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DEVELOPMENT OF EQUIPMENT TO MEASURE WETTING OF STORED GRAIN

by

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B. S., Universidad de America, Bogotá, Colombia 1968

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Grain Science and Industry

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1973

Approved by

Major Professor

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NOMENCLATURE

M - Instantaneous moisture content, lb. of water per lb. of seed.

Mo - Initial moisture content of grain, lb. of water per lb. of seed.

Me - Equilibrium moisture content of grain, lb. of water per lb. of seed.

MR - Moisture ratio.

Po - Observed vapor pressure at RH relative humidity, inches of mercury.

Pat - Vapor pressure at saturation for the temperature under consideration, inches of mercury.

To - Initial temperature of grain, absolute temperature ^oR.

Tat - Temperature under consideration, absolute temperature ^oR.

h - Total depth of grain in the silo, ft.

x - Depth from the bottom, ft.

ν - Kinematic viscosity of water vapor, ft^2 per hour.

θ - Time, hours.

INTRODUCTION

It is a well known fact that grain changes its moisture content during storage, and that the change implies either gaining or losing moisture depending on the environmental conditions, temperature and relative humidity, under which grain is stored.

In countries located within the tropic zone, like mine, Colombia, that variation of moisture is a real problem because it always ends up with the gaining of moisture by grain. Grain always follows that pattern because of the high temperatures and high relative humidities. Temperature is usually around 100° F and relative humidity is above 70% in most of the places where we built our grain elevators. Those conditions are rather constant throughout the whole year.

When we receive our grain, we have to dry it below 13% moisture content in order to keep it safe for a certain period of time, and when we learn that the temperature inside the silo is increasing, we take our grain out and dry it again. We do not know how often we will have to dry our grain or what its moisture is at different levels after some period of time. We do need something to tell us how that variation in moisture content of grain in a concrete silo takes place.

In a concrete silo the original moisture content of grain can be changed when water vapor goes through the concrete walls or when grain is in contact with the air of the environmental conditions.

In order to know the moisture content variation of grain when it is exposed to the environmental conditions the solution of a mathematical equation is proposed. However, the equation cannot be solved without the development of an equipment designed for that purpose.

This research was planned to develop the equipment and to present some data related to concrete permeability.

REVIEW OF LITERATURE

Sun-Won Park, et al. (1) found that in order of importance the factors influencing the adsorption rate of water vapor by yellow corn samples of 20 gr. in weight were relative humidity, initial moisture content, and temperature, and they stated that:

a) At a constant relative humidity, the adsorption rate increased with air temperature.

b) At a constant temperature, the adsorption rate increased with relative humidity.

c) The adsorption rate increased when both relative humidity and temperature increased, but was not in the order of partial pressure of water vapor in the air.

d) At constant temperature and relative humidity, adsorption rate of water vapor increased rapidly when moisture content decreased.

As they said: "Although the adsorption isotherms of grain have been studied extensively, the adsorption kinetics of water vapor by grain have not been well explored."

This is the only published paper on water vapor absorption by grain. However, the data found in it cannot be used for a big mass of grain stored in a silo, as it will be shown later on.

Fundamental concepts of concrete permeability

For any condition under which water passes through a given material, a general equation may be written between the forces acting and the resulting flow. Such an equation takes into account the fact that the amount of flow of fluids through any permeable medium is a function of three variables: (1) the inherent property of the material to resist flow, (2) the area subject to permeability, and (3) the force tending to produce flow.

The amount of water vapor that goes through concrete is defined, as was done by Barre (2), by the following equation

$$Q = K \cdot A \cdot \Delta P \cdot \frac{t}{\ell} \qquad (1)$$

where Q = amount of water vapor in lb.

K = water vapor permeability coefficient for concrete under consideration in in. per hour.

A = area exposed to water vapor in in^2.

ΔP = difference in vapor pressures or force tending to produce flow in lb. per in^2.

t = time of exposure in hour.

ℓ = thickness under consideration in in.

Samarai (3) concluded that the amount of water vapor is greatly reduced with longer moist curing periods. Using a 28-day curing period instead of a 7-day period the moisture tightness of concrete was reduced to one-half. He also studied the effect of the aggregates on the permeability of concrete containing them. Limestone, quartzite and gravel were studied. Concrete containing gravel showed the highest gain of moisture and the one containing quartzite had the lowest gain.

Other workers (2, 4, 5, 6) indicated that water vapor permeability is affected by the following factors:

a) It is increased by relative humidies above 75%.

b) Specimens of different mixes do vary water vapor permeability.

c) It is decreased with age.

d) It is decreased with NaCl at a concentration of 1.5%.

e) It is increased with a decrease in maximum particle size of aggregate.

f) It is increased with an increase in the water-cement ratio.

Because of so many factors involved in water vapor permeability for concrete, it is very difficult to state a definite value for the coefficient "K". Akroyd, T. N. W. (7) has suggested a value between 1.418×10^{-5} and 1.418×10^{-9} in. per hour, which makes concrete relatively impermeable, but yet not impervious.

WATER VAPOR MOVEMENT THROUGH A CONCRETE SILO

According to Milo S. Ketchum (8) and to the United States Department of the Interior (9) the concrete walls of a silo must be designed to meet the following specifications:

a) One part of cement.

b) Two parts of sand. When it is dried, it should pass through a screen having $\frac{1}{4}$" in diameter.

c) Four parts of aggregate broken to pass a $1\frac{1}{2}$ inch ring, and when it is dried, it should not pass a screen having $\frac{1}{4}$" in diameter.

d) The water-cement ratio by weight has to be 0.55 ± 0.02.

Based upon those data and assuming a concrete silo is 80 feet in height, 23 feet in interior diameter, and 7 inches in thickness, Table 1 was prepared.

The temperature and relative humidity of the environmental conditions was assumed to be 89° F and 73% respectively. Values for moisture content change of rough rice, yellow corn, sorghum and hard red winter wheat were calculated for a two-month period.

The temperature inside the silo, 77° F, was assumed to be constant during that period of time. Because of that fact when moisture content of grain increased, the relative humidity inside the silo had to increase, too. Increments in relative humidity were interpolated from Table 2.

It was very difficult to find the exact water-vapor permeability coefficients for a 0.55 water-cement ratio by weight. So that, they were interpolated too.

Table 1. **Variation of moisture content of some grains due to water vapor going through the concrete walls of a silo.**

Time (days) Permeability coefficient "k" (ft/hr)	Rice Moisture Content	Rice Relative Humidity	Corn Moisture Content	Corn Relative Humidity	Sorghum Moisture Content	Sorghum Relative Humidity	Wheat Moisture Content	Wheat Relative Humidity
t = 0	9.69	44.13%	9.405	37.18%	9.875	40.066%	9.87	40.275%
t = 3 K = 1.77×10^{-5} (1)	9.734	44.482	9.443	37.45	9.913	40.366	9.903	40.522
t = 7 K = 0.95×10^{-5} (1)	9.766	44.74	9.4701	37.644	9.94	40.58	9.927	40.702
t = 14 K = 0.56×10^{-5} (1)	9.80	45.0	9.50	37.857	9.97	40.82	9.952	40.89
t = 23 K = 0.39×10^{-5} (1)	9.84	45.13	9.54	38.143	10.0	41.05	9.985	41.137
t = 60 K = 0.23×10^{-5} (1)	9.90	45.75	9.587	38.479	10.06	41.526	10.03	41.475
t = 60 K = 3.53×10^{-5} (2)	11.46	58.20	11.185	47.75	11.693	56.93	11.46	52.2
t = 60 K = 3.4×10^{-8} (3)	9.6917	44.146	9.4067	37.191	9.876	40.074	9.871	40.2825

(1) Values of "K" were found by H. W. Brewer (11).

(2) Griggin and Henry's value (6).

(3) Samarai, M. A. (3) coefficient.

Notes: a) At time = 0 The values for moisture content were determined by the Air Oven Standard method, and they were the initial moisture of grains.

b) It was assumed a temperature of 77° F inside the silo for the calculations.

c) See Appendix A for calculations.

d) Environmental conditions 89° F and 73% relative humidity.

e) Moisture content (w.b) in percent.

Table 2. Adsorbed moisture in equilibrium with air of various humidities at room temperature(1)

(Approximately 77° F)

Moisture content (w.b) in percent							
Relative humidities (percent)	15	30	45	60	75	90	100
Corn	6.4	8.4	10.5	12.9	14.8	19.1	23.8
Rough rice	5.6	7.9	9.8	11.8	14.0	17.6	---
Sorghum	6.4	8.6	10.5	12.0	15.2	18.8	21.9
Wheat, hard red winter	6.4	8.5	10.5	12.5	14.6	20.1	25.3

(1) Extracted from Agricultural Engineers Yearbook. 1971.

Three different values for the coefficient of permeability, from three different sources, were used in the solution of the equation number 1.

The capacity of the silo was determined assuming the apparent density for rough rice, yellow corn, sorghum, and hard red winter wheat, was 34, 45, 42, 48 pounds per cubic foot, respectively. Values extracted from Feed Manufacturing Technology (10).

DIMENSIONAL ANALYSIS

As it was indicated before, grain does change its moisture content when it is exposed to an environmental condition. It is well known that grain stored in places, where temperature and relative humidity are high, adsorb moisture much faster than when it is stored under lower conditions.

When we talk about the change in moisture content of grain in a concrete silo, there are many variables that have to be taken into account. Those variables that were considered pertinent in this study are listed in Table 3.

They were considered to be the most important. However, there are others that can affect the moisture of grain. Among them we have the diameter of the silo, the specific heat of grain, the coefficient of conduction, the velocity of filling, the density of grain and gas, the particle diameter and the thermal diffusivity.

One way to combine all the pertinent factors into a mathematical equation is to use the experimental data to develop such an equation. This method is known as Dimensional Analysis. One such method of development commonly used is the Buckingham Pi groups method (12).

The Buckingham Pi groups method is based on the fact that the number of dimensionless and independent quantities that can be used to express a relationship between the variables, is equal to the difference between the total number of quantities involved and the number of dimensions in which those quantities may be measured. This equation may be written as:

$$s = n - b$$

Table 3. Pertinent variables for moisture content change.

No.	Symbol	Description	Units	Dimensions*
1	MR	Moisture ratio = $\frac{M - Me}{Mo - Me}$	---	---
		M = Instantaneous moisture content	$\frac{\text{lb. water}}{\text{lb. seed}}$	---
		Mo = Initial moisture content	$\frac{\text{lb. water}}{\text{lb. seed}}$	---
		Me = Equilibrium moisture content	$\frac{\text{lb. water}}{\text{lb. seed}}$	---
2	Po	Observed vapor pressure	lb./ft^2	FL^{-2}
3	Pat	Vapor pressure at saturation	lb./ft^2	FL^{-2}
4	To	Initial temperature of grain	^oR	T
5	Tat	Temperature under consideration	^oR	T
6	h	Total depth of grain	ft.	L
7	x	Depth from the bottom	ft.	L
8	ν	Kinematic viscosity	ft^2/hr.	$L^2\theta^{-1}$
9	θ	Time	hr.	θ

*Fundamental dimensions selected were length, time, temperature and force (L, θ, T, F) where s = the number of Pi terms

n = the total number of quantities involved

b = the number of basic dimensions involved

The Pi terms must be dimensionless and independent.

A general relationship indicating the dependence of MR to other variables, may be written as:

$$MR = f(Po, Pat, To, Tat, h, x, \alpha, \theta) \tag{2}$$

Equation (2) may be written as:

$$C \quad (MR)^{C_1} (Po)^{C_2} (Pat)^{C_3} (To)^{C_4} (Tat)^{C_5} (h)^{C_6} (x)^{C_7} (\alpha)^{C_8} (\theta)^{C_9} = 1 \tag{3}$$

MR forms a Pi group by itself because it is dimensionless, and it will be designated in the same way, MR.

The corresponding dimensional equation is:

$$(MR)^{C_1} (FL^{-2})^{C_2} (FL^{-2})^{C_3} (T)^{C_4} (T)^{C_5} (L)^{C_6} (L)^{C_7} (L^2\theta^{-1})^{C_8} (\theta)^{C_9} = 0 \tag{4}$$

From which four auxiliary equations may be written:

$$F: \quad C_2 + C_3 = 0 \tag{5}$$

$$L: \quad -2C_2 - 2C_3 + C_6 + C_7 + 2C_8 = 0 \tag{6}$$

$$T: \quad C_4 + C_5 = 0 \tag{7}$$

$$\theta: \quad -C_8 + C_9 = 0 \tag{8}$$

Since four equations are available for solving the eight unknowns, arbitrary values must be assigned to four of the unknowns. Let C_2, C_6, C_4, C_8 be the unknowns chosen.

The determinant of the coefficients of the remaining terms (C_3, C_5, C_7, C_9) is:

$$\begin{vmatrix} 1 & 0 & 0 & 0 \\ -2 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} = -1$$

Since this is not equal to zero, the resulting equations are independent and the selection is valid.

Values are assigned (arbitrarily) as follows: $C_2 = 1$, $C_4 = C_6 = C_8 = 0$. These values are substituted into equations (5), (6), (7), and (8), giving $C_3 = -1$, $C_5 = C_7 = C_9 = 0$.
From this and equation (3), dropping $C \alpha$

$$\pi_2 = \frac{Po}{Pat}$$

which is dimensionless.

From the Pi Theorem $s = n - b$, it is seen that a total of five Pi terms must be determined. Another term may be found by selecting a different combination of arbitrary values for the selected exponents, for example, $C_6 = 1$, $C_2 = C_4 = C_8 = 0$. These values are substituted into equations (5), (6), (7), and (8), giving $C_7 = -1$, $C_3 = C_5 = C_9 = 0$.
Hence

$$\pi_3 = \frac{h}{x}$$

Similarly, two more independent Pi terms are developed by letting C_4, and C_8 in turn, equal unity, with the other selected exponents equal to zero.

$$\pi_4 = \frac{To}{Tat}$$

$$\pi_5 = \frac{\tau\,\theta}{x^2}$$

The Pi group determined by the moisture ratio dimensionless group is:

$$\pi_1 = MR = \frac{M - Me}{Mo - Me}$$

A general solution may therefore be written as

$$_1 = f(\pi_2,\ \pi_3,\ \pi_4,\ \pi_5) \tag{9}$$

or

$$MR = f\left(\frac{Po}{Pat},\ \frac{h}{x},\ \frac{To}{Tat},\ \frac{\tau\,\theta}{x^2}\right) \tag{10}$$

The equation derived from this relationship can be

$$MR = C\left(\frac{Po}{Pat}\right)^{C_1}\left(\frac{h}{x}\right)^{C_2}\left(\frac{To}{Tat}\right)^{C_3}\left(\frac{\tau\,\theta}{x^2}\right)^{C_4} \tag{11}$$

To determine the equation, the constant C and the exponents $C_1 \ldots C_4$ must be found.

That can be done by holding all the independent groups involved in the function except one constant, and varying that one to establish a relationship between it and π_1. This procedure is repeated for each of the Pi terms in turn, and the resulting relationship between π_1 and the other individual Pi terms combined to give a general relationship. By plotting this relationship on log paper, a linear regression curve can be found. The slope of the line would give the exponent.

In order to solve the equation (11) four different tests have to be made. That cannot be done if we do not have an equipment designed to meet those requirements. By means of that equipment we have to be able to

a) Control relative humidity, which is $\frac{Po}{Pat} \times 100$

b) Control temperature

c) Take samples at different points along the height of the simulated bin

d) Keep temperature and relative humidity constant for a determined number of days, so that, samples can be taken during that period of time.

EQUIPMENT

The equipment for measuring wetting of stored grain is shown in Plates I and II. It was intended to be as simple as possible.

The equipment was an arrangement whereby grain could be stored in four insulated plastic pipes, 6" in diameter x 72" in length x 1/8" in thickness. Several small plastic pipes, 1" in diameter x 6" in length x 1/8" in thickness, were inserted to the former pipes in order that samples of grain could be taken. Fiber glass was used as insulator material. Its thickness was $2\frac{1}{2}$ inches. The upper ends of the four pipes were connected to a wooden box while the lower ends were on the floor.

Within the wooden box a heat source, three sixty-watt light bulbs, was installed to heat air on top of grain. Light bulbs were used as a heat source because the volume of air to be warmed was not large, and the required temperature was not high. Temperature was controlled by means of a bulb thermostat. The bulb sensitive indicator of temperature was protected by a sheet of aluminum foil to avoid the action of radiant heat. On the lower right end of the box a metallic pan was bolted to the wooden box. The pan was installed to heat water in by means of another heat source that was set right below the water pan. The heat source was composed of three sixty-watt light bulbs. Light bulbs were used as a heat source because the volume of water to be warmed was not large, and the required temperature was not high.

Temperature to warm water was controlled by means of another bulb thermostat with its bulb sensitive indicator of temperature immersed in the upper portion of water.

Two dry bulb thermometers, one wet bulb thermometer and one hygrometer were set in the wooden box to read temperature and relative humidity.

In order to increase the area of vaporization a piece of heavy material, canvas, was hung up from the upper part of the wooden box. The lower end of the piece of canvas was in the water of the water pan.

Two $\frac{1}{4}$" pieces of cement asbestos board were set, one below the other above the heat source in order to prevent wood from being burned.

The wooden box with all the implements attached to it was supported on two metallic strips attached to the ceiling of the floor.

All the details can be seen on Plates I and II.

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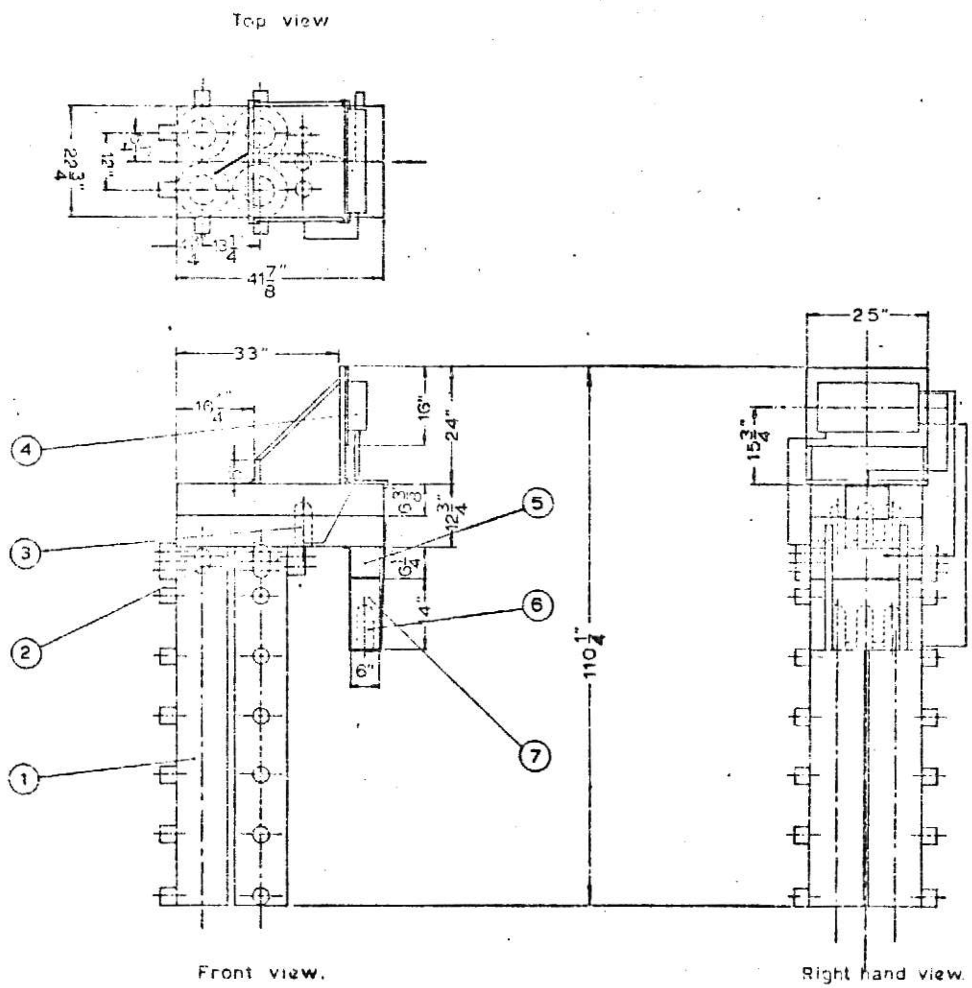
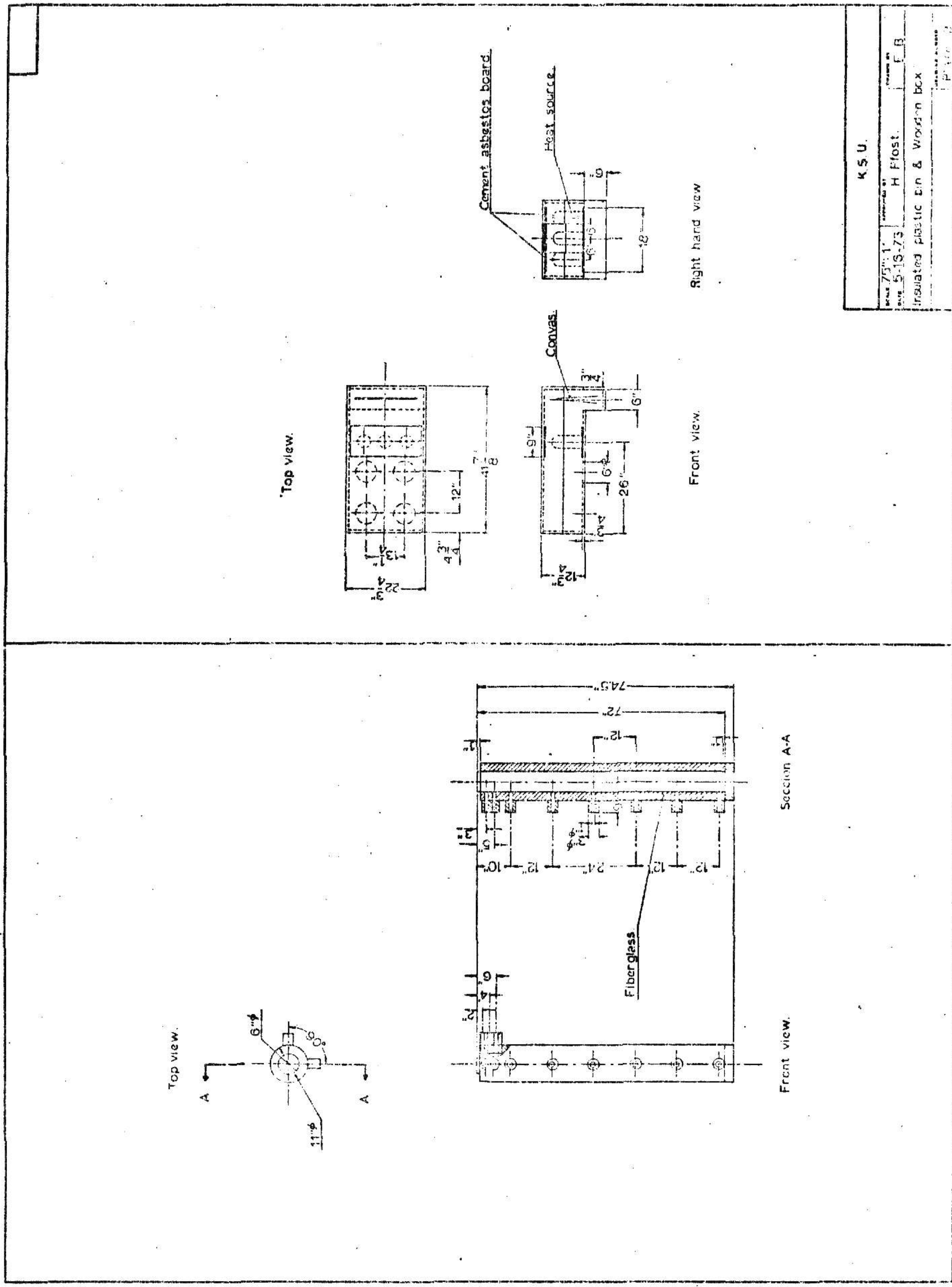


Nº	Qtt	Description
7	1	Metalic box
6	1	Heat source
		3 60 w. light bulbs
5	1	Metalic pan. See pate 2
4	1	Dust proof electric box
		2 Bulb thermostats 110 volts
		0-90°F
3	1	Heat source
		3 60 w. light bulbs
2	1	Wooden box. See plate 2
1	4	Insulated plastic [illegible] See [illegible]

EQUIPMENT

Scale 75" 1' — Date 5-16-73 — H. Pfost — [illegible]

Plate 1



Cement asbestos board
Heat source
Right hand view
Convas
Top view
Front view
Section A-A
Fiberglass
Top view
Front view
K.S.U.
H. Frost
F. B.
5-15-73
Insulated plastic bin & Wooden box

PROCEDURE

After the equipment was assembled and set in place, it was decided to store some grain in the plastic pipes and study how the moisture content changed with time at a fixed temperature and relative humidity.

Four different kinds of grain, rough rice, yellow corn, sorghum and hard red winter wheat were dried below 10% moisture content.

Rough rice was dried from 10.6% to 9.69% moisture (w.b), at 110.7° F; yellow corn from 16.5% to 9.405% at 130.8° F; sorghum from 16% to 9.875% moisture (w.b) at 123° F; and wheat from 10.6% to 9.87% moisture (w.b) at 140° F. The drying temperatures were within the limits recommended by the Feed Manufacturing Technology (10) for commercial milling purpose.

After the grain was dried, one bushel of each was stored in plastic sacks and kept in a metallic drum to prevent its moisture content change.

Before filling the plastic pipes with grain, the equipment was put through a two day test. Temperature above grain was set at 89° F, and water temperature at 86° F. Temperature and relative humidity were read constantly during that period. At no time did the temperature above the grain drop below 88° F or rise above 89° F. The relative humidity was between 73 and 74%. This was considered to be an adequate test run of the equipment, and proof that the two bulb thermostats would maintain the temperatures at the required 89° F and 86° F respectively.

After the equipment was tested, the four grains were stored in the four plastic pipes. It was planned that the test run would be for a period of 20 days during which samples of all grains at seven different points for each grain would be taken and tested for moisture content change. It was hoped that after that period of time an appreciable change in moisture would be detected. It must be emphasized that no information was available that indicated how long a time would be required for a perceptible change to be established. The temperature and relative humidity were 88° - 89° F and 73% - 74% respectively during the 20 day period.

It was planned that at the same time that the samples were taken the grain temperature would be read at all different points. However, that could not be done, and grain temperatures were read after the 4th day test.

The time intervals in getting samples for the moisture test were:

a) 12 hours between samples for the first 10 days

b) a final sample after the 20th day.

Temperatures of the grain were read with a thermocouple indicator

a) every 24 hours between the 5th and 10th day

b) a final reading after the 20th day.

The initial moisture content and the moisture of all the samples during the 20 day period were determined in an air-oven by drying for two hours at 130° C, which is a standard method.

RESULTS AND DISCUSSION

Figures 3, 4, 5, and 6 show the effect of a temperature of 88-89° F and a relative humidity of 73-74% on adsorption of water in rough rice, yellow corn, sorghum, hard red winter wheat with time. Each figure shows the moisture content (w.b) variation of each one of those grains at seven different points for a twenty day period.

The four figures were plotted using the values in Tables 4, 5, 6, and 7 which were the moisture content of each grain on the bottom, at 1 foot, 2, 3, 4, and 5 feet from the bottom and on the top of the grain in the plastic pipe for the 20 days.

Tables 8, 9, 10, and 11 show the grain temperature variation on the 5th, 6th, 7th, 8th, 9th, 10th, and the 20th day on the bottom, at 1 foot, 2, 3, 4, and 5 feet from the bottom and on the top of the simulated bin for each grain.

From the limited amount of data taken in this investigation it does not seem possible to draw extensive conclusions. However, the data in general shows that the experiment as now constructed will operate as intended, and that further experimentation will improve the accuracy of the data obtained.

It can be easily seen that the moisture content of all grains did change during the test period. All of them increased in moisture during the first days, but after that, the increase was very small and in some cases there was a decrease. The reason for that was the change in grain temperature.

A grain temperature increase is produced only when certain amount of heat is added to the grain. However, the addition of heat

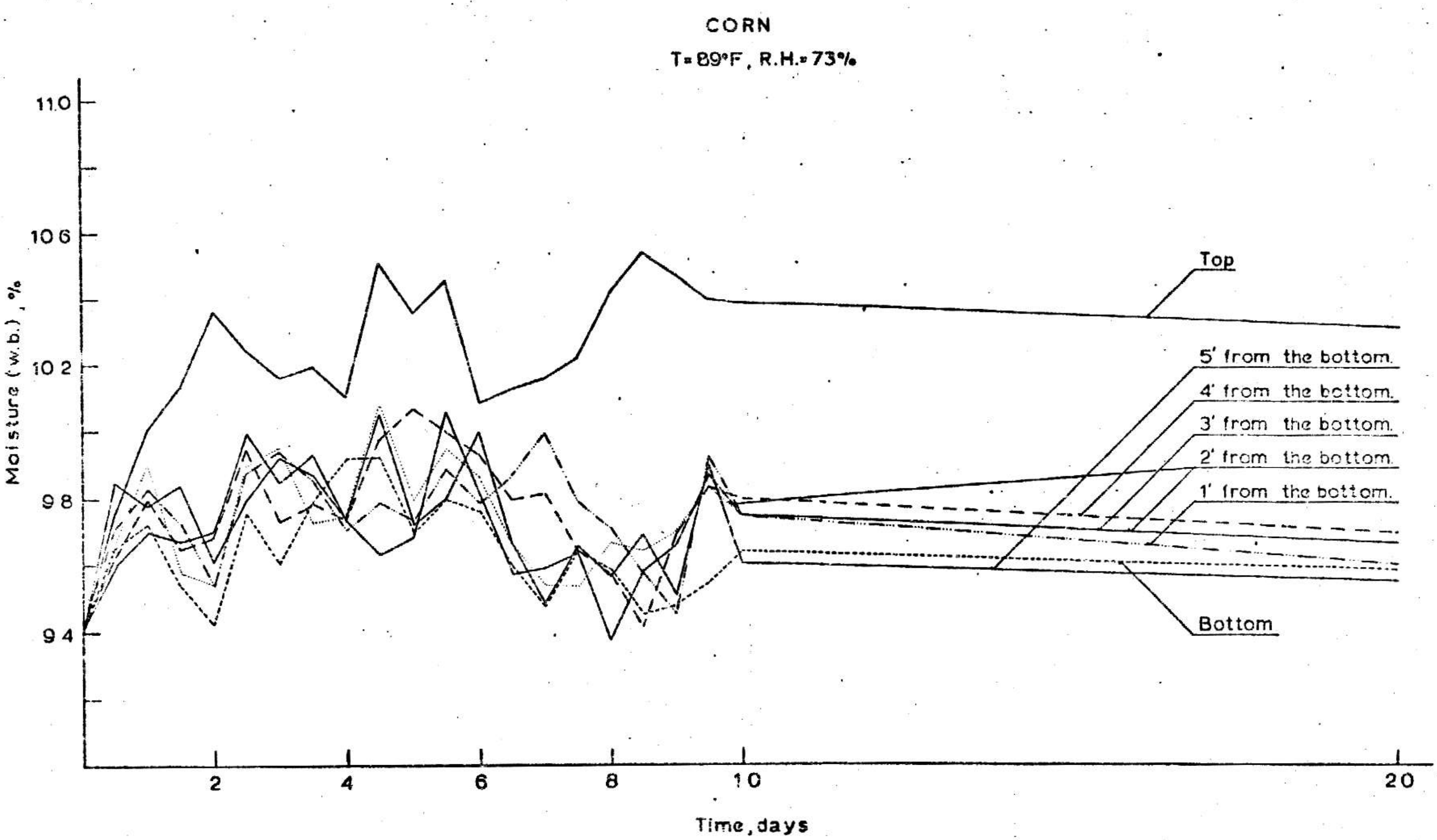


Figure 3 - Moisture content change in stored corn.

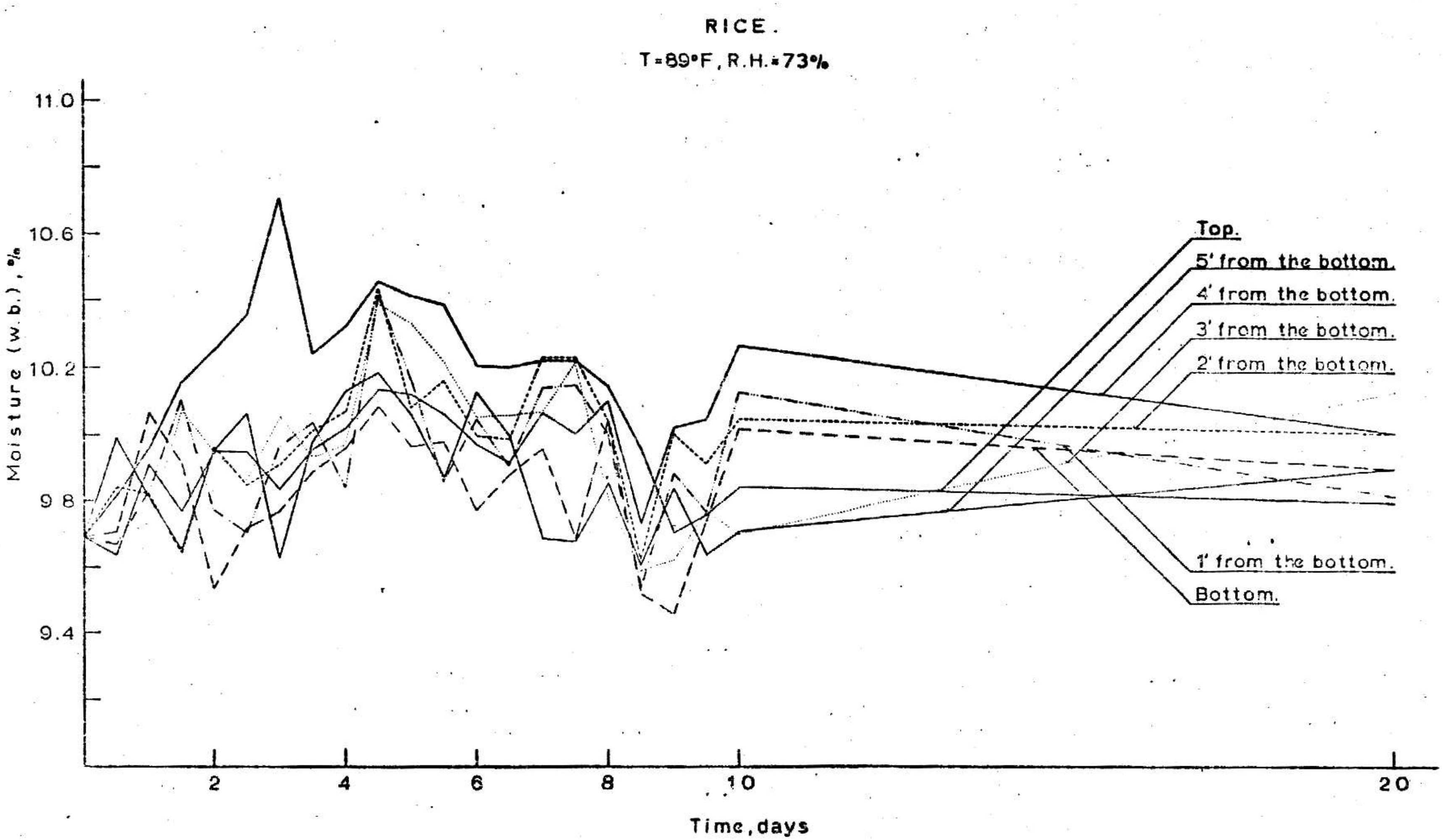


Figure 4 - Moisture content change in stored rice.

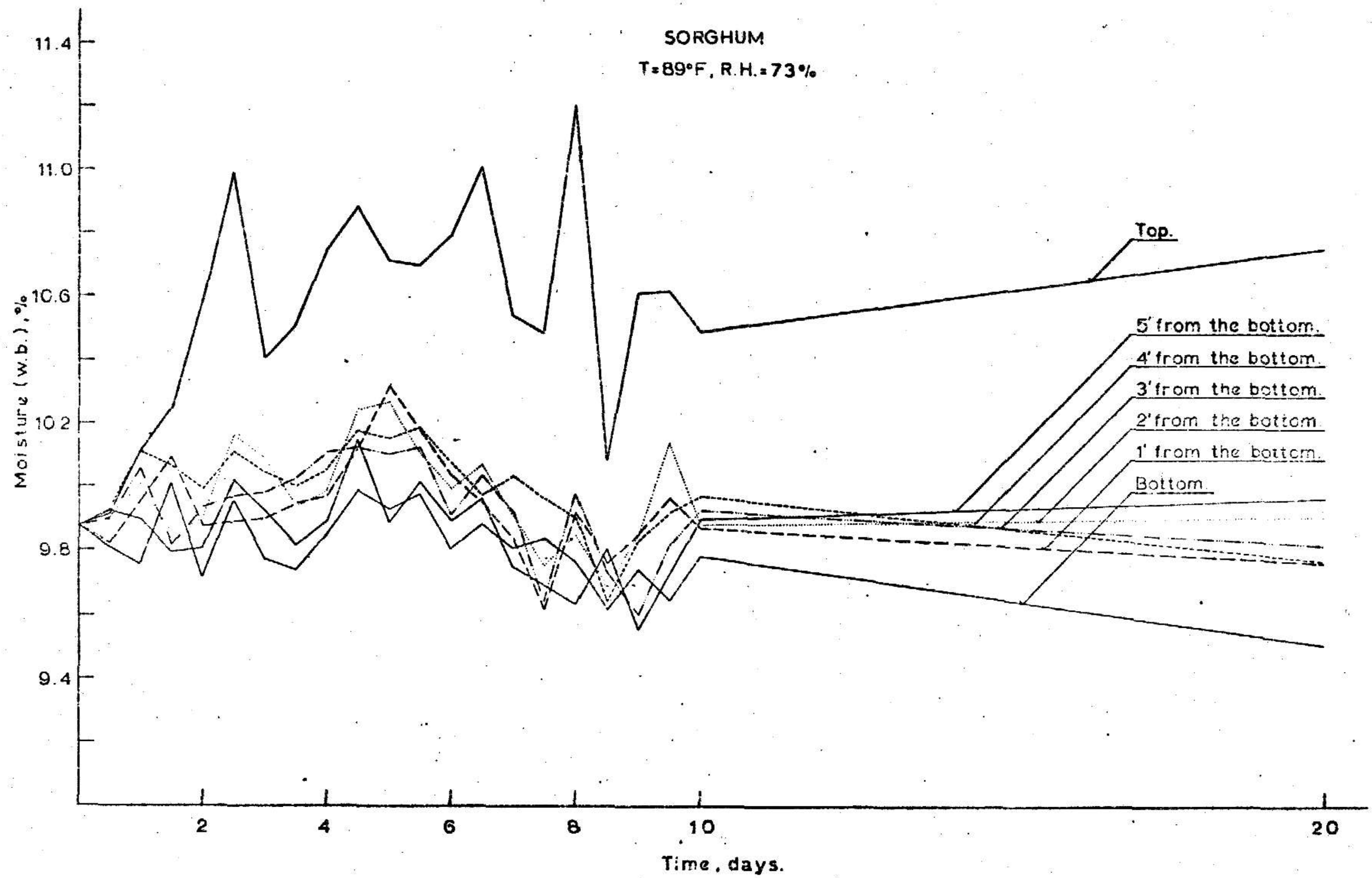


Figure 5- Moisture content change in stored sorghum.

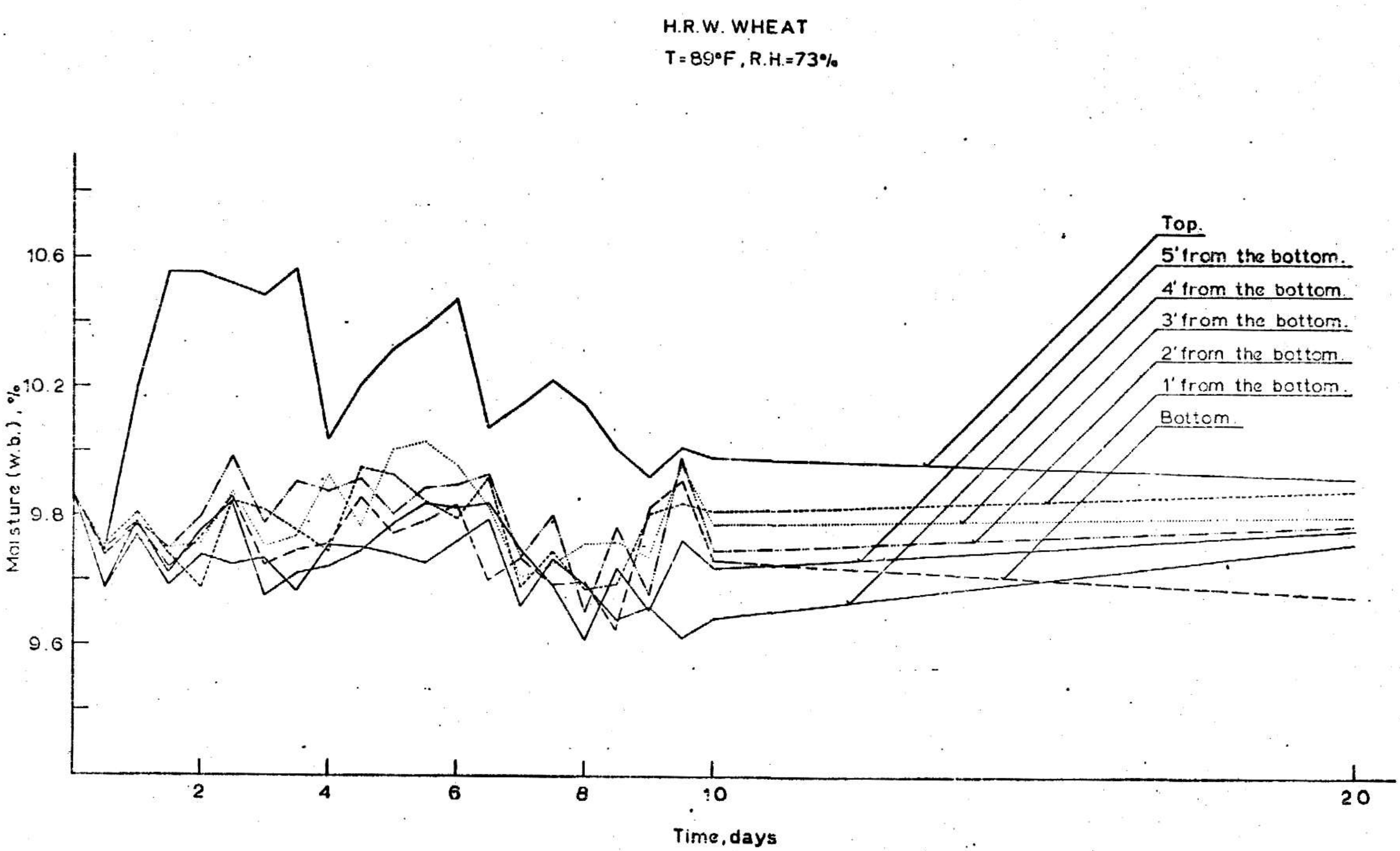


Figure 6- Moisture content change in stored wheat.

Table 4. Variation of moisture content of rough rice at different depths from the bottom for 20 days.

Initial moisture content 9.69% (w.b)

time (days)	Moisture (w.b) in percent TOP	5 ft FROM THE BOTTOM	4 ft	3 ft	2 ft	1 ft	BOTTOM
0.5	9.81	9.99	9.635	9.68	9.84	9.665	9.705
1	9.955	9.815	9.91	9.73	9.82	9.825	10.07
1.5	10.155	9.645	9.765	10.075	9.65	10.10	9.92
2	10.25	9.955	9.95	9.945	9.965	9.77	9.53
2.5	10.345	10.06	9.95	9.865	9.845	9.70	9.715
3	10.305	9.92	9.83	10.055	9.905	9.96	9.76
3.5	10.24	9.975	9.955	9.93	10.01	10.035	9.885
4	10.315	10.125	10.015	9.965	10.055	9.84	9.95
4.5	10.455	10.185	10.135	10.385	10.43	10.41	10.085
5	10.41	10.06	10.12	10.33	10.075	10.17	9.96
5.5	10.39	9.865	10.065	10.22	10.16	9.865	9.98
6	10.205	10.125	9.97	10.05	9.995	10.05	9.77
6.5	10.20	10.005	9.915	10.055	9.985	9.905	9.87
7	10.22	9.685	10.065	10.065	10.23	10.14	9.955
7.5	10.22	9.675	10.00	10.21	10.23	10.15	9.68
8	10.15	9.855	10.10	9.81	10.045	10.00	10.04
8.5	9.96	9.605	9.725	9.585	9.63	9.535	9.515
9	9.70	9.84	10.02	9.615	10.00	9.88	9.455
9.5	9.755	9.635	10.04	9.77	9.91	9.76	9.725
10	9.84	9.705	10.265	9.695	10.045	10.125	10.015
20	9.795	9.90	10.005	10.13	10.01	9.815	9.90

Table 5. Variation of moisture content of yellow corn at different depths from the bottom for 20 days.

Initial moisture content 9.405% (w.b)

time (days)	Moisture (w.b) in percent						
	TOP	5 ft	4 ft	3 ft	2 ft	1 ft	BOTTOM
			FROM THE BOTTOM				
0.5	9.76	9.845	9.62	9.66	9.60	9.71	9.65
1	10.055	9.775	9.80	9.9	9.7	9.835	9.72
1.5	10.125	9.84	9.645	9.575	9.67	9.73	9.535
2	10.365	9.605	9.685	9.545	9.695	9.535	9.425
2.5	10.245	9.795	9.945	9.89	10.005	9.875	9.755
3	10.16	9.92	9.73	9.95	9.845	9.94	9.60
3.5	10.195	9.87	9.785	9.725	9.935	9.855	9.79
4	10.095	9.74	9.735	9.745	9.735	9.70	9.915
4.5	10.505	10.055	9.97	10.085	9.63	9.79	9.925
5	10.355	9.72	10.065	9.795	9.685	9.735	9.69
5.5	10.455	9.795	10.005	9.945	10.06	9.885	9.80
6	10.085	9.95	9.93	9.865	9.83	9.785	9.765
6.5	10.125	9.665	9.795	9.66	9.57	9.865	9.595
7	10.155	9.485	9.815	9.54	9.59	9.99	9.47
7.5	10.215	9.655	9.645	9.525	9.635	9.79	9.64
8	10.415	9.56	9.57	9.665	9.375	9.71	9.585
8.5	10.54	9.69	9.41	9.64	9.58	9.575	9.45
9	10.47	9.505	9.685	9.695	9.65	9.45	9.475
9.5	10.395	9.895	9.83	9.83	9.87	9.925	9.545
10	10.385	9.60	9.795	9.745	9.745	9.745	9.64
20	10.315	9.565	9.70	9.665	9.67	9.605	9.585

Table 6. Variation of moisture content of sorghum at different depths from the bottom for 20 days.

Initial moisture content 9.875% (w.b)

time (days)	Moisture (w.b) in percent						
	TOP	5 ft	4 ft	3 ft	2 ft	1 ft	BOTTOM
		FROM THE BOTTOM					
0.5	9.915	9.925	9.895	9.925	9.9	9.82	9.81
1	10.11	9.90	10.06	10.11	10.01	9.955	9.765
1.5	10.235	9.795	9.815	10.065	9.845	10.09	10.01
2	10.57	9.805	9.935	9.99	9.90	9.875	9.715
2.5	10.985	10.02	9.97	10.11	10.165	9.89	9.96
3	10.405	9.925	9.985	10.045	10.09	9.90	9.775
3.5	10.505	9.815	10.025	10.00	9.94	9.955	9.74
4	10.74	9.89	10.11	10.05	9.985	9.97	9.85
4.5	10.88	10.15	10.125	10.175	10.245	10.115	9.99
5	10.71	9.885	10.105	10.15	10.27	10.32	9.93
5.5	10.695	10.015	10.125	10.19	10.11	10.185	9.98
6	10.78	9.89	9.91	10.075	9.995	10.035	9.805
6.5	11.005	9.96	10.035	9.975	10.07	9.955	9.885
7	10.54	9.75	9.925	10.035	9.90	9.845	9.81
7.5	10.485	9.68	9.645	9.965	9.75	9.615	9.84
8	11.20	9.63	9.98	9.905	9.85	9.92	9.77
8.5	10.185	9.805	9.74	9.64	9.685	9.76	9.62
9	10.61	9.555	9.60	9.83	9.85	9.85	9.745
9.5	10.615	9.72	9.815	9.92	10.14	9.97	9.645
10	10.49	9.90	9.925	9.975	9.88	9.87	9.785
20	10.755	9.97	9.82	9.77	9.91	9.765	9.51

Table 7. Variation of moisture content of hard red winter wheat at different depths from the bottom for 20 days.

Initial moisture content 9.87% (w.b)

time (days)	TOP	5 ft	4 ft	3 ft	2 ft	1 ft	BOTTOM
	Moisture (w.b) in percent		FROM THE BOTTOM				
0.5	9.69	9.575	9.575	9.695	9.685	9.705	9.675
1	10.185	9.78	9.735	9.78	9.725	9.81	9.77
1.5	10.555	9.62	9.585	9.70	9.695	9.68	9.64
2	10.555	9.73	9.68	9.715	9.795	9.575	9.73
2.5	10.075	9.84	9.65	9.875	9.985	9.845	9.86
3	10.48	9.55	9.67	9.705	9.775	9.82	9.65
3.5	10.565	9.62	9.56	9.735	9.905	9.755	9.695
4	10.035	9.645	9.715	9.925	9.875	9.685	9.71
4.5	10.205	9.69	9.705	9.77	9.915	9.95	9.86
5	10.315	9.775	9.685	10.01	9.805	9.93	9.745
5.5	10.385	9.84	9.655	10.03	9.885	9.845	9.78
6	10.47	9.825	9.72	9.96	9.895	9.79	9.835
6.5	10.075	9.845	9.795	9.83	9.93	9.915	9.60
7	10.145	9.695	9.52	9.61	9.67	9.58	9.67
7.5	10.22	9.59	9.67	9.665	9.805	9.695	9.59
8	10.15	9.41	9.595	9.715	9.50	9.575	9.60
8.5	10.01	9.645	9.48	9.72	9.77	9.585	9.45
9	9.92	9.505	9.52	9.675	9.555	9.81	9.825
9.5	10.015	9.73	9.425	9.965	9.985	9.845	9.915
10	9.985	9.64	9.485	9.775	9.695	9.815	9.665
20	9.925	9.765	9.72	9.81	9.78	9.885	9.555

Table 8. Temperature of sorghum at different depths from the bottom.

Initial temperature 73° F

day	TOP	5 ft	4 ft	3 ft	2 ft	1 ft	BOTTOM
			Temperature °F FROM THE BOTTOM				
5th	86.5	78.5	77	77.5	79	80.5	83.5
6th	86	82	79.5	79	79	80.5	87
7th	87	85	83	82.5	82.5	83.5	90
8th	87	84.5	84	84	84	86	90
9th	85.5	82	79	78.5	78.5	80.5	85
10th	85.5	77.5	76	76	77	79	82
20th	85.5	77	77	77	77.5	79	84

Table 9. Temperature of rough rice at different depths from the bottom.

Initial temperature 73° F

day	TOP	5 ft	4 ft	3 ft	2 ft	1 ft	BOTTOM
			Temperature °F FROM THE BOTTOM				
5th	82.5	78	77	76.5	77	78	83.5
6th	84.5	80.5	78.5	78.5	79	80	87
7th	87	83.5	82.5	82.5	82.5	84.0	91
8th	87	85	84.5	84.5	84.5	86	90
9th	80	77	77	77	79	80.5	85
10th	80.5	77	75.5	75	75	76.5	82
20th	80	77.5	76.5	77	77	79	84.5

Table 10. Temperature of hard red winter wheat at different depths from the bottom.

Initial temperature 74° F

day	TOP	5 ft	4 ft	3 ft	2 ft	1 ft	BOTTOM
			Temperature °F FROM THE BOTTOM				
5th	81	77	76.5	76.5	76.5	78	82.5
6th	85	80	78.5	78	78	79.5	84.5
7th	86.5	83	82	81	81	83	88.5
8th	87	85	83.5	83.5	83.5	85	90
9th	80	79	78	78	79	81	84
10th	79	77	75.5	75.5	77	77.5	81.5
20th	80	76.5	76.5	77	77	79	84

Table 11. Temperature of yellow corn at different depths from the bottom.

Initial temperature 72° F

day	TOP	5 ft	4 ft	3 ft	2 ft	1 ft	BOTTOM
			Temperature °F FROM THE BOTTOM				
5th	84	77	76.5	76.5	77	79	81
6th	87.5	83	79	79	79	80	85
7th	88	84.5	83	82.5	82.5	82.5	87
8th	88	86	85	84	83	84	87
9th	86.5	81	78.5	78.5	78.5	78.5	82
10th	83	79	77	75.5	75.5	76	79
20th	85.5	79	77.5	77	77	78.5	81.5

makes grain lose water resulting in a decrease in moisture content of the grain itself.

As an example, let us see what happens to rough rice, hard red winter wheat and yellow corn when temperature increases from 70° to 80° F and from 80° to 90° F.

The amount of heat added to any material giving a raise in temperature is:

$$q = CW\,(T_2 - T_1)$$

where q = heat added, BTU

C = specific heat, BTU/lb. °F

W = weight, lb.

T = temperature, °F

The heat added to grain divided by the heat of vaporization of grain gives us the amount of water removed from grain. That is true because the heat of vaporization is BTU/lb. of water.

Robayo, V. F. (13) found that the specific heat of rough rice and its heat of vaporization are

$$C = 0.265 + 0.0107\,M_W$$

$$H = (1094 - 0.57T)\,(1 + 1.67e^{-20.062M_D})$$

where C = specific heat, BTU/lb. °F

M_W = moisture content, wet basis

H = heat of vaporization, BTU/lb. of water

T = temperature, °F

M_D = moisture content, dry basis

Thompson and Foster (14) found the following specific heat and heat of vaporization for corn.

$$C = 0.35 + 0.00851\ M_W$$

$$H = (1094 - 0.57T)\ (1 + 4.35e^{-28.25M_D})$$

Kazarian and Hall (15) found that the specific heat of wheat is

$$C = 0.301 + 0.00733M_W$$

The following heat of vaporization for wheat at 80° F and 90° F was found extrapolating values given by Thompson and Shedd (16):

$$H_{80} = 1283.36$$

$$H_{90} = 1275.25$$

Table 12 shows the amount of water released by rough rice, corn and wheat when temperatures increase from 70° to 80° F and from 80° to 90° F. Heats added to grain, specific heats, heats of vaporization and amount of moisture given by grain are also shown.

Table 12. Amount of water removed from different grains when temperature increased from 70° to 80° F and from 80° to 90° F.

Grain	Moisture (3) (w.b) percent	Moisture Lost (w.b) percent	Specific heat BTU/lb. °F	Heat of (2) vaporization BTU/lb. water	Heat added (1) 70°-80° F BTU	Heat added (1) 80°-90° BTU	Water removed lb.
Rice	10 %	0.2978	0.372	1236.889	0.372		0.003007
	9.9%	0.2974	0.3709	1234.80		0.3709	0.003003
Corn	9.85%	0.3419	0.4338	1256.607	0.4338		0.003452
	9.5775%	0.3364	0.4315	1270.284		0.4315	0.003396
Wheat	9.62%	0.2868	0.3715	1283.36	0.3715		0.002895
	9.566%	0.2883	0.3711	1275.25		0.3711	0.0029096

(1) q is the heat added to one pound of grain

(2) the first value for each grain is at 80° F, the second one at 90° F

(3) Average values taken from tables 4, 5, and 7 for the 6th and 8th day in which the temperatures were higher. Moisture on top were not taken into account.

Note: See Appendix for calculations.

So that, the temperature factor is very important, and it is responsible for the small increase or decrease in moisture content of the grains under test.

Although the temperature affected the moisture content of the grains, it can be seen on Figures 3, 4, 5, and 6 that the highest moisture was found always on the top of the grain stored in the simulated bins. To a certain extent, that was to be expected because grain was first exposed to the environmental conditions at that particular point.

From the same figures we see that moisture does change along the depth of the stored grain. It is not constant at different depths from the bottom. That is the reason because the equation found by Park, et al. (1) could not be used for this work, the depth factor was not considered by them. However; they found that the increase in moisture for corn was very small, between 2 and 4% of its original weight for a 12 hour period. Similar values were found in this work.

The highest increases in temperature were found on the top and on the bottom of the bins. That is the reason because the moisture content on the top was not higher and the moisture on the bottom was the lowest one, most of the time.

It is quite possible that the increase in temperature on the bottom of the four bins was due to the lack of more insulation.

It looks like the four grains do not respond in the same way to a definite environmental condition because wheat was the most strong and sorghum the least one. However; more tests are needed.

Studying the data presented before, in the water vapor movement through a concrete silo section, it can be easily seen that the amount of water-vapor adsorbed by grain is too small to wet grain to the extent of endangering the grain quality during storage when special care has been taken in the concrete production. However, the moisture content of grain can be increased, real fast, in more than 2% (initial moisture + 2%) when that is not true. That increase can be done with a water-vapor premeability coefficient higher than 3.53×10^{-5} ft./hr.

CONCLUSIONS

1. The equipment, as developed and described operates satisfactorily, though some modifications may be desirable as the investigation continues.

2. Data from the investigation is not sufficient to warrant a definite conclusion on the amount of water moved through stored grain. The definite, though small, moisture change seems to indicate that grain becomes wet on the top of the bin faster than in any other place.

3. The effect of grain temperature increase is too important to be left without further investigation.

4. The proposed equation can be solved with the equipment.

5. Having a good quality concrete makes the possibilities of wetting stored grain through the concrete walls of the silo almost none.

ACKNOWLEDGEMENTS

The writer wishes to express his gratitude to his research advisor, Dr. H. B. Pfost, whose valuable aid as a guide and in making suggestions made this paper materialize; to Dr. D. S. Chung and Dr. T. O. Hodges of the Department of Agricultural Engineering for counsel and facilitation of materials; and to the members of the Department of Grain Science and Industry who most willingly gave assistance during the course of this paper.

Indebtedness is acknowledged to his wife, parents and IDEMA, the company that he works for, for their continued encouragement during this study.

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APPENDIX A

Example for a typical determination of moisture content increase in rough rice due to water-vapor movement through concrete.

Assuming that:

The environmental conditions are 89° F and 73% r. h.

The grain conditions are 77° F and 9.69% m. c.

The silo is 80 ft. high, 23 ft. I. D. and 7 in. in thickness.

From Table 2 for 77° F, 9.69% m.c and rough rice the relative humidity is 44.13%.

By using the psychrometric chart

for 77° F and 44.13% r. h P = 0.4126 in-Hg.

for 89° F and 73% r. h P = 1.0059 in-Hg.

Area of the silo exposed to water-vapor

$$A = \pi \Delta \cdot h = \pi \cdot 24.17 \cdot 80$$

$$A = 6074.60 \text{ ft.}^2$$

Solving equation 1

$$Q = K \cdot A \cdot \Delta P \cdot \frac{t}{\ell}$$

where $K = 3.53 \times 10^{-5}$ ft./hr.

$A = 6074.60 \text{ ft.}^2$

$\Delta P = 1.0059 - 0.4126 = 0.5933$ in-Hg.

$= 0.5933 \times 70.73 = 41.964 \text{ lb./ft.}^2$

$\ell = 7/12$ ft. $= 0.5833$ ft.

$t = 60$ days $= 60 \times 24$ hr.

$$Q = \frac{3.53 \times 10^{-5} \times 6074.60 \times 41.964 \times 60 \times 24}{0.5033}$$

Q = 22580 lb. of water

Amount of grain in silo = volume x density

$$= \frac{\pi D^2}{4} \cdot h \cdot 34$$

$$= \frac{\pi \times 23^2}{4} \cdot 80 \cdot 34$$

= 1130092 lb.

It m.c = 9.69% and the amount of grain is 1130092 lb. the amount of water will be 109505 lb.

So then, the new moisture content (w.b) will be

$$M_{w.b} = \frac{109505 + 22580}{1130092 + 22580} = 0.1146$$

$$M_{w.b} = 11.46\%$$

Example for determination of water removed from 1 lb. of rough rice when temperature increased from 70° to 80° F, it, the initial moisture of grain was 10% (w.b)

$$Q = CW\Delta T$$

where W = 1 lb.

$\Delta T = 80 - 70 = 10°$ F

$C = 0.265 + 0.0107\ M_W$

$= 0.265 = 0.0107 \times 10$

$= 0.372$

Then Q = 0.372 x 1 x 10 = 3.72 BTU

Amount of water (lb.) = $\frac{Q}{H}$

where H = heat of vaporization at 80° F

$$= (1094 - 0.57T)\ (1 + 1.67e^{-20.062\ M_D})$$

$$M_D = \frac{100M_W}{100 - M_W} = \frac{100 \times 10}{100 - 10} = 11.11$$

$$H = (1094 - 0.57 \times 80)\ (1 + 1.67e^{-20.062 \times 0.1111})$$

$$= 1236.8897 \text{ BTU/lb. water}$$

$$\text{Amount of water removed} = \frac{3.72}{1236.8897} = 0.0030075 \text{ lb.}$$

Removing 0.0030075 lb. of water the new moisture content will be

$$M = \frac{10 - 0.3307}{1 - 0.003007} = 9.702217\%$$

which means a decrease of

$$\Delta M = 10 - 9.7022 = 0.2978\%$$

DEVELOPMENT OF EQUIPMENT TO MEASURE WETTING OF STORED GRAIN

by

EDGARD M. BRETON-CANEVA

B. S., Universidad de America, Bogotá, Colombia 1968

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Grain Science and Industry

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1973

In a concrete silo, grain can change its moisture content when it is exposed to the environmental conditions, or when water vapor goes through the concrete walls.

Some of the variables that were considered pertinent in the study of moisture content of grain when exposed to the environmental conditions were combined into a mathematical equation

$$MR = C \left(\frac{Po}{Pat}\right)^{C_1} \left(\frac{h}{x}\right)^{C_2} \left(\frac{To}{Tat}\right)^{C_3} \left(\frac{\mu\,\theta}{x^2}\right)^{C_4}$$

To determine the equation, the constant C and the exponents $C_1 \ldots C_4$ must be found. That can be done by holding all the independent groups involved in the function except one constant, and varying that one to establish a relationship between it and MR. This procedure is repeated for each of the groups in turn, and the resulting relationship between MR and the other individual groups combined to give a general relationship.

An equipment was developed to make the solution of the equation possible, and it was tested with four different kinds of grain, rough rice, yellow corn, sorghum and hard red winter wheat, for a 20 day period.

Besides the development of the equipment some data related to concrete permeability is also presented in this paper.

In the light of this investigation, it can be said:

1. The equipment, as developed and described, operates satisfactorily, though some modifications may be desirable as the investigation continues.

2. The definite, though small, moisture change seems to indicate that grain becomes wet on the top of the bin faster than in

any other places.

3. The effect of grain temperature increase is too important to be left without further investigation.

4. The proposed equation can be solved using the equipment.

5. Having a good quality concrete makes the possibilities of wetting stored grain through the concrete walls of the silo almost none.