THE CAUSES OF MOISTURE MIGRATION IN STORED GRAIN

by

GEORGE LEWIS PRATT

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INTRODUCTION

When compared with other food stuff, grain is a relatively easy product to store in reserve for future use. Nevertheless, there are problems involved in grain storage that must be dealt with if grain is to be stored economically, and if it is to retain its quality while in storage. Some of these problems are as follows: bin construction, insect control, moisture control, and rodent control. These problems are often interrelated. For example, excessive moisture and insect infestations are conditions that are often found together.

If a condition of excessive moisture exists in stored grain, many other unfavorable conditions will develop. High moisture contents in grain cause the rate of respiration of the grain to increase. It also causes conditions favorable for fungus growth. These two effects will in turn create heat which increases the respiration rate of the grain and the growth rate of the fungi still further. These conditions continue to develop until the grain dies and decomposes.

One of the most common problems is created by storing grain in a damp condition. Other moisture problems are found in grain that is stored in a dry condition and later develops regions with excessive moisture. There are several ways that this condition could develop. One of them is due to a phenomenon in which moisture moves from one part of a bin of grain to another. Moisture migration, moisture translocation, and moisture redistribution are terms that are used to describe the process. It has been found that the problem is more acute in large storage bins than in smaller ones.

Two theories are commonly used to explain the movement of moisture from the warm part of the bulk of grain to the cool part. One theory explains it as being the result of a difference in vapor pressures in regions of different temperatures. The other explains the translocation of moisture as being the result of convection currents set up because of the temperature differential. The vapor is carried in the air that is moved by convection. The purpose of this investigation was to determine which of these theories correctly explains moisture migration in a grain bulk.

REVIEW OF LITERATURE

History

Fenton (13) tells of a Commodity Credit Corporation wheat storage program in which there was much damage done by moisture migration. In August, 1939, the wheat was harvested and stored on farms. In June, 1940, it was transferred to Commodity Credit Corporation storage bins. The wheat averaged approximately 12 percent moisture and was in very good condition when it was transferred. No damage was expected, but in February, 1941, there were reports of damage in the grain. Moisture had migrated to such an extent in the bins that there was a very large loss.

Anderson et al. (3) tells of the construction of many additions to country elevators in Canada in 1940 and 1941 which were used to store the surplus wheat that was accumulating in that country. They were 60 feet long by 30 feet wide and 20 feet to the eaves. The buildings were designed to keep out rain and snow. Each annex was filled with about 30,000 bushels of sound wheat. In the spring, trouble occurred in many of the annexes because a layer of damp grain one to two feet deep had developed at or near the surface. The Commodity Credit Corporation of the United States Government (8) has also encountered this development of high moisture grain in the surface layers of their stored grain.

The problem has apparently been widely noticed since Kiesel et al. (16) in Russia conducted an experiment to determine its cause. It was found that moisture migrated from areas of high temperatures to areas of low temperatures. Cooling coils were placed in flasks of grain and allowed to stand for 30 days. The grain near the cooling coils had a sharp increase in moisture content. Anderson et al. (3) in Canada verified the results from Russia by an experiment on a larger scale. Wheat at 14 percent moisture content was placed in a vapor sealed box that measured 6' x 2' x 20". A tank containing warmed water was placed on one end of the box in contact with the wheat. At the other end a tank containing an ice bath was placed. At the end of 316 days a sample from the cool end tested 29.6 percent moisture and one from the warm end tested 10.9 percent.

Equilibrium Moisture Content of Grain and Air

The phenomenon of the equilibrium moisture content of grain and air is an important part of any theory of moisture translocation. Fenton (12) states that grains are hygroscopic in nature; that is, they gain or lose moisture when the vapor pressure in space surrounding the grain is greater or less than the vapor pressure exerted by the moisture within the grain. Grains tend to reach and maintain an equilibrium moisture content with the surrounding air. Kent - Jones (15, p. 436) explains it in the same way. His description states that when placed in air of high relative humidity, wheat and particularly flour, will pick up moisture and gain in weight. Conversely, when the humidity is low the flour will tend to lose moisture and hence to lose weight. The moisture in wheat or flour exerts a certain vapor pressure and whether there is a tendency for water to evaporate from, or for moisture to be absorbed by the material depends upon the relative values of this vapor pressure and that of the moisture in the atmosphere in which the product exists. If the two vapor pressures are different, there will be an exchange of moisture between the product and the surrounding atmosphere, resulting in a gain or loss of moisture by the product, until a state of equilibrium is reached. In other words, whether the moisture content of a cereal product increases, decreases, or undergoes no change upon storage is bound up with the relative humidities of the atmosphere in which it is kept. The moisture content possessed by the product will, of course, depend upon the relative humidity of the air.

Fenton (12), Alberts (1), Robertson et al. (19), Gane (14), Coleman and Fellows (7), and Bailey (5) have each worked with one or more types of grain to determine the equilibrium moisture content of that grain at various relative humidities. There was variation in the results which would indicate either variation between the grain samples or imperfections in the determination procedures.

Figure 1 is a plot of the results of determinations made by Fenton (11) of the equilibrium moisture contents of winter wheat in Kansas. The curves show the relative humidity of air at three different temperatures at which there will be no gain or loss of moisture at the corresponding grain moisture content.

Vapor Pressure Differential As a Cause of Moisture Migration

An explanation of the molecular action of gases is given by Deming (10, p. 45). The molecules of a gas are in continuous motion. This motion causes the molecules to strike each other as well as the walls of any container in which the gas may be contained. This motion results in a pressure that could be measured on the container wall. The pressure that a gas exerts increases with increased temperature. This would indicate that the molecules move more swiftly with higher temperature, and hence deliver harder blows upon the vessel walls. If the walls are flexible, they will be driven out; in other words, the gas will expand.

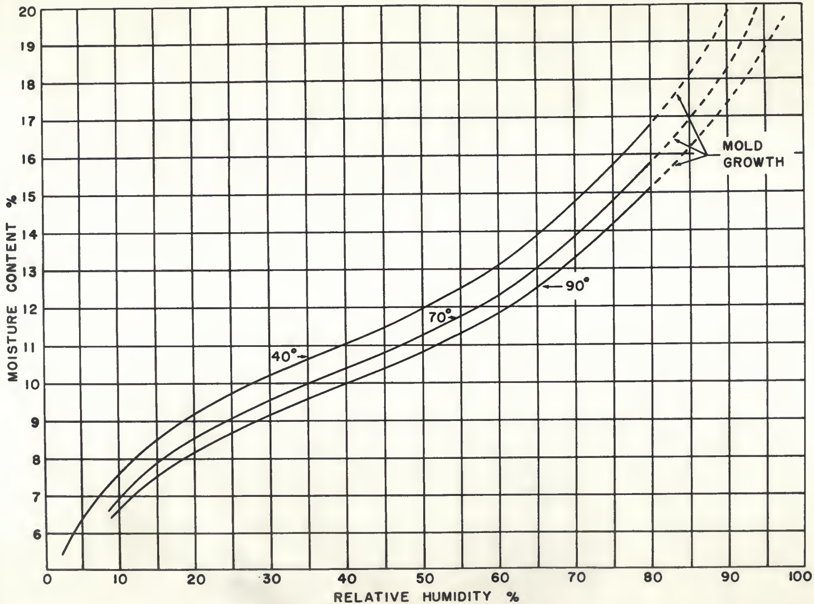


Fig. 1. Equilibrium moisture curves of wheat in Kansas from Fenton (11).

The air and the water vapor in grain follow the action of gases described by Deming. The characteristics of air are very nearly like a perfect gas while the characteristics of water vapor are noticeably different than a perfect gas. Nevertheless, the general pattern followed by each is similar.

When a part of a bulk of grain becomes warmer than the rest, a greater pressure is exerted by the vapor in that warmer part than in the surrounding cool parts. The trend will be toward an equalization of the vapor pressures in the bulk of grain. This will cause the water vapor to leave the warm region and enter the cool region. The loss of vapor in the warm area plus the increased temperature causes a lowering of the relative humidity. This brings about the conditions that cause moisture to leave the grain kernel and enter the air.

The process is exactly reversed in the regions of low temperature. The vapor then exerts less partial pressure. Vapor enters the region in an effort to keep the vapor pressure constant. Relative humidity goes up as the temperature goes down. The vapor pressure in the grain becomes less than in the air, so moisture enters the grain.

Oxly (18), Anderson et al. (3) and Barre (6) all explain moisture migration in this manner. Theoretically, the process could reach a state of equilibrium if the grain were in a closed container and had a constant temperature differential. This would be achieved when the moisture content of the grain and air were at equilibrium and a uniform vapor pressure existed throughout the container. Anderson et al. (3) in Canada found that equilibrium moisture conditions were achieved very slowly in such a container. It was found that the speed of moisture translocation increased as the temperature gradient steepened in a given mass of grain.

Convection of Air As a Cause of Moisture Migration

McAdams (17, p. 1) defines convection as the transfer of heat from one point to another within a fluid, gas, or liquid by mixing of one portion of the fluid with another. In natural convection the motion of the fluid may be entirely the result of differences of densities resulting from temperature differences. The air with its water vapor in a grain mass would be governed by this process if a temperature difference were established. At the same time the processes that cause moisture to enter or leave the grain kernel would be in action. A cool region would have a high relative humidity which would cause the grain to take moisture from the air. Dense, cool air in the upper part of a bulk of grain would tend to displace the less dense warm air below, and the warm air would tend to rise. The removal of moisture by the grain from the cool air would dry the air so it would be in a condition to remove moisture from the grain as it settled and warmed. The opposite effect would occur as the warm air rose.

Anderson et al. (3) credited part of the phenomenon of the translocation of moisture in grain to the action of air convection. Babbit (4) conducted a laboratory experiment to determine the thermal properties of grain in bulk. He shifted the position of his heat transfer equipment in an effort to produce natural convection. He found that it had very little effect in transferring heat in grain. If there was little heat transferred by convection, there would be little moisture transferred because of the process. Oxley (18) used paper baffles to prevent heat transfer by convection in a container filled with grain. He obtained results similar to Babbit. Oxley suggests that a lateral movement of air may be necessary to set up extensive convection currents in grain. Conditions may be more favorable for this in large bulks of grain than in laboratory tests. The results reported in the final report of the Commodity Credit Corporation Grain Storage Project (9) would indicate that this was true. A record was kept for nearly a year of the temperatures and moisture contents of corn that was stored in several bins. The bins were located in several states throughout the Middle West. Moisture translocation began to take place when cold weather started. The phenomenon was explained as follows: As the air cooled on the sides of the 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. As the warm air reached the cool surface, moisture was lost from the air to the grain. This dried the air so that when it was circulated back down the sides and toward the center again, it could warm up and take moisture from the grain. This would then be carried to the surface of the grain. The high moisture accumulations at the center of the bins in the test would indicate that translocation was caused by convection.

THE INVESTIGATION

Plan of Experiment

A laboratory experiment was conducted to determine the effect that a vapor pressure difference and convection currents had upon moisture migration. Three columns of wheat were used in the test. They were contained in wooden boxes that measured 7 3/4 inches by 7 3/4 inches square and were 6 feet long.

One column was placed in a horizontal position. Heat was added to the wheat at one end and the grain was cooled at the other end. A second column was placed in a vertical position. Heat was added at the top and the grain was cooled at the bottom. The third column of wheat was placed in a vertical position. Heat was added at the bottom and the grain was cooled at the top.

In the second column the conditions were favorable only to moisture migration caused by a vapor pressure difference since the cool dense air at the bottom of the column could not rise and replace the warm, less dense air at the top of the column. In the third column a vapor pressure difference plus extreme conditions favorable to the creation of convection currents would exist to cause moisture migration. The cool dense air at the top of the column would tend to settle and the less dense warm air at the bottom would tend to rise. This would create a convection current. In the first column a vapor pressure difference would exist, and in addition convection currents might be set up.

Equipment

Type of Grain. Wheat was selected to be used in the test because its action is typical of grains in general. It was comparatively easy to handle in the experiment. In addition, it is grown in Kansas so the supply was adequate. The wheat used in the test was grade number 2, hard red winter wheat. Its test weight was 59 pounds per bushel, and its average moisture content was 12.6 percent. This was dry wheat in good storage condition.

The Wheat Containers. The columns of wheat were contained in boxes made of 1/4" weatherproof plywood. The inside dimensions of these boxes were 6 feet long and 7 3/4 inches x 7 3/4 inches. All of the joints were nailed and glued. Three coats of exterior type waterproof varnish were applied to the inside of the boxes to act as a partial vapor seal. The exterior of the boxes were covered with aluminum foil to complete the vapor seal. After two weeks of operation, glass-wool insulating blankets, 2 inches thick, were wrapped around the boxes to decrease the heat transfer through the walls.

Heat Supply. Air chambers with sheet aluminum plate to contact the grain were constructed. The interior dimensions were 8 inches by 8 inches by 10 inches. Except for the aluminum plates, the chambers were constructed of wood. A 50 watt, 220 volt electric light bulb was used as the heat supply. It was located on the end of the chamber opposite the aluminum plate.

The direct rays of the light bulb were shielded from the contact plate by a sheet iron shield. The light bulb could be replaced through a door in the side of the chamber. A Cenco-Dekhotinsky Thermoregulator was wired in the circuit with the light bulb to control the heat supply. The temperature-sensitive bimetallic-helix element of the thermoregulator was placed between the sheet iron shield and the aluminum grain contact plate. This heating system produced a very nearly uniform temperature at all points on the aluminum grain contact plate.

The heaters were attached to the containers with metal brackets and were sealed to the containers with asphalt.

Cooling System. Sheet-metal cooling tanks were used to cool one end of each of the grain columns. They were designed to fit on the ends of the wooden boxes in contact with the grain. A supply of cold water was automatically maintained in a milk can cooler. A pump operated continuously to circulate the cold water from the milk can cooler through the cooling tanks and back to the milk can cooler. Copper tubing was used to carry the water through the circuit. It was insulated with 1 inch of glass wool. The outside layer of glass wool was coated with tar to prevent condensation. This reduced the heat that was transferred from the air to the cold water. The temperature of the circulated water was maintained at approximately 40 degrees Fahrenheit.

The cooling tanks were attached to the containers with metal brackets and were sealed to the containers with asphalt.

Temperature Measurements. Copper-Constantan Thermocouples were used to determine the temperatures at various places in each column. The wire was enamel coated and covered with cotton. One copper and one constantan wire were led to each point where a temperature record was desired. At that point the enamel was removed from the wire and a soldered junction was made. Five thermocouples were placed on a wooden dowel and the dowel was then inserted into the grain container. The dowel was sealed to the container with asphalt. The thermocouples were equally spaced on the dowel so that one thermocouple was at the center of the grain column, one was at each edge, and one was between each edge of a column and the center. Six dowels equipped with thermocouples were spaced in a plane the length of each column as shown in Plate III. The end dowels were 1 1/2 inches from the end of the grain bulk and the other four dowels were spaced equally along the column. On the horizontal grain column the dowels were placed so that readings were obtained in a vertical plane through the length of the column.

The thermocouples from each dowel were connected to a female type plug. A male type plug joined the thermocouples with a selector switch. By using the selector switch, each thermocouple could be connected to a potentiometer. One female was needed for the thermocouples on each dowel. This made a total of 18 plugs necessary. Only one male plug and one selector switch were needed.

A Rubicon temperature-calibrated potentiometer was used to read the temperatures. It was calibrated so that temperatures

EXPLANATION OF PLATE I

The Grain Containers

1. Heaters
2. Cold water tanks
3. Insulated pipes for circulating cold water
4. Potentiometer
5. Thermocouple selector switch
6. Thermocouple selector panel

PLATE I

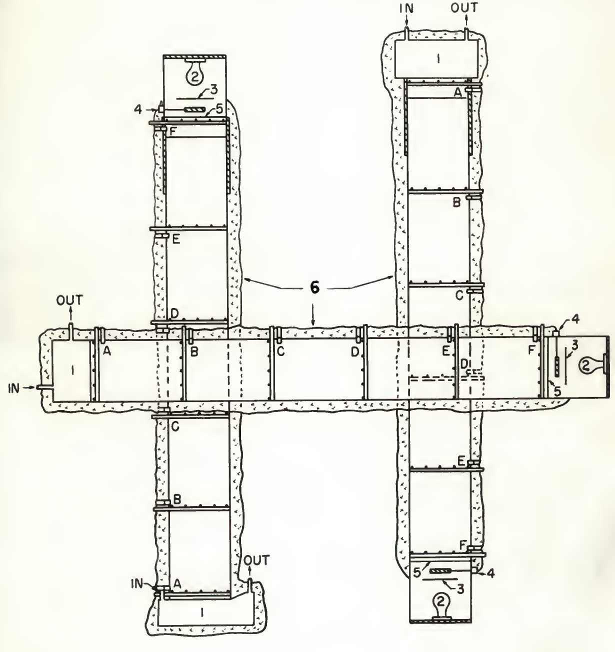
EXPLANATION OF PLATE II

Cross Sections of Wheat Containers

A, B, C, D, E, and F: Thermocouple dowels and sampling holes

1. Cold water tanks
2. Light bulb
3. Sheet iron shield
4. Cenco Decotinsky thermoregulator
5. Sheet aluminum plate
6. Glass wool insulating blanket

PLATE II



EXPLANATION OF PLATE III

Water Cooling System. It is located back of the grain containers, and is separated from them by the wall that is shown.

1. Milk can cooler. The tank is half filled with water
2. Circulating pump behind pulley wheels
3. Pipes for conveying the cold water

PLATE III

could be read directly in degrees Fahrenheit.

Grain Sampling Equipment. Grain sampling holes were located at each set of thermocouples. These holes were closed with rubber stoppers. Samples were taken in the plane through which the thermocouples passed. It was necessary to sample the grain to determine the moisture content at various points in each grain column. A small probe was constructed to slide into the grain columns by way of the holes in the grain containers. The probe took three samples across the narrow axis of each container at each sampling hole. One sample was taken at the center and each of the other samples was 3/4 inch from the center sample and 3/4 inch from the edge of the column. The average weight of each sample was 3 grams. Small aluminum cans with covers were used to hold the samples. An electric (air) oven, a set of chemical balances, and a Hobart grinder were needed for determining the moisture content of the samples.

Procedure

Starting the Test. On April 3, 1951, the containers were filled with wheat and the heating chambers and cooling tanks were put in place. On April 5, the heaters and cooling system were put into operation. The plan was to heat one end to 100° F. and cool the other end to 40° F. This created a vapor pressure difference or driving force of 0.6 pound per square inch between the grain bulks at each end of the columns. The high temperature was easily maintained, but some trouble was encountered in maintaining the low temperature.

Temperature Readings. From April 5 to April 10, 1951, temperatures at each thermocouple junction were read at equal intervals four times each day. By the end of that period the daily temperature change was small. From April 10 until May 24, 1951, temperatures were recorded two times each day. After that date, temperatures were taken once every two days. When grain temperatures were taken, the temperature of the room and the temperature of the cooling water were recorded.

Moisture Testing. After the experiment had operated one month, each column was sampled so that moisture determinations could be made. Each column was sampled again after another month of operation. Two more samplings were made at the end of the second and fourth week of the final month of the test.

A standard air oven method (18, p. 22) was used in determining the moisture content of the samples. The method prescribed is as follows:

> Apparatus: (1) Metal dishes with covers. (2) Oven capable of being maintained at approximately 130° (±3°) Centigrade and provided with an opening for ventilation. (3) Thermometer passing into the oven in such a way that the tip of the bulb is level with the top of the moisture dishes and is not directly exposed in currents of escaping water vapor. (4) Small grain grinder (a Hobart grinder was used adjusted to a number 2 setting).
>
> Determinations: Weigh accurately approximately 2 grams of the well-mixed, ground-up sample into a covered dish that has been dried previously at 130° (±3°) Centigrade, and weighed soon after attaining room temperature. Uncover the sample and dry the dish cover and contents in the oven at 130° (±3°) Centigrade for one hour after the oven regains a temperature of 130° Centigrade. Cover the dishes while in the oven, and weigh soon after room temperature is attained. Report the flour residue as total solids and the loss in weight as moisture. (The moisture content was expressed as a percent of the wet weight of the sample).

<u>Insulation</u>. For the first two weeks that the experiment was in operation, there was no insulation around the grain columns. It was felt that effects of the heaters and cooling tanks on the grain columns during that period were not adequate. The two inch glass-wool-insulating blankets were, therefore, added to increase the amount of grain that was heated and cooled in each column.

RESULTS

Grain Temperatures

Figures 2, 3, and 4 show that within one day after the experiment was started a temperature gradient had been set up over the length of each column. Thereafter this temperature gradient was maintained, and it changed only in response to fluctuations in air temperatures.

Until April 14, the columns of grain were not insulated. Fluctuations of room temperatures caused corresponding fluctuations of grain temperatures. It was difficult to keep very much of the grain in each column cooled or warmed. The addition of insulation around the columns, however, increased the quantities of grain that were heated and cooled. Also, it reduced fluctuations in the temperatures of the grain.

From April 5 until May 1, the cold water circulating system was not insulated. The circulating cold water gained heat from the air faster than the cooling equipment could remove it. Therefore, the water temperature was higher than was desired. During

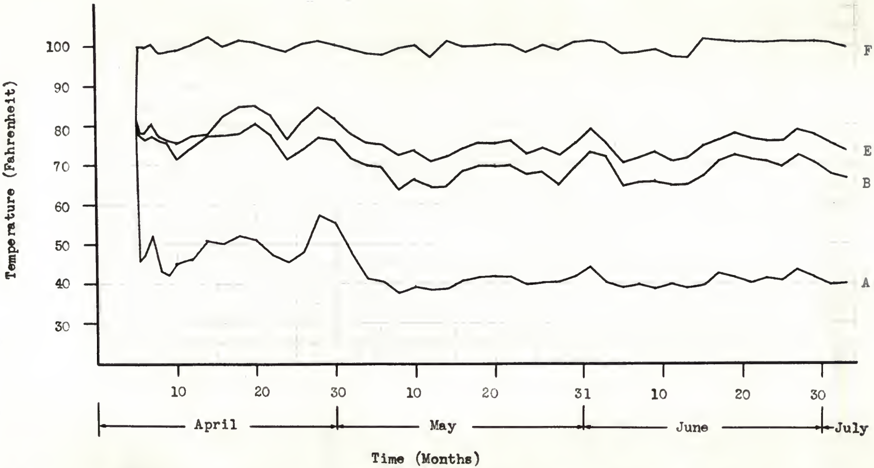


Fig. 2. Temperature variations at the center thermocouple on the dowels lettered A, B, E, and F (Plate II) in the container that was placed in a horizontal position.

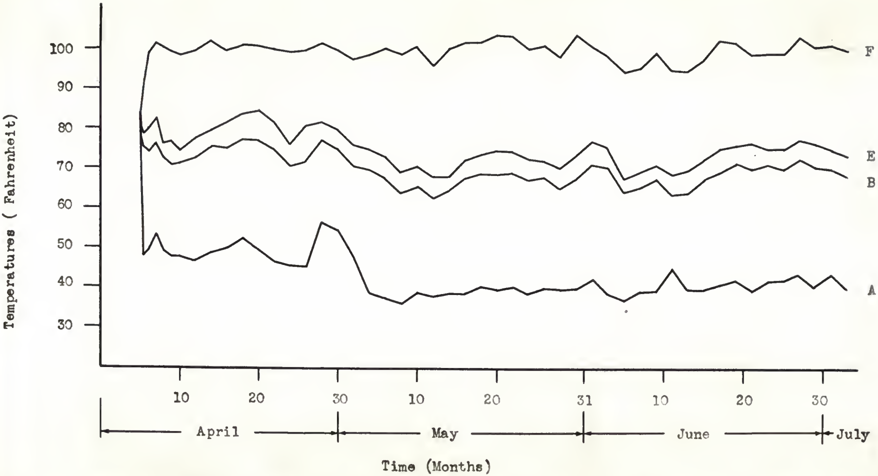


Fig. 3. Temperature distributions at the center thermocouple on the dowels lettered A, B, E, and F (Plate II) in the container that was placed in a vertical position with a cold bath at the bottom and a heater at the top.

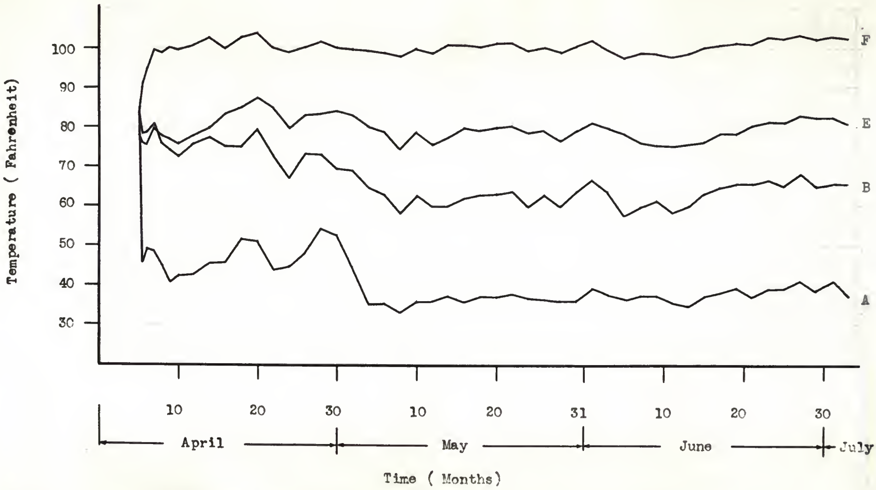


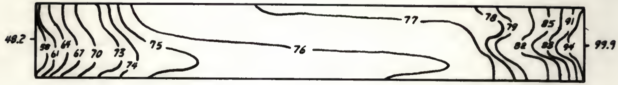
Fig. 4. Temperature variations at the center thermocouple on the dowels lettered A, B, E, and F (Plate II) in the container that was placed in a vertical position with a cold bath at the top and a heater at the bottom.

this period, the water temperature was greatly affected by fluctuations in room temperatures. On May 1, the water circulating pipes were insulated. The water temperatures were lowered and the effects due to fluctuations of room temperatures were reduced. For the remainder of the experiment, the water temperature averaged about 36° F.

The heat that was added to the grain traveled along the column. As it was transferred through the grain, part of this heat was dissipated into the air. At the cold end of the column, heat was removed from the grain bulk. The heat that was removed was partially replaced by heat from the air.

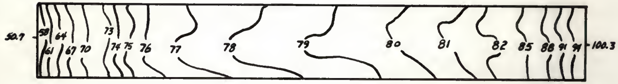
Figures 5, 6, and 7 are diagrams of the grain columns showing the lines of equal temperatures. Daily temperatures at each thermocouple were averaged over a period of several days and the resulting iso-thermal lines were ploted on the diagrams. The result was a general picture of the temperature gradient for the period. Care was taken in selecting the periods to be averaged. Conditions were nearly constant in the grain during each period for which an average was made.

The temperatures in the grain columns were affected by the position of the column. Figure 5 illustrates the temperature distribution in the column that was placed in a horizontal position. The top side of the column was warmer than the lower side. This effect was very distinct in the column before it was insulated. After the column was insulated, the diagrams showing the temperature patterns still showed higher temperatures at the top side of



Apr.7–Apr.14

Av. room temp.–78.3



Apr.20–Apr.30

Av.room temp.–78.7

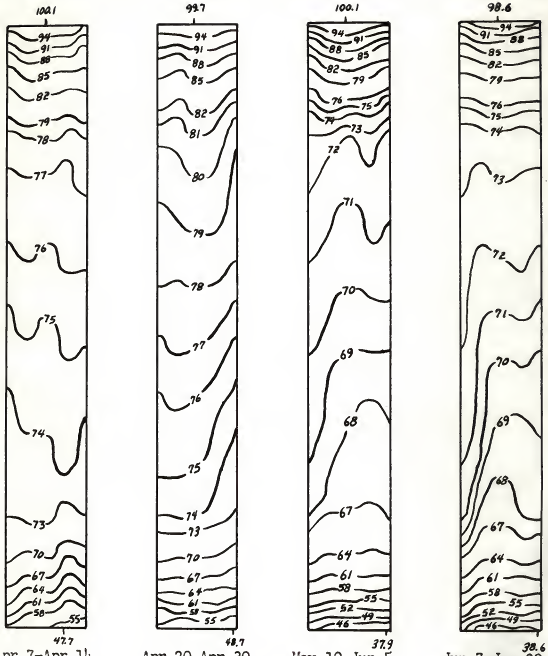
May 10–Jun.5

Av. room temp.–70.3

Jun.7–Jun.29

Av. room temp.–72.1

Fig. 5. Average temperature distribution in the container that was placed in a horizontal position. Three degrees separate the lines of equal temperature where steep gradients exist.



Apr.7-Apr.14

Av. room
temp.-78.3

Apr.20-Apr.30

Av. room
temp.-78.7

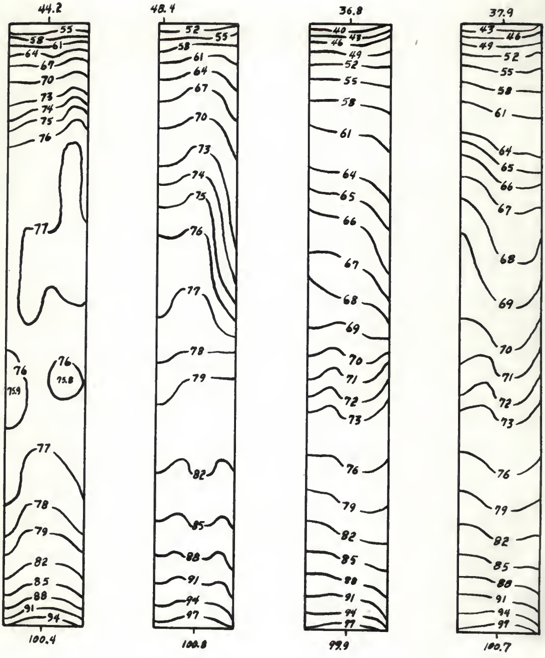
May 10-Jun.5

Av. room
temp.-70.3

Jun.7-Jun.29

Av. room
temp.-72.1

Fig. 6. Average temperature distributions in the container that was placed in vertical position with a cold bath at the bottom and a heater at the top. Three degrees separate the lines of equal temperature where steep gradients exist.



Apr.7–Apr.14 — Av. room temp.–78.3

Apr.20–Apr.30 — Av. room temp.–78.7

May 10–Jun.5 — Av. room temp.–70.3

Jun.7–Jun.29 — Av. room temp.–72.1

Fig. 7. Average temperature distributions in the container that was placed in a vertical position with a cold bath at the top and a heater at the bottom. Three degrees separate the lines of equal temperature where **steep gradients** exist.

the grain column. This could indicate some air convection in the grain.

Figure 6 illustrates the temperature distribution in the vertical column that was heated at the top and cooled at the bottom. The air temperature in the room increased from lower levels of the room to higher levels. This aided in the establishment of a temperature gradient in the column. As the distance from the heat source increased, the temperature decreased; and as the distance from the cold bath increased, the temperature increased. There was a steep gradient out 1 1/2 feet from each end. Over the center 3 feet of the column there was only a small temperature gradient.

Figure 7 illustrates the vertical column that was heated at the bottom and cooled at the top. The heat transfer through the column was counter to the vertical temperature gradient in the room. Before the column was insulated, the heat was lost from the warm end and gained by the cold end so rapidly that no temperature gradient existed in the center 3 feet of the column. The loss was so extreme that the lower temperatures at lower levels in the room caused a slight reversal in the temperature gradient through the wheat. The grain was warm at the bottom of the column; it became cooler as the distance from the heat supply increased; it then became warmer for a distance along the column because of the temperature gradient of the room air; and along the rest of the column it became cooler because of the effect of the cooling tank. Insulating the column removed this condition and created a temperature gradient that was the most uniform of the 3 in the test. The gradients 1 1/2 feet from each end were steep, and the gradient in the center 3 feet of the column was not as steep as at the end. However, the gradient established in the center 3 feet of this column was steeper than in corresponding regions of the other 2 units. Some of the lines of equal temperature indicated that air may have been circulated in the column to some degree by convection. The differences in air densities created very good temperature distribution in the column.

Grain Moisture

Figures 8, 9, and 10 are diagrams showing the lines of equal moisture content of the grain in each column. The diagrams illustrate conditions in a plane that passes through the thermocouple dowels in each column. Because the limited number of samples that could be obtained, it was impossible to make an exact diagram of the moisture conditions in the grain. The plots were made to conform as closely as possible to the way that conditions were indicated from the sampling.

In general, the values of the moisture contents of the grain in each column appear to be quite accurate. The data presented for April 27, 1951, on Fig. 8 and for July 3, 1951, on Fig. 10 seem to be slightly higher than should be expected. These results might have been caused by excessive drying of the samples during the moisture determinations. This would have caused some of the volatile oils to have been driven off. The relative positions of grain with either high or low moisture contents can still be

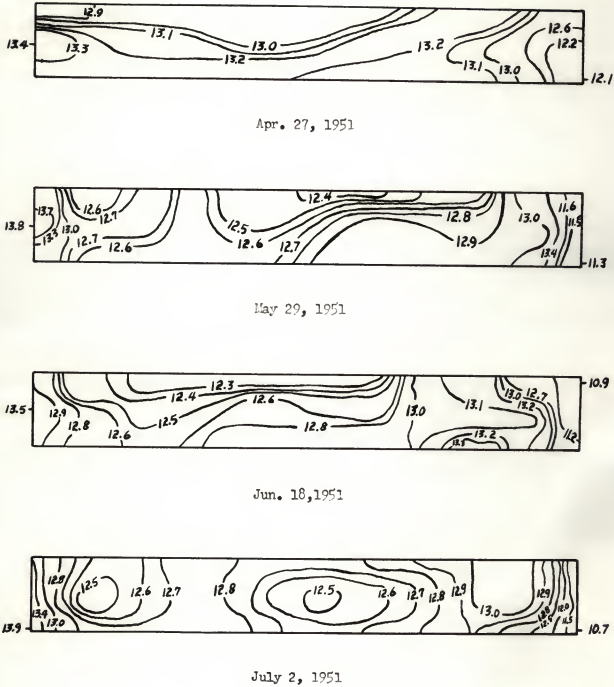


Fig. 8. Moisture distributions in the container that was placed in a horizontal position.

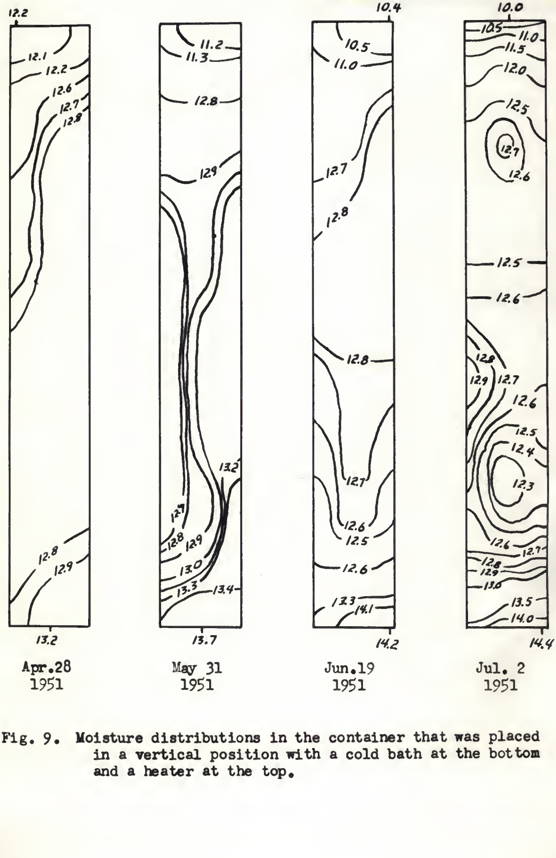


Fig. 9. Moisture distributions in the container that was placed in a vertical position with a cold bath at the bottom and a heater at the top.

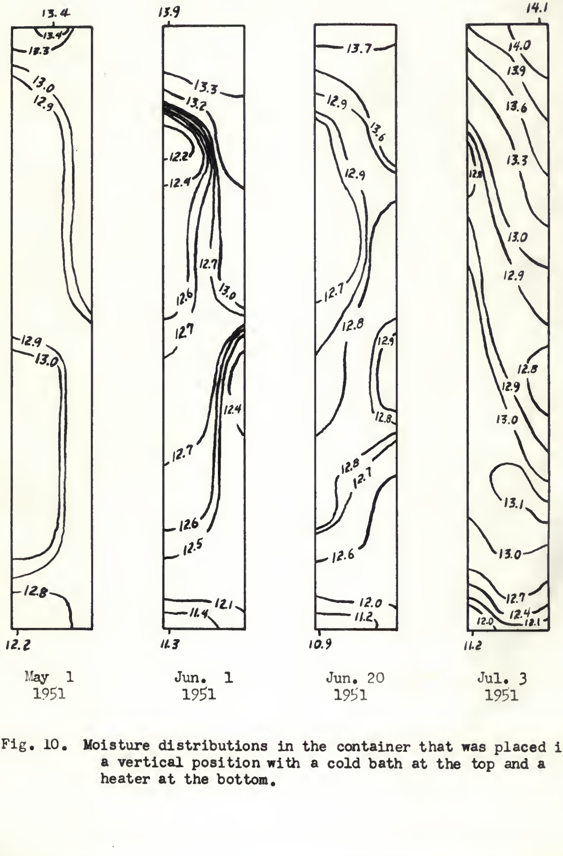


Fig. 10. Moisture distributions in the container that was placed in a vertical position with a cold bath at the top and a heater at the bottom.

determined from these diagrams.

At the cold end of each grain column, there was an increase of grain moisture content. At about the line where the sharp temperature gradient ended, toward the center of the column, there was a decrease in the grain moisture content.

At the warm end of each grain column, there was a decrease of grain moisture content. At about the line where the sharp temperature gradient ended toward the center of the column, there was an increase in the grain moisture content. Where there was a steep temperature gradient, moisture migrated rapidly. The condition is reversed at the cool end. Where the steep gradient ended, the migration continued much more slowly.

The final moisture distribution patterns in each container have various distinct characteristics. The results of the first sampling of each column of grain produced moisture distribution patterns that proved to be similar to the patterns produced from succeeding samplings. The patterns became more distinct as the time of operation of the experiment lengthened.

On the upper part of the horizontal column, about 6 inches from the heat source, a layer of high moisture grain developed. On the lower side of the column a layer of dry grain was created. Exactly reversed conditions developed at the cool end. This condition was most noticeable at the time of the final sampling.

In the vertical column of grain that was heated at the top and cooled at the bottom, a relatively uniform moisture gradient was developed. The lines of equal moisture content were generally quite horizontal across the column.

In the vertical column of grain that was cooled at the top and heated at the bottom, the lines of equal grain moisture content were asymmetrical. The diagrams show a region of high moisture content grain extending down the right side of the column. From the warmed bottom of the column, a region of low moisture content grain extends up the left side.

Maximum and minimum grain moisture contents were about equal in all of the columns at the end of the test.

INTERPRETATION OF RESULTS

The distances between heated or cooled bulks of grain affected the rate at which moisture migrated. This was illustrated in all of the columns of grain. About 1 1/2 feet from each end, moisture migrated rapidly. This was where the steepest temperature gradients existed. Through the center of each column the rate of migration was slow. These rates varied with the steepness of the temperature gradients.

In the vertical column that was heated at the top and cooled at the bottom no convection currents were expected. The moisture distribution patterns were quite symmetrical so this would indicate that only a vapor pressure difference caused the migration of moisture. At the cold end of the column, the grain became as dry as in the other columns. It differed in that the quantity that became dry or that became moist was not as great as in the other two columns.

In the horizontal column a vapor pressure difference appears to have caused much of the moisture migration. In addition, the moisture distributions could be interpretated as being affected by air currents that were created by convection. At the cool end, it appears that the cooled air at the surface settled and lost some of its moisture on the bottom side of the column. This would dry the air so that if it reheated and rose again to the upper side of the column, it could take moisture from the grain in the upper regions. Upon cooling again, it would carry the moisture to the lower side of the column. At the warm end it appears that the heat source warmed the air and caused it to rise. The warming would increase its capacity to hold moisture. Cool air away from the heat supply would settle leaving space for the warm air on the upper side of the column. As the warmed air moved away from the heat supply, it would cool and thus lose some of its moisture to the grain. When it had cooled and settled back to the bottom side of the column, much of its moisture would have been lost. As it moved back toward the heat supply, it would be warmed and thus made capable of picking up more moisture. This would account for the higher moisture content in the upper part of the column at the warm end than in the lower part.

The action of the convection currents, if it existed in the horizontal column, was made up of two separate systems, one of which existed at each end. In the vertical column that was heated at the bottom and cooled at the top, much of the moisture migration was no doubt caused by the differences in vapor pressures in various parts of the column. In addition, the moisture patterns appear to indicate that air was convected through the columns. The patterns suggest that moisture was carried up the right side of the column in warmed air. As the moisture reached the cool areas, it was lost to the grain. At the cooling tanks the air was thoroughly cooled and began to settle down the left side of the column. As the air settled down, it was warmed. This increased its capacity for holding moisture so moisture was taken from the grain by the air. It appears that one convection current circulated through the entire column.

CONCLUSIONS

It is difficult to draw definite conclusions from the data taken in the test. It appears that moisture migration was still going on at the end of the experiment. This would indicate that an equilibrium condition had not been approached in the boxes of wheat. More conclusive results may have been obtained if the test had operated for a longer period.

The lines of equal temperature that are illustrated in Figs. 5, 6, and 7 do not indicate conclusively that air moved through the wheat by convection, but the moisture distribution patterns show results that could well be explained by the action of convection currents. The small diameter of the containers seems to have restricted the possible creation of convection currents.

If a larger bulk of grain had been used in the test, conditions would have been more favorable for the creation of convection currents.

Since grain gained moisture at the cool end and lost moisture at the warm end of all containers, it seems safe to conclude that a vapor pressure difference does cause moisture migration. From the tests, it is difficult to determine the added effect that convection currents had on the rate of moisture migration.

A large temperature difference in a bulk of grain seems to cause more rapid migration of moisture than a smaller temperature difference. About a foot and a half from each end of the columns there was a steep temperature gradient. Migration through these gradients was rapid. The grain in the center 3 feet of each column did not have a steep temperature gradient so the migration was slow.

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THE CAUSES OF MOISTURE MIGRATION IN STORED GRAIN

by

GEORGE LEWIS PRATT

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A major problem in long term storage of relatively large bulks of grain is a process by which moisture moves from one part of the bulk to another. The phenomenon is referred to as moisture migration, moisture translocation, or moisture redistribution. From previous experiments it has been found that moisture will move from a part of a grain bulk that has a high temperature to a part that has a low temperature.

The experience that has been obtained from actual storage projects has been that a layer of grain with very high moisture contents develops at the surface of a grain bulk. This occurs in grain that was orginally stored in good condition. The effects are the same as in any grain that is excessively moist. The respiration rate of the grain increases; insects multiply; fungus growths begin; and the temperatures become high. This causes the grain to die, spoil, and become worthless.

Two general theories have been proposed to explain this 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. These vapor pressure differences are created by temperature differences.

The phenomenon of the equilibrium moisture content of grain and air is an important part of any theory of moisture translocation. One description of it is that because the grains are hygroscopic in nature, they gain or lose moisture when the vapor pressure in the space surrounding the grain is greater or less than the vapor pressure exerted by the moisture within the grain. The moisture in grain exerts a certain vapor pressure, and whether there is a tendency for moisture to escape from or to be absorbed by the material depends upon the relative values of this vapor pressure and that of the moisture in the atmosphere in which the product exists. If the two vapor pressures are different, there will be an exchange of moisture between the product and the surrounding atmosphere resulting in a gain or loss of moisture by the product, until a state of equilibrium is reached.

The theory of air convection currents that is used to explain moisture migration can be described as follows: In the winter the surface and the sides of a bulk of grain become cool while the central mass of grain is still warm. The cooled grain has a high relative humidity so moisture is absorbed from the air by the grain. The cool air is more dense than the warmer air below it, so it tends to settle and the warmer air rises, thus creating convection currents within the grain. The cool air after being dried settles and becomes warmer. This makes it possible for this air to remove moisture from the warmer grain. As the circulation continues, moisture is removed from the warmer grain in the lower regions of the bin and deposited in the cooler upper regions of the bin.

The theory of a vapor pressure difference that is used to explain moisture migration can be explained as follows: When a part of a grain bulk becomes warmer than the rest, a greater pressure is exerted by the vapor in the warmer part than in the surrounding cooler parts. The trend will be toward an equalization of the vapor pressures in the bulk of grain. This will cause the water vapor to leave the warm region and enter the cool region. Warming the grain increases its vapor pressure. This brings about the conditions that cause moisture to leave the grain kernel and enter the air. The process is exactly reversed in the regions of low temperature. The grain when cooled exerts less vapor pressure so moisture enters the grain from the air.

The purpose of this investigation was to determine which of these processes is responsible for the migration of moisture. A laboratory experiment was set up in an attempt to shed light on the problem. In the laboratory test a temperature difference was set up, thus creating a vapor pressure difference in the grain. By the location of the cool and warm areas of grain, an attempt was made to determine the effect of convection currents on the migration of moisture.

Procedure

Three columns of wheat were used in the test. They were contained in plywood boxes 7 3/4" x 7 3/4" x 6'. One column was placed in a horizontal position. Heat was added at one end of it and a cooling tank was placed at the other. A second column was placed in a vertical position. Heat was added to it at the top and a cooling tank was placed at the bottom. The third column was placed in a vertical position. Heat was added at the bottom of it and a cooling tank was placed at the top.

In the second column the conditions present were favorable only to migration of moisture caused by a vapor pressure difference. In the third column a vapor pressure difference plus extreme conditions favorable to the creation of convection currents would exist to cause moisture migration. In the first column a vapor pressure difference would exist and in addition convection currents might be set up.

Results

Provisions were made so that temperatures and moisture content records could be taken at several points in the columns. The temperature and moisture data from the vertical column that was heated at the top and cooled at the bottom indicated that no convection currents were set up. Moisture migrated to the cool region, nevertheless. This can be considered to have been caused by a vapor pressure difference.

The temperature and moisture records of the horizontal column indicate that convection currents as well as a vapor pressure difference caused moisture to migrate. The action of the convection currents, if it existed in the horizontal column, was made up of two separate systems, one of which existed at each end.

The temperature and moisture records of the vertical column that was heated at the bottom and cooled at the top showed that one convection current was set up in the column. The result was that the grain became moist at the cool end and down one side while at the warm end and up the opposite side, it became dry. The vapor pressure difference also helped to cause moisture migration.

The migration was most rapid in each column where a steep temperature gradient existed.

Conclusions

It is difficult to draw definite conclusions from the data taken in the test. It appears that moisture migration was still going on at the end of the experiment. This would indicate that an equilibrium condition had not been approached in the boxes of wheat. More conclusive results may have been obtained if the tests had operated for a longer period.

The temperatures in the columns do not indicate conclusively that air moved through the wheat by convection, but the moisture distribution showed results that could well be explained by the action of convection currents. The small diameter of the containers seem to have restricted the possible creation of convection currents. If a larger bulk of grain had been used in the test, conditions would have been more favorable for the creation of convection currents.

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