A STUDY OF THE MOVEMENT OF MOISTURE IN STORED WHEAT DUE TO TEMPERATURE DIFFERENTIAL

by

FELIPE LIAN-FUY SIY

B. S., National Taiwan University, China, 1953

A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1956

TABLE OF CONTENTS

INTRODUCTION

Past records and experiences on grain storage show that the moisture content of stored grain varies from month to month and from season to season during its storage period. Very often moisture moves from one part of a bin of grain to another. This movement of moisture is particularly evident in the winter time in bins of relatively large capacity. The result of the moisture accumulation is one of the hazards of deterioration in grain storage.

As the accumulation of moisture exceeds a maximum limit for safe storage, mold begins to develop under favorable temperature condition. Mold growth causes heating and finally spoils the grain. The phenomenon described above is known as the moisture migration and has been assumed to be a result of a temperature differential which exists in a grain bulk.

Moisture migration has caused very large losses in stored grain during the past years. Anderson et al (1) reported that in Canada increases in moisture were observed in layers at or near the surface of dry grain in country elevator annexes which held about 30,000 bushels of wheat. The trouble was generally discovered in the spring. Carter and Farrar (5) studied soybeans of uniform moisture content (12 percent), stored in a watertight farm bin. In a few weeks as a result of decreasing external temperature, moisture concentrations of 16 to 19 percent were created in the upper layer of beans with a corresponding reduction of moisture in the cental warmer bulk of the grain. The same trouble has also been encountered in many of the wheat storages of the Commodity Credit Corporation of the United States Government (6).

Fenton (8) tells that in some winters damage due to moisture migration in wheat storages is very severe in Kansas. He has observed examples of moisture migration on the cool exterior side walls of steel bins, on the cold concrete floor, on the ventilating flues in the center of bins and on the top surface of the grain. Moisture at the last location is the most troublesome and damaging of all.

The problem has been widely noticed and investigated in recent years. The attempt of the previous works was to determine the causes of the moisture migration, to establish a theory to explain the phenomenon, and furthermore, to search for a method of preventing it in practical grain storage. The purpose of this study is to determine the causes and the limitation of moisture migration in stored wheat.

REVIEW OF LITERATURE

Moisture in Cereal Grain

Water which is absorbed by the kernels of cereal grain becomes a part of the kernel itself. The terms moisture, moisture content, or water content of a cereal grain have the same meaning as applying to a grain kernel. In order to understand the role of water involved in the problem of migration in grain storage, it is necessary to know the properties of the water which is absorbed in various substances of the grain.

Grain is a biocolloid material; it possesses an organised structure and is hygroscopic in nature. Generally speaking, there are three kinds of water in a grain kernel. First, water which is held in the pores of the material is classified as free water; it has its usual properties and the molecules of the absorbing substance are not concerned except as a supporting structure. Second, water which is more associated with the absorbing substance may be classified as absorbed water. There is an interaction between the water molecules and those of the substance, and the properties of water are influenced by the properties of the absorbing substance. Third, water which is chemically combined with the substance may be classified as combined water; it is an integral part of a given substance and no longer possesses the properties of ordinary water. This water can be removed only under vigorous conditions at times employed for moisture determination.

The term "bound water" is sometimes applied to define the water which is between the free and the chemically combined water. Robison and Hlynka (1[illegible]) stated that the term "bound water" carries two implications. It implies that some water absorbed by the grain is held by forces stronger than those of simple cohesion between water molecules themselves. Traditionally, bound water also implies a quantitative stoichiometric relationship between water and the absorbing substance. However, there is no definite boundary for the bound water.

Any method which is used to determine bound water is one which more or less arbitrarily selects some point on the adsorption isotherm curve of grain. Water present and possessing a relative pressure above this point is called "free", while water adsorbed with a greater energy than that corresponding to this point is called "bound". The term "bound water" is thus relative, and the methods for the estimation of bound water are arbitrary.

Factors that Govern the Change of Moisture of Grain Kernel

A common phenomenon of cereal grain is that when it is exposed to the atmospheric air of constant temperature and relative humidity, a condition which never exists for long, its temperature and moisture will both reach a condition of equilibrium with the surrounding atmosphere. This means that when the moisture content of a grain is higher than that of equilibrium moisture content, it will lose moisture, and vice versa. To explain this phenomenon, it is assumed that the water within the grain kernel is in molecular form. The water molecules exert a certain pressure on the walls that confine them, this pressure is assumed equal to the vapor pressure of atmosphere at the equilibrium condition. Consequently, any condition such as of temperature or moisture that change either one of these pressures that is originally in equilibrium will cause an exchange of moisture between the grain and the atmosphere, resulting in a gain or loss of moisture by the grain (Fenton, 7).

While the atmospheric temperature and humidity change continually, it is interesting to note the changes of the moisture in grain kernel. The fact that there is no stable boundary between the free and bound water is an important factor that affects the change of grain moisture content. Kiesel et al (12) stated that there are three factors accounting for the separation of water from grain colloids: (1) adsorption energy between the colloids and the water, (2) amount of water available, (3) temperature both of the grain and the medium.

The adsorption energy depends on the physical structure of the absorbing surface and its constitution, as well as on the physical and chemical properties of water. Oxley (14) studied the water content of single kernels of wheat. He found the physical differences in water content and the rate at which they are able to exchange water vapor with the atmosphere. Fisher and Jones (10) found the same result by mixing wheats at different moisture contents, under strictly similar conditions. Durum wheat may absorb water vapor from air at a rate 20 percent faster than soft and starchy English wheat. The results show that the adsorption energy is a resultant of various effects.

The moisture content of stored wheat ranges from 10 percent to 14 percent under normal storage conditions. Moisture content above 13 percent is considered unsafe for long time storage. The higher the amount of free water, the higher the water vapor pressure inside the grain kernel will be. Therefore, grain at a high moisture content will always tend to lose water to the atmosphere provided that the vapor pressure of the grain is greater than the vapor pressure in the air.

It has been mentioned above that the moisture content of grain changes with the atmospheric conditions. It can be seen that the water inside the kernel should have a high mobility. The ratio of the free to bound water should be expected to vary continually with temperature against the background of constancy in the physical and chemical condition of the colloids.

The foregoing discussion may be considered as the fundamental hypothesis in regard to the problem of moisture movement in stored wheat.

Causes of Moisture Migration

Moisture migration has been assumed to be a result of temperature differences which occur within a grain bulk. The problem is "by what means does the water vapor move from the warm to the cold grain?" Obviously, the process consists of three stages: first, the moisture must be extracted from the warm grain; second, it must be carried away from the warm region to the cold region; third, it must be absorbed by the cold grain. The first and the last stages can be easily explained by the foregoing discussion; the argument remains on the second stage. Pratt (17) summarized the previous works and stated two theories which have been proposed to explain the moisture migration. One of them describes it as resulting from moisture being transported through the grain bulk in air that is circulated by convection currents. The other describes it as resulting from the differences of the partial pressures of the water vapor in the air.

By diffusion process, the water vapor is transferred from a warm region to a cold region through the vapor pressure difference along its path. When one part of a grain bulk becomes warmer than an other, a greater pressure is exerted by the vapor in that warm part than in the cold part. Diffusion processes tend to equalize these pressures through the interstitial air. This will cause the water vapor to leave the warm region and enter the cold region. The loss of water vapor in the warm region causes a lowering of the relative humidity. This in turn brings about the condition that cause moisture to leave the grain kernel and enter the air (17).

In cold regions, the air is humidified by the water vapor coming from warmer regions. Therefore, its relative humidity increases and an increase in moisture content of wheat will be the immediate result.

The same reasoning may be applied to the convection process except that the water vapor when leaving the warm region is by mass transfer. This causes a faster transport of moisture than the diffusion process. In actual cases, as the air was cooled on the sides of bins, it became more dense and settled down through the grain. The warm air in the center of the grain mass became less dense and rose through the grain. This caused an air current to be set up that followed a path down the sides of the bin and up through the center of the bin of grain.

Factors Which Cause Temperature Differences in Grain Bulk

The principal causes affecting the temperature differences in a grain bulk are (1) the effects of atmospheric temperature, (2) the effects of heat produced by local pockets of insect infestation, and (3) the effects of heat produced by respirations of wheat and micro-organisms due to high and uneven distribution of moisture content.

Insect respiration generally occurs in wheat at moisture levels below 15 percent (13). The temperature may reach a maximum of 100°-108° F. Damp grain heating usually occurs at moisture levels above 15 percent and may reach temperatures as high as 131° F in grain bulk of sufficient size to provide adequate insulation (13). These two sources of heating are beyond the scope of the present study.

The fact that the grain is a fair thermal insulator is the most important factor which affects the temperature differences between the grain bulk and the atmosphere. During the winter time, when atmospheric temperature falls to zero or even lower, the temperature inside a grain bulk of sufficient size might be able to maintain a temperature above the freezing point or higher (70° to 80° are not uncommon) by the heat which is produced originally in the grain by normal respiration of the grain. Once the temperature gradient is set up, there will be a movement of moisture from the warmer to the cooler parts of the grain (15 and 16).

Babbitt (2) used his data to calculate the effects of daily and annual temperature fluctuations of atmosphere on the grain bulk temperatures. He found that (1) if the day-to-night temperature change is about 20°F, the grain temperature fluctuation will be reduced to 1°F, i.e. it will be scarcely detectable at a depth of 5.1 inches. Daily fluctuations, therefore, do not penetrate below 6 inches to an appreciable extent; (2) if the annual mean temperature range is 77°F, the range is reduced to 1°F at a depth of about 13 feet.

In addition to the reduction in temperature range, with increasing depth the advancing temperature wave is very much slowed by bulk wheat. The actual temperature records of six 3000-bushel bins in Larned, Kansas shows that the minimum temperature at the center of the bin falls about three months behind the minimum temperature of the ambient air. (9). The steel bin is 18 ft. in diameter and 16 ft. high and has no ventilation facility. The average maximum difference in temperatures between the grain, at the center of the bin and at a 6½ ft. depth, and the ambient air is about 35°F. This is shown in Table 1.

Table 1. Temperature differential between the grain and the ambient air, 3000 bushel wheat bin, no ventilation.

Location	Sept. (1954)	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr. (1955)	May	June	July	Aug.
Average Ambient Air Temp. °F.	74	57	51	41	37	29	41	62	66	69	81	80
Grain Temp. at center 6½' depth (Ave.)	73	77	72	68	67	64	60	52	51	54	64	66
Horizontal Temp. Grad. °F/9'	1	20	21	27	30	35	19	10	15	15	13	14

From the above discussion, it is evident that the temperature differences between the atmosphere and the grain bulk during the winter is very marked. Therefore, under normal storage conditions, the temperature within a large grain bulk will be determined by (1) the initial temperature when it was placed in storage, and (2) the total mass of the grain which is large enough to produce sufficient heat to maintain the temperature of grain bulk, as well as to reduce the heat which escapes from the center of the bulk.

MATERIAL AND METHODS

This study consists of two main experiments. The first experiment was to determine the effects of the locations of the hot region to the cold region on the transference of moisture and to study the traveling path of the water vapor involving in the transfer process. The second experiment was to determine the relations between the temperature difference and the moisture content of wheat and derive the limitations of moisture migration in stored wheat.

Experiment I

Equipment. Three oil barrels of the same construction each containing about 460 pounds of hard red winter wheat were placed in an arrangement as shown in Fig. 1. Both ends of the barrels were taken off. After the barrels were filled with the wheat, the ends were sealed by a plastic cloth and two water cans each holding about 9.7 gallons of water were then fastened to the ends of the barrel. One can was circulated with hot water of about 115° F. and the other was circulated with cooling water of about 40° F. Seven sampling tubes were provided on the wall of the barrel. Wood stoppers and scotch tape were used to prevent leakage of wheat and vapor. The barrels and the cans were all wrapped in a one inch thermal insulation cloth. Figure 2 shows the construction of barrel A with the cans. The other two barrels were exactly the same as this one.

The hot water was heated by two electric heaters which were automatically controlled by a thermostatic device. A small centrifugal pump was used to circulate the hot water from the hot water tank to each water can and back to the tank. Three check valves were used to control the flow of water to each

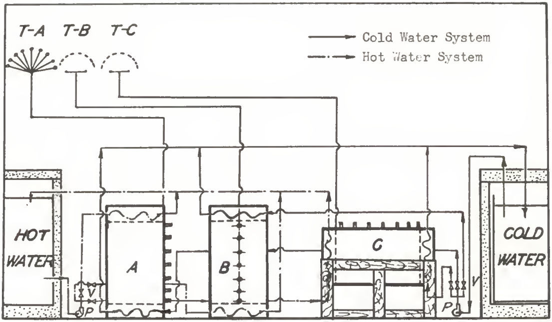


Fig.1- Diagram showing the experimental equipment: A, Barrel A with a hot bath at the top and a cold bath at the bottom; B, Barrel B with a cold bath at the top and a hot bath at the bottom; C, Barrel C was placed in a horizontal position. T-A, T-B and T-C are thermocouples of Barrels A, B. and C respectively. P--water pumps. V--valves.

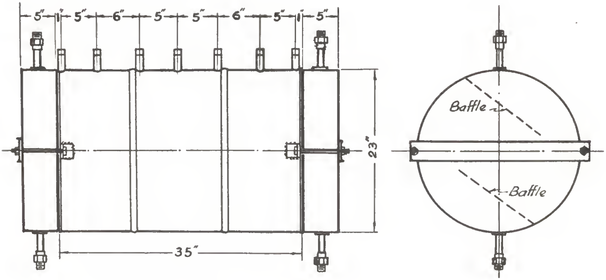


Fig. 2 - Construction of the Meat Container

can. These valves served as temperature control devices. The temperature of the can was regulated by adjusting the valve.

A refrigerator was used to make the cooling water; it was also thermostatically controlled. Pump and check valves were used also in the cooling water system to control water flow and temperature.

A small sampling probe was made to take 20-gram samples of wheat from the barrels.

Seven thermal couples were set at the central line of the barrel. Each corresponded to a sampling tube. A potential meter was used to measure these temperatures. One thermal couple was also attached to the inner side of each water can to read the temperature of the can which was in contact with the plastic cloth.

Procedures. About 1500 pounds of wheat was well mixed to obtain a uniform distribution of moisture content before it was placed in the barrels. The wheat was in good condition. Nine samples were taken off to determine the initial moisture content. Moisture content was determined by air oven method. Two grams of ground wheat, which was passed through a screen of No.30 mesh, was placed into a forced-ventilation air oven at $130^{\circ} \pm 3^{\circ}$ C., drying for one hour. The moisture content was expressed as a percentage of the wet weight of the sample. Moisture content over 13 percent was determined by two-stage drying method. A 20 gram sample was first spread on a tray to dry to equilibrium with the surrounding air; the moisture loss was obtained by weighing. A subsample was then ground to determine the remaining moisture. The average initial moisture content of wheat in this experiment was 12.0 percent.

The temperatures of the cold and hot water were recorded once each day, and the average values were then obtained after one week, two weeks, one month, two months, and three months of experiment. The data of temperature and moisture of wheat were also taken at these intervals.

Results. The moisture content of wheat at the center lines of the barrels A, B, and C are shown graphically in Figs. 3, 4, and 8 respectively. Each point represents the average of duplicate samples. Figs. 5, 6, and 7 are the corresponding wheat temperatures at the time when samples were taken. The total average moisture content in each barrel at different intervals of time is shown in Table 2.

Table 2. Total average moisture content of wheat in different barrels at different times.

Barrel	Time - Days: 7	14	30	60	90
A	12.5	12.2	12.6	12.4	12.2
B	12.6	12.3	12.7	12.0	12.6
C	13.1	13.1	14.5		

The gain and loss of moisture content of wheat at a distance one half inch from either end of the barrels is shown in Table 3.

Table 3. Moisture gain and loss by the cold and hot wheat at ½ inch from the end of barrel.

Time Days	Moisture Gain by Cold Wheat %				Moisture Loss by Hot Wheat, %			
	Barrel A	Barrel B	Barrel C 1	Barrel C 2	Barrel A	Barrel B	Barrel C 1	Barrel C 2
7	0.7	0.7	4.3	0.3	0.6	0.7	1.2	1.1
14	0.9	0.9	4.8	0.7	2.0	1.7	1.6	1.3
30	1.5	1.7	8.2	1.2	2.5	2.3	2.3	1.9
60	1.6	1.3		1.3	3.3	4.1		3.5
90	1.6	1.9			3.7	3.0		

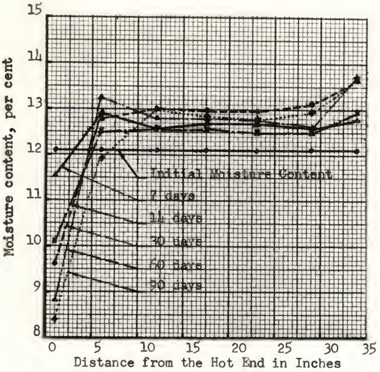


Fig. 3 - Curves showing changes of moisture content of wheat at the center line of the Barrel A.

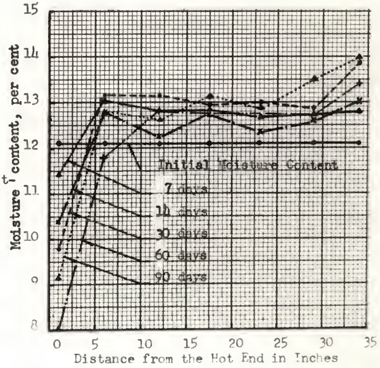


Fig. 4 - Curves showing changes of moisture content of wheat at the center line of the Barrel B.

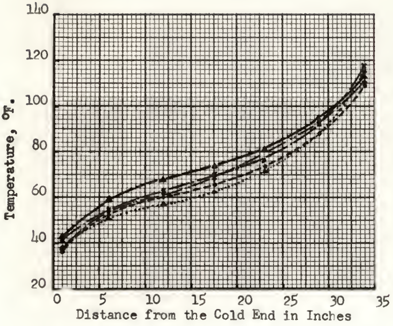
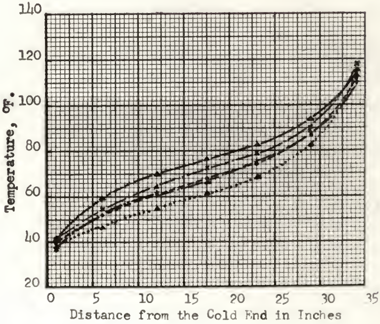


Fig. 5 - Curves showing changes of temperature of wheat at the center line of the Barrel A.

Fig. 6 - Curves showing changes of temperature of wheat at the center line of the Barrel B.



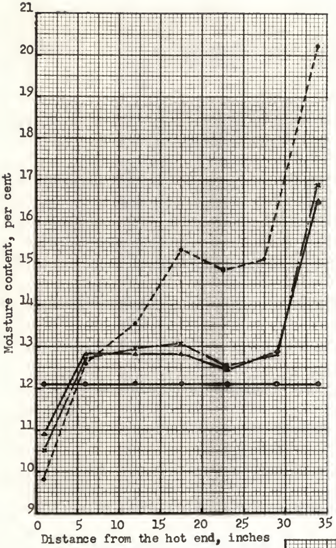
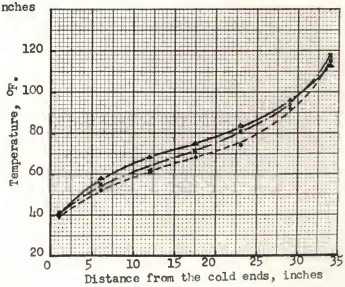


Fig. 7 - Curves showing changes of moisture content of wheat at the center line of Barrel C.

- o Initial moisture content
- ▲ 7 days
- x 14 days
- • 30 days

Fig. 8 - Curves showing changes of temperature of wheat at the center line of the Barrel C.



The average temperature of the water baths are given in Table 4.

Table 4. Average temperature of the hot and cold baths.

Time: Days	Barrel A Hot Bath °F	Barrel A Cold Bath °F	Barrel A Difference °F	Barrel B Hot Bath °F	Barrel B Cold Bath °F	Barrel B Difference °F	Barrel C-1 Hot Bath °F	Barrel C-1 Cold Bath °F	Barrel C-1 Difference °F
7	113.3	43.3	70.0	112.1	40.8	71.3	112.7	40.5	72.2
14	119.2	41.6	77.6	118.9	42.4	76.5	119.2	41.1	78.1
30	115.6	40.8	74.8	115.9	39.9	76.0	115.4	39.9	75.5
60	116.9	38.5	78.4	116.9	38.5	78.4			
90	110.2	37.7	72.5	110.3	38.4	71.9			

Barrel C was a faulty installation because the top of the barrel was not completely filled with wheat. This gave a temperature of 115° F within 35 inches of the cold end at some 40° F. With the humidity supplied by grain at 12 percent, it is simple to see that the dew point was reached at some point near the middle of the barrel. So we had here a simple case of condensation in the cold end of the barrel. Under these conditions the maximum moisture content increased as much as 8.2 percent after 30 days and the wheat was sprouted. This defect was corrected and the experiment repeated with the barrel completely filled with wheat. The results are shown in Table 2.

Interpretation of Results. The total average moisture content of the wheat increased about 0.5 percent in all three barrels throughout the entire course of the experiment. The variations of the total average moisture content at different periods of time also indicated that there was an exchange of water vapor between the interstitial air and the atmosphere. This caused the warm wheat to lose its moisture faster, as compared with the results given by Anderson et al. (1), who maintained the wheat at a temperature difference of

60° F. in a sealed box, six feet long, in which only 0.8 percent moisture was increased at the cold end after 100 days. The same is true as compared with Pratt's experiment (17). He maintained 60° F. temperature difference in a wheat column six feet long. The moisture increased about 0.8 percent at cold end and lost about 1.3 percent at the hot end after 22 days.

From Table 1, it can be seen that the deviation of moisture of the wheat in the three barrels is not too far apart. If this can be ignored, it is evident that the moisture gained and lost by the wheat in Barrels A and B is no different for the first two weeks. However, after 30 days to 90 days Barrel A shows a more stable change. This is because the warm air remains at the top of Barrel A, and carries the water vapor down to the bottom by merely the diffusion process. Diffusion is such a slow process that it almost did not cause any increase during the last 30 days of the experiment. Barrel B is quite a different situation; it has hot air at the bottom which carries the water vapor up to the top through a random path that causes an irregular moisture distribution in Barrel B, as shown in Fig. 4.

Barrel C is a special case of the experiment. It consists of two tests. The first test showed a rapid increase in moisture at the cold end. It was stopped after 30 days because of molding and sprouting of the grain. An investigation on Barrel C showed that there were air pockets remaining at the top of the barrel when it was filled with the wheat. Warm air has less resistance through these air pockets than through the interstitial air space. When warm air carrying water vapor reaches a cooler region, it gives up some moisture to the cold grain. The interchange usually takes place in vapor form; however, when warm air reached an extremely cold surface in the storage space such as that air space in barrel C, air was cooled down below its dew point.

Therefore, the water vapor condensed on the walls of the barrel and dripped down to the surface of the grain.

From Fig. 7 it can be seen that after 30 days the rapid increase of grain moisture begins at the middle of the barrel. Obviously, the warm air (at 115°F and about 45 percent R.H., this relative humidity is determined by assuming that it corresponds to the grain moisture of about 10 percent at warm end) has cooled down to its dew point in this section.

From Fig. 8 the grain temperature at this section is found to be about 75° F. If a line is drawn between these two points on a psychrometric chart, it can be seen that this is a process of cooling and dehumidifying.

The low vapor resistance and the condensation of water vapor have caused the grain in barrel C to increase its moisture content rapidly at the middle section and the cold end. The explanation can be shown b· the results of the second test. In this test three large filling tubes were added to Barrel C, and the wheat was well filled and packed through these tubes. Then the experiment was repeated. The results showed a slower change in moisture, as compared with the other two barrels. The phenomenon suggests that the bulk density of grain also affects the rate of movement of moisture in a grain bulk.

The temperature curves shown in Figs. 5, 6 and 8 are all sigmoid in shape. There are no significant differences between these curves. The effect of room temperature on the center section of the barrel is evident. Since the experiment started on October 6, the room temperature decreased with atmosphere as the time passed. This caused a lowering in temperature at the center sections while the temperatures of cold and hot baths remained the same.

The last record was taken on January 6. This showed a raise in grain temperature because the heater in the neighboring room was on, and the room temperature in which the barrels were placed increased.

From the psychrometric chart, it can be seen that at any level of relative humidity the water vapor pressure and the actual weight of water vapor per cubic foot of air increased with increasing temperature. This resulted in a movement of air and the water vapor from the hot region into a cooler region. The process is either by diffusion or by mass transfer, or both.

In the transfer of water vapor in a gaseous system, the chemical substance, water, may be carried by the individual water molecules moving with random thermal motion or the motion of molar aggregates carrying a high concentration of water vapor. The former is called diffusion and the latter is called convection or mass transfer (11). The difference between these two processes is distinguished by the quantity of the moving mass and the speed and path at which it moves. The factors that determine this latter process depend on many variables, such as temperature difference, vapor resistance of grain, type and position of the heating surface in relation to the cold surface, density of the air, etc.

The most important factor is the temperature difference which directly affects the vapor pressure, i.e. the higher the temperature difference the higher the vapor pressure difference will be. When this difference approaches a certain value, convection current will set up. Horton, Rogers and Morrison (11 and 19) have developed an expression of critical temperature difference for convection in porous medium, but whether this expression can be applied for grain bulk or not still remains to be investigated.

The vapor resistance of the grain affects the speed with which the water molecules move (3). A tendency of the results existing in this experiment that the moisture content of wheat next to the hottest sample gains more moisture than the sample second to the hottest. On the other hand, the sample next to the coldest loses moisture at first instead of gaining. The phenomenon indicated that a rapid interchange of moisture took place where temperature gradient was steepest. When warm air carrying water molecules flows to a cooler place, the grain which comes in contact with this warm and humid air at first will absorb more moisture than the grain which is further apart from the hot area. The vapor resistance in a grain bulk therefore depends upon not only the thickness of the grain bulk but also the conditions (temperature and moisture content) of the existing grain.

Conclusion. From the theoretical analysis and the data obtained from the experiment, the following conclusions may be derived:

(1) The moisture migration in stored wheat is due to temperature difference existing in the grain bulk.

(2) The process of moisture migration involves three steps: First, moisture is abstracted from the warm grain; second, moisture is transferred to the cold grain by either diffusion or mass transfer, or both; third, moisture is absorbed by the cold grain.

(3) The force that brings about the transport of water vapor, i.e. the second step, is by the difference in water vapor pressure existing between the hot grain and the cold grain.

(4) The speed at which the moisture moves depends on the process it takes. Diffusion process is much slower as compared with the convection process.

(5) Since the vapor resistance of a grain bulk is unfavorable to the conditions for setting up a convection current, it seems feasible for this process to take place in a small grain bin where temperature difference between the center part and the surface of the

grain bulk is not evident in the winter time. However, mass transfer may occur in a bin which holds sufficient grain to maintain a temperature gradient in during the winter and the early spring months.

Experiment II

Equipment. Two grain containers A and B of the same type, but different in size, were used to test the relation between the temperature differences and the moisture content of wheat. Container A has a diameter of six inches and is twelve inches high. It consists of three different sizes of grain strainers which separated the wheat into four concentric, cylindrical layers. The strainer was made of 1/16 inch hardware cloth which permits the water vapor to pass freely and yet restricts the wheat from mixing together. Fig. 9 shows the construction of Container A. An electric heating coil was inserted in a 5/8 inch copper tube; the tube was soldered to the center of the cover of the container. A thermocouple measuring the surface temperature of the tube was connected to an electronic device which controlled the temperature of the heating element. A variable transformer connecting the heating coil and the control device was used to lower the voltage of the power supplied. Fig. 10 shows the wiring diagram of the heating system both for containers A and B. The laboratory balance has an error of about .6 percent in the determination of the weight of samples.

Container B consists of a copper tube of 1 1/8 inches diameter; no grain strainer was used. The heating coil was placed inside the tube and the temperature control device was the same as Container A. The container has a diameter of 12 1/4 inches and is 14 1/2 inches high. It holds 50 pounds of wheat in test.

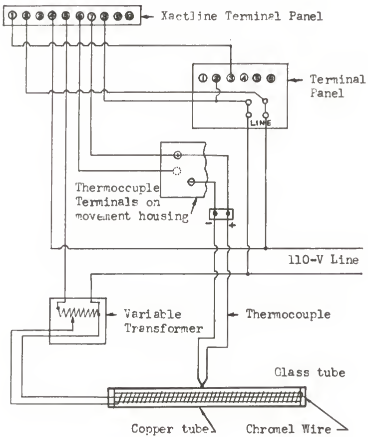


Fig. 10 Wiring Diagram of the Controlling Pyrometer and the Heating Element.

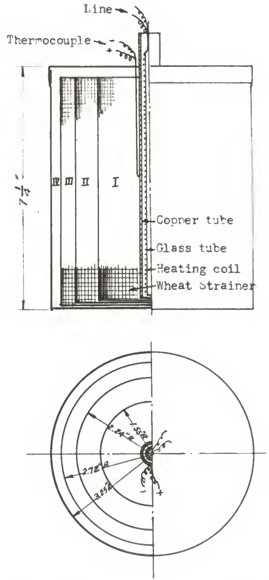


Fig. 9 Construction of the Wheat Container A.

These two containers were placed in a cold storage during the test. The temperature of the storage was controlled by a thermostat which controlled the operation of the refrigerator.

Procedures. Equal amounts of wheat were placed in the separate strainers of Container A. However, 150 to 200 grams of wheat were added to the outside layer in order to bring the wheat to the same level. The heating element was then inserted into the center layer of wheat, and the cover was sealed with electric tape. The container was then placed in the cold storage which maintained a temperature of about 35° F. The temperature of the heating element was set to 55° F, 75° F, 95° F, and 115° F for each particular moisture content of wheat. This made a series of temperature differences of 20° F., 40° F, 60° F and 80° F, respectively, between the surface of the heating tube and the outside surface of the container.

The initial moisture content of wheat was determined by a Tag Heppenstall electric moisture meter and the increase in moisture content after eight days of test was calculated by the increase in weight of the wheat.

The moisture content of wheat in Container B was determined by an electric moisture meter at the beginning and after eight days of test. The moisture content of wheat in the outside layer was the average of four samples taken at different locations of this layer.

Results. Table 5 shows the results of a series of temperature differentials against three different levels of moisture content of wheat. Nos. I, II, III, and IV in columns 6 and 7 represent the wheat in sections I, II, III and IV of the container A respectively.

Table 6 shows the results of a series of temperature differentials against one level of moisture content of wheat.

Table 5. Moisture changes of Container A.

Test No.	High Temp °F.	Low Temp °F.	Temp Diff °F	Initial M.C%	Duration of Exp Days	M. C. after 8 Days of Experiment, % I	II	III	IV	Loss and Gain of Moisture, % I	II	III	IV
1	55	35	20	11.64	8	11.24	11.57	11.97	12.08	- .40	.07	.33	.44
2	75	35	40	11.64	8	10.04	11.56	11.84	12.79	-1.60	.08	.20	1.15
3	95	35	60	11.64	8	9.14	11.57	12.19	13.24	-2.50	.07	.55	1.60
4	115	35	80	11.64	8	8.04	11.46	12.47	14.34	-3.60	-..18	.83	2.70
5	55	35	20	15.5	8	14.3	15.5	15.5	16.7	-1.20	.00	.00	1.20
6	75	35	40	16.0	8	13.14	15.63	16.78	18.2	-2.86	-.37	.78	2.20
7	95	35	60	15.5	9	10.85	14.87	16.18	19.22	-4.65	-.63	.68	3.72
8	115	35	80	15.5	8	9.70	14.40	16.67	20.40	-5.80	-1.10	.97	4.9
9	52	32	20	20.0	8	17.40	19.76	20.33	22.40	-2.60	- .24	.33	2.40
10	72	32	40	20.0	8	14.40	19.32	20.76	24.60	-5.60	- .68	.76	4.6
11	92	32	60	20.0	8	11.90	19.02	20.56	26.70	-8.10	- .98	.56	6.70
12	112	32	80	20.0	8	9.00	18.49	21.07	28.80	-11.00	-1.51	1.07	8.90

Table 6. Moisture changes of Container B.

Test No.	High Temp °F.	Low Temp °F.	Temp Diff °F.	Initial M.C. %	Duration of Exp Days	M. C. after 8 Days of Experiment, %			Loss and Gain of Moisture, %		
						Inner Sec.	Middle Sec.	Outer Sec.	Inner Sec.	Middle Sec.	Outer Sec.
1	55	35	20	11.2	8	10.1	11.2	11.8	-1.1	0	0.6
2	75	35	40	12.4	8	10.8	12.2	13.0	-1.6	-2	0.6
3	95	35	60	11.6	8	10.7	12.1	14.1	-0.9	.5	2.5
4	115	35	80	11.6	8	9.4	12.0	13.8	-2.2	.4	2.2

<u>Interpretation of Results</u>: In Column 8 (loss and gain of moisture) of Table 5 the increase and decrease in percent of moisture content are not balanced because the wheat in the outermost layer was 200 grams more than the inner layers throughout the experiments. However, the difference of the total loss and gain is below 0.1 percent and this error, as already mentioned in the

preceding section, is due to the inaccuracy of the laboratory balance.

Column 8 also shows that the changes of moisture content in Sections II and III are less than 1 percent except for the experiment Nos. 8 and 12. The phenomenon is very similar to the actual grain storage where only the extreme cold surface of the grain has appreciable increase in moisture content.

Figures 11 and 12 are constructed by plotting the data in Section I and IV of Column 8. These figures show that for a given level of moisture content the increase of moisture in cold grain is in proportion to the increase of temperature differential. The same is true for the hot grain only that the loss of moisture in it is faster than that of the moisture gain in the cold grain. This result indicates that when water vapor leaves the hot region, it travels along the temperature gradient, and the water vapor is partly absorbed by the grain existing in the path, but most of it is absorbed by the grain which is near the coldest portion of the container.

Figure 13 is obtained by rearranging the data in Fig. 11. It is evident that when the amount of free water within the grain is increased, the percent of moisture increased due to temperature differential increases rapidly.

In Fig. 11 if the moisture content line is prolonged to intersect the horizontal axis, it gives a minimum temperature differential for each different level of moisture content. For instance, a moisture content of about 11 percent will give a minimum temperature differential of about 10° F. This means that for such a moisture level, the minimum temperature differential for moisture migration would be 10° F. However, this interpretation can only be applied in such a laboratory setting, because the amount of moisture that can be transferred depends not only on the grain moisture but also on the time that the temperature differential is maintained. Furthermore, it is also

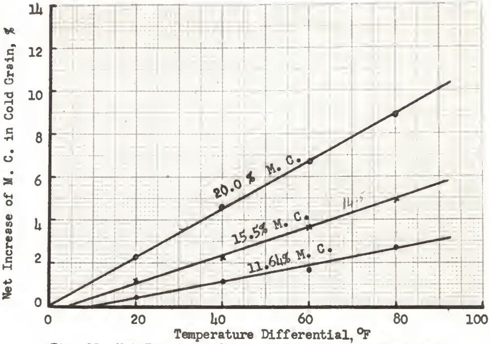


Fig. 11 Net Increase of Moisture Content of Wheat at Different Temperature Differentials and Initial Moisture Contents.

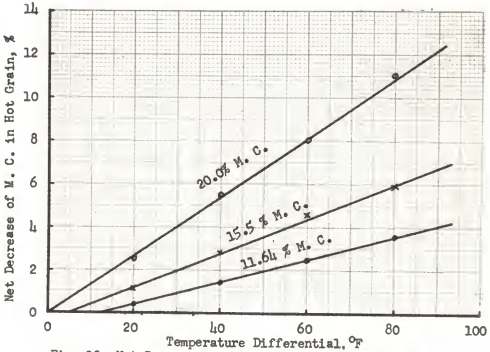


Fig. 12 Net Decrease of Moisture Content of Wheat at Different Temperature Differentials and Initial Moisture Contents.

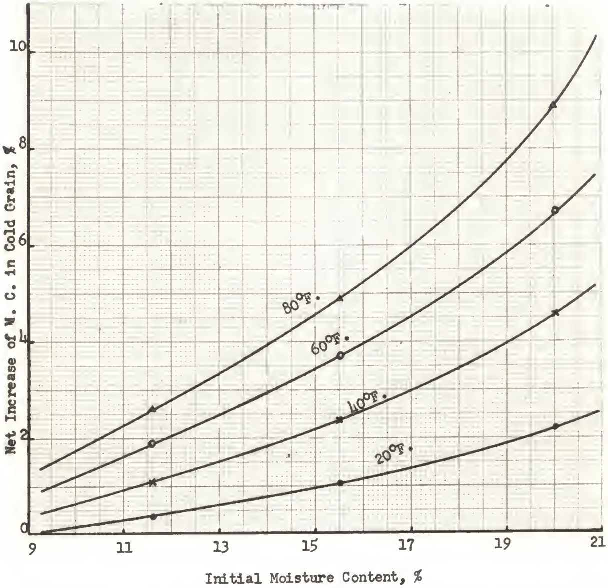


Fig. 13 Curves showing the Relations of Initial Moisture Content of Wheat, Temperature Differential, and the per cent of Moisture Increased for a Grain Bulk of about 5.7 lbs. and a Duration of 8 Days.

affected by the distance between the highest temperature and the lowest temperature, as well as by the mass of the warm grain.

An attempt has been made to investigate the effects of these several factors to the moisture migration. Unfortunately, this needs considerable time and a careful design of the testing equipment. The data secured from the experiment of the Container B is not enough to make comparisons with Container A. However, from Fig. 13 one can see that the moisture migration is so slow at the low moisture content and low temperature difference that even the cold grain was only three inches apart from the warm grain. The net increase of moisture content does not exceed 0.5 per cent in a period of eight days. This suggests that the moisture migration can be prevented by using ventilation facilities to reduce the temperature difference within a grain bulk.

RECOMMENDATIONS FOR FURTHER STUDY

There are certain factors that need to be determined in order to estimate the number of days it will take to cause a harmful moisture accumulation for a certain quantity of grain mass under a given initial moisture content and temperature differential. These are: (1) The effects of the horizontal and vertical distances between the warmest grain and the coldest grain; (2) The effect of the temperature range to the rate of moisture movement; (3) The daily increase of the moisture content for each moisture level and temperature differential; (4) The ratio of the mass of warm grain to cold grain with relation to the amount of moisture accumulation. Knowing these factors, would make it possible to determine a minimum rate of air flow which will prevent the moisture migration of grain storage. However, if all these factors are ignored, Fig. 13 may serve as a guide in designing a ventilation system for a grain storage to prevent the moisture migration. It should be noticed that Fig. 13 is for a grain mass of about six pounds and a horizontal distance of three inches from warmest grain to the coldest grain, and with the warm grain about equal to the cold grain.

CONCLUSION

The data obtained from this experiment support the following conclusions:

(1) If one part of the grain bulk is warm and another part is cold, the coldest grain absorbs most of the moisture that is lost by the warmest grain. The increase of moisture content in the middle section of the grain bulk is seldom larger than one percent through a period of eight days. This may be applied to the actual wheat storage of any size without appreciable error.

(2) When the temperature differential increases, the rate of moisture movement is increased. The relation of these two variables is a straight line within the ranges of 20° to 80° F. temperature differential and moisture level from 10 percent to 20 percent.

(3) Moisture migration can be reduced by reducing the temperature difference existing in the grain bulk. Since the process is rather slow, it is reasonable to estimate that a temperature difference of 10° F. will not cause a harmful hazard in a grain bin of 5000-bushel capacity under normal conditions throughout the winter season.

Method of Prevention of Moisture Migration: Several methods have been suggested in the prevention of moisture migration in stored grain. These are:

(1) Turning the grain during its period of storage.

This is the major method in preventing the moisture migration. It is used by most of the owners of the large-capacity elevators in the past and at the present time. The advantage of turning the grain is the uniformity of the grain temperature and moisture distribution throughout the bin. The method of turning is to transfer the grain from one bin to the other. In a large elevator, this requires a stand-by or auxiliary bin and a set of equipment for conveying grain into and out of the bins. In extremely cold weather, repeated transfers are necessary for effective cooling, though other methods, such as "cold blasting", or running the grain through the outside cold winter air may bring its temperature down to within a few degrees of the outside air.

(2) Drawing air downward in the bin.

This method of preventing moisture migration is designed for eliminating the upward effect of the warm air in the center of the grain bulk. A large capacity fan is installed on the ground and several ventilation holes are provided at the top of the bin. Air is drawn out of the bottom of the bin and the fresh air comes down from the top. This method has been used more in flat storage where grain depths are in the order of 10 to 12 feet. However, the effectiveness of this method is still in the experimental stage.

(3) Eliminating temperature differential.

Using a small capacity fan to ventilate the grain has been experimentally found (9) to be effective in preventing the moisture migration during the winter season. The object of ventilation is to eliminate the temperature differential between the grain bulk and the atmospheric air. By using the temperature and humidity control devices, a selective air temperature and relative humidity automatically and intermittently ventilates the grain throughout the seasons. This method of preventing the moisture migration appears to be most economical and effective in those bins of 3,000-bushel capacity.

(4) Selling the top foot.

Some grain storage owners who do not have grain turning equipment and ventilating facilities have found it a good idea to sell the top layer of their grain before it has time to spoil or become damaged. However, this is not a basic method of solving the moisture migration problem.

(5) Raking the surface grain.

Dry air is a factor of reducing the moisture migration. Relative humidity of 10 percent has been reported in Kansas. Raking the surface grain will help to accelerate the rate of moisture evaporation in the dry days, thus preventing the hazard of excessive moisture accumulation.

(6) Using the vapor-proof material.

This is a new propose in preventing the moisture migration in stored grain. The method is to place some vapor-proof paper in the grain bulk to separate the grain into several layers, so that the moisture can not be transferred from one layer to the other when temperature differential exists in the grain bulk.

ACKNOWLEDGMENT

The author wishes to express his appreciation to Professor F. C. Fenton, Head of the Department of Agricultural Engineering, for his guidance in carrying out this study. Appreciation is also extended to the staff members in the Departments of Agricultural Engineering and Milling Industries for their generous assistance.

Thanks are also due to Butler Manufacturing Company for the financial support in this study, and to Mrs. F. C. Fenton, Miss Sandra Wilson, and Mrs. Wilma Caldwell for assistance in preparing the manuscript.

LITERATURE CITED

1. Anderson, J. A., J. D. Babbitt, and W. O. S. Meredith.
The effect of temperature differential on the moisture content of stored wheat. Can. J. Res. 21C:297-306. 1943.

2. Babbitt, J. D.
Thermal properties of grain in bulk. Can. J. Res. (F) 23:388-401. 1945.

3. Barre, H. J. and L. L. Sammet.
Farm structures. PP 116-168. John Wiley & Sons, N. Y. 1950.

4. Boxworth, R. C. L.
Heat transfer phenomena. John Wiley & Sons, N. Y. 1952.

5. Carter, D. G. and M. D. Farrar.
Redistribution of moisture in soybean bins. Ag. Eng. 24:296. 1943.

6. Commodity Credit Corporation Progress Report on Engineering Phases of Commodity Credit Corporation Corn Storage Research Project. 1950.

7. Fenton, F. C.
Storage of grain sorghums. Ag. Eng. 22:185-189. 1941.

8. Fenton, F. C.
Electricity in wheat storage. Kansas State College Twenty Ninth Annual Report of the NCREA. 1953.

9. Fenton, F. C.
Wheat storage research project of commodity credit corporation. Kansas State College. 1954-55.

10. Fisher, E. A. and C. R. Jones.
A note on moisture interchange in mixed wheats, with observations on the rate of absorption of moisture by wheat. Cereal Chem. 16:573-583. 1939.

11. Horton, C. W. and F. T. Rogers.
Convection currents in a porous medium. J. of Appl. Phys. 16:367-70. 1945.

12. Kiesel, A., N. Vassilieva, and G. Tsygankova.
Translocation of moisture in the bulk of stored grain. Compt. Rend. Acad. Sci. URSS 24:786-790. 1939.

13. Milner, M. and W. F. Geddes.
Respiration and heating, storage of cereal grain and their products. 1954.

14. Oxley, T. A.
Study of the water content of single kernels of wheat. Cereal Chem. 25:111-127. 1943.

15. Oxley, T. A.
Scientific principles of grain storage. Northern Publishing Company, Ltd. Liverpool, England. 1948.

16. Oxley, T. A.
The movement of heat and water in stored grain. Trans. Am. Assoc. Cereal Chem. 6:84-112. 1948.

17. Pratt, G. L.
The causes of moisture migration in stored grain. Kansas State College, Master's Thesis. 1951.

18. Robison, A. D., and I. Hlynka.
Moisture and its measurement. Storage of Cereal Grains and Their Products. 1954.

19. Rogers, F. T., and H. L. Morrison.
Convection currents in porous midia III. Extended theory of the critical temperature gradient. J. of Appl. Phys. 21:1177-80. 1950.

A STUDY OF THE MOVEMENT OF MOISTURE IN STORED WHEAT DUE TO TEMPERATURE DIFFERENTIAL

by

FELIPE LIAN-FUY SIY

B. S., National Taiwan University, China, 1953

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1956

Because of the mass productions of wheat and the expansion of trade of grain elevators there has been a tendency in recent years to increase capacity of grain storage structures. With larger units of storage has come unexpected trouble because of moisture migration in stored grain. The phenomenon has been found frequently in large grain bulk and is particularly serious in the winter. The increase in moisture due to moisture migration at the cold surface can be of sufficient magnitude to cause grain heating, and mold, and large losses have been reported.

Owing to the low thermal conductivity of the grain bulk, the advancing temperature wave is slowed so much by bulk wheat that the maximum temperature at 6 foot-depth of the bulk may fall behind the maximum atmospheric temperature by about three months. As winter comes, grain near the walls and roof of the bin becomes cooler than grain in the center part. A maximum temperature difference thus occurs at this time or in the early spring.

Grain is a biocolloid material with organised structure. It absorbs or gives up moisture in accordance with the changes of atmospheric temperature and relative humidity. The force that brings about this process is the vapor pressure difference. When vapor pressure within the grain is higher than that of atmospheric pressure, it gives up moisture, and when its vapor pressure is less than that of atmospheric pressure, it absorbs moisture. With this nature of grain, it should be expected that a change of grain moisture will occur when the surrounding temperature changes. That is, when a temperature differenece exists in a grain bulk, there should be a different moisture distribution of the grain.

Moisture migration has been found as a result of temperature differences which occur in a grain bulk. However, there is argument on the problem of the path of which the water vapor moves in a grain bulk. Some writers suggest that the result is due to diffusion, while other describe it as a result of convection current. This study is intended to clarify this argument and to determine the effect of the temperature differential on the moisture migration.

In the first experiment, three grain containers, A, B, and C, were used to determine the effect of the positions of the cold region with respect to the hot region. Container A has a hot bath at the top and a cold bath at the bottom; Container B has a hot bath at the bottom and a cold bath at the top; Container C was placed in a horizontal position with water baths at each end. A temperature differential of about 74° F was maintained in each container. With such an arrangement it should be expected to have a different rate of moisture movement in each containers. For, in the first case, it would be impossible to create a convective current; the second case would favor a convection process, while the third case would be either a diffusion or convection or both.

The duration of the experiment was three months. At the end of the second week the percent of moisture increase at 1/2-inch from the cold end of the containers A and B showed no difference. At the same time the moisture increase in Container C was about four times as much as that in Containers A and B.

From the results of this experiment it can be concluded that both diffusion and convection could occur in a grain bulk. One important factor that effects the process is the magnitude of the vapor resistance of the bulk grain. The higher the resistance, the lower is the rate of moisture movement. Temperature gradient is also important in determining a process of convection or diffusion. It should be expected that for different levels of moisture content of wheat, there should be a different critical temperature differential for building up a convection current in such a porous medium as grain. Other factors that effect the convection are the geometry of the container and the relative positions of the hot and cold grain. These factors present interesting problems for further study.

In the second experiment, two containers, A and B, of the same type but different in size were used to test the relation between the temperature differences and the moisture content of wheat. Container A has a diameter of 6 inches and is 12 inches high. It holds about 6 pounds of wheat. Container B has a diameter of 12-1/4 inches and is 14 inches high. An electric heating coil was inserted at the center of each container. Temperature of the heating element was controlled by an electronic temperature controller. These containers were placed in a cold storage with a constant temperature of about 35° F, and the required temperature differential was obtained by raising the temperature of the heating element. The temperature differentials used in this experiment were 20°, 40°, 60° and 80° F for three different levels of moisture content; namely, 11.64, 15.5, and 20 percent.

Container A consisted of three separate grain containers which were made of 1/16-inch hardware cloth. These containers separated the wheat into four concentric, cylindrical layers, each layer weighing 600 grams. The outermost layer was 200 grams more than the inner layers. The increase of moisture content after a duration of eight days was calculated by the amount of weight increase. Container B had no grain separator, and the moisture content was determined by a Tag Heppenstall electric moisture meter.

The results of twelve tests in Container A indicated that the moisture increased in the cold grain directly proportional to the temperature difference.

However, for a given temperature differential the accumulation of moisture in the cold grain increased rapidly when initial moisture content is above 15 percent wet basis.

The results of four tests in Container B did not show a great moisture movement as compared with the first four tests in Container A. It is not accurate to use electric moisture meters to determine the moisture content in such an experiment. Therefore, a further study is required in order to make comparisons between containers A and B. However, one may conclude from the experimental data that the coldest grain absorbs most of the moisture from the hottest grain, regardless of how big the grain bulk is; that the moisture migration is a slow process; that even a laboratory scale as Container A, it takes eight days to increase about 0.2 percent of moisture under a constant temperature difference of 20° F and an initial moisture content of 11 percent. The data also show that the rate of movement is increased by decreasing the temperature difference. This means that the moisture migration could be prevented by cooling the warm grain.

Since the problem of "what temperature difference in grain bulk is required to cause a moisture accumulation on the cold grain", involves not only the relation of temperature difference and the moisture content of the grain, but also the ratio of the mass of the warm grain to the cold grain, therefore, a further study on the effects of these factors is recommended.

Several methods of preventing the moisture migration have been suggested. They are:

(1) Turning the grain.
(2) Drawing air downward into the bin.
(3) Eliminating temperature differential.
(4) Selling the top foot before it has time to spoil.
(5) Raking the surface grain.
(6) Using the vapor-proof material.