area with ducts spaced four feet apart will compare very favorably in performance with perforated floor ventilation systems.

Cleaning grain will reduce the pressures required to ventilate it slightly, though wheat harvested with a properly adjusted combine does not contain enough cracked kernels or foreign material to present a problem. The amount of tramping which grain normally undergoes in a farm bin will have very little effect on ventilation pressures. The density of high-moisture grain is less, and the ventilation pressure requirements less, for a given rate of air flow than for the same grain after it has been dried to a lower moisture content. However, in a batch drying operation, shrinkage of the kernels tends to loosen the fill as the grain dries. This loosening offsets any increase in pressure requirements that would be expected as a result of reduced moisture content.

