DEVELOPMENT OF A LABORATORY APPARATUS FOR GRAIN DRYING STUDIES

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Storrs, Connecticut

1950

Submitted to the Faculty of the Graduate School of
the Oklahoma Agricultural and Mechanical College
in Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE
1952

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ACKNOWLEDGMENT

The design of the laboratory apparatus for grain drying studies was accomplished under the Oklahoma Agricultural and Mechanical College Agricultural Experiment Station Project 697, "Adaptation of Storage Structures for Mechanically Conditioning Crops on Farms."

The author wishes to express his appreciation for the assistance given him in this study by Professor G. L. Nelson, who was the writer's thesis adviser. The author is also indebted to Professor E. W. Schroeder, Head of the Agricultural Engineering Department, for use of departmental facilities and staff.

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I. INTRODUCTION

Each year farmers throughout the country suffer an annual loss in income from grain deterioration due to excess moisture being present in grain when placed in storage. Not only is there a loss in income, but also a loss of grain quality for consumption or processing. The Oklahoma Crop Improvement Association reports that approximately forty percent of referee samples submitted for certification from the 1948 crop were rejected primarily because excess moisture had lowered germination. By striving to control the grain moisture content, producers' incomes can be stabilized.

In recent years, one of the approaches to grain moisture content control has been the use of forced circulation of heated or unheated air by mechanical means. In October of 1947,[2] a committee was set up by the American Society of Agricultural Engineers to investigate crop conditioning equipment. At Oklahoma Agricultural and Mechanical College, a joint program has been set up between the agricultural engineering and agronomy departments to study adaptation of storage structures for mechanically conditioning crops on farms. The agricultural engineering department has constructed a portable experimental drying bin for obtaining data on drying characteristics and quality effects of mechanical drying for

Oklahoma grain crops in large scale operation, but there is still little data known on drying characteristics of small grain samples.

II. OBJECTIVES

The purpose of this study was to approach the problem of grain drying by developing a small scale laboratory apparatus from which data could be obtained for large scale grain drier operation. Specific objectives were:

1. To develop and design a small scale grain drier which would meet laboratory conditions for collecting grain drying data by controlling air temperatures and air velocities.

2. To obtain data, by experiment, for determining the grain drying behavior for air temperatures, ranging from room temperature to 160 degrees Fahrenheit, and air velocities, ranging from 20 f.p.m. to 80 f.p.m.

III. REVIEW OF LITERATURE

Air performs the following functions in drying grain: heats the grain, transfers heat for vaporization of grain moisture, and removes the vaporized water.[15] There are many factors governing the drying behavior of grain by forced air. Among these are:

1. equilibrium moisture content.
2. grain moisture content.
3. air and grain temperatures.
4. relative humidity.
5. air velocity.

Badger and Clark[3] define the equilibrium moisture content under specified conditions as follows:

> "In general, a given material, if brought into contact with air of definite temperature and humidity, will reach a definite moisture content that will be unchanged by further exposure to the same air."

Applying this concept to grain, equilibrium moisture content is the grain moisture content existing when the vapor pressures of the moisture in the grain and air, respectively, are equal at identical temperatures of air and grain.

When the initial grain moisture content is high, there is a greater amount of moisture removal in attaining the desired safe storage condition of 12 percent for grain sorghum.[7] Obviously, if other conditions are equal, more fuel and time will be expended if the initial grain moisture content is high than if it is low.

High temperatures will aid the grain drying process to a certain extent, but above a certain temperature, precaution must be taken to prevent injury to grain quality. Grain drying studies made by Sorenson, Smith, Hollingsworth and Montfort[15] indicated that for low-moisture content grain (14 to 16 percent) dried to 12 percent, a higher velocity and low temperature would be most economical. The most efficient air temperature for drying low-moisture content grain was found to be 150 degrees Fahrenheit at a velocity of 80 to 90 feet per minute. For drying medium-moisture content grain (17 to 20 percent), 175 degrees Fahrenheit was found best, and for high moisture content grain (above 20 percent), 200 degrees Fahrenheit proved most efficient at velocities of 80 to 90 feet per minute. From these studies, data indicated that for higher moisture content grain, shorter drying time was accomplished by use of high temperatures. If the fastest drying rate were desired, concentration would be on high temperatures under operating conditions, but the goal desired is the minimum drying time at least cost.

Grain drying with heated forced air involves a heat transfer coefficient. According to Brown and Marco,[4] if the size and shape of the stream are expressed in terms of the diameter, the surface coefficient of convection heat transfer may be stated as a function of fluid stream diameter, velocity, absolute viscosity, density, specific heat at constant pressure, and thermal conductivity. If this relationship were made

applicable to forced air grain drying, the only major factor would be the velocity since the other properties are relatively constant at grain drying temperatures.

According to Hukill,[13] drying rate is independent of air velocity.

Where grain depth is involved, which is true in most grain drying operations, a zone effect[13] will occur whereby the first layers of grain will dry more rapidly than the upper layers of grain. As the air passes upward through the grain, the capacity of the air for moisture removal decreases because of the increased humidity due to the moisture gain in the initial layers.

The relative humidity of the incoming air will have a decided effect upon the drying rate due to the equilibrium moisture content[9] already explained. In humid areas, it is a factor of particular importance as the high humidity, which often exists, will decrease the effectiveness of air to remove moisture.

IV. APPARATUS AND EQUIPMENT

The laboratory grain drier was designed for drying small grain samples of about 100 grams. Air was admitted into an air tempering chamber at various velocities from a compressed air flask or air compressor. The air was then heated to the desired temperature and passed through the grain sample. Starting from the supply, air flowed through a ¼" pipe line, gate valve, silica gel dehydrator, pressure regulator, orifice, air tempering chamber, and then through the grain sample. Instruments for obtaining temperature data and pressure measurement were installed as indicated in the schematic diagram (Fig. 6).

Air Supply

For the calibration run (Fig. 5), compressed air flasks held the air supply, while for the grain drying tests, a ½ horsepower electric compressor and a 1½ horsepower gasoline engine compressor served as the source of air supply. The compressed air flask was 12" in diameter and 24" long. Each flask was filled to approximately 250 psig pressure. A 300 psig Bourdon pressure gauge, placed at one end of the flask, safeguarded against the hazard of overfilling.

Flask filling was accomplished by transferring air from compressed air bottles to the flask using a piece of ¼" copper

tubing. One end was fastened to the compressed air bottle, while an air coupling adapter was brazed to the other end. A coupler was attached to a piece of ¼" pipe projecting from the flask permitting ease of engaging and disengaging. Another air coupling adapter was permanently fixed to the ¼" pipe supply line attached to the air tempering chamber. Twelve fillings were possible from one bottle of compressed air having a capacity of approximately 244 cu. ft. This method of flask filling was chosen because one flask could be filled within a few minutes, which was considerably faster than the use of either air compressor.

Stabilization of the moisture content entering the air tempering chamber was accomplished by placing a silica gel dehydrator between the pressure regulator and gate valve. The silica gel dehydrator was installed after the photo in Figure 5 was taken.

Air Tempering Chamber

Overall dimensions of the air tempering chamber (Fig. 1) were as follows: length 5' 6", depth 8", and height 14". The reduced section was 9" in height, a minimum size to facilitate heating element changes. Construction material consisted mainly of 1/8" masonite and 1" soft pine, except for the use of ¼" plywood on the surface surrounding the grain container and the removable section. Steel strips, with ¼" holes at each end were placed on the removable section. Opposite the steel strips, aluminum right angle brackets, having ¼" holes at each

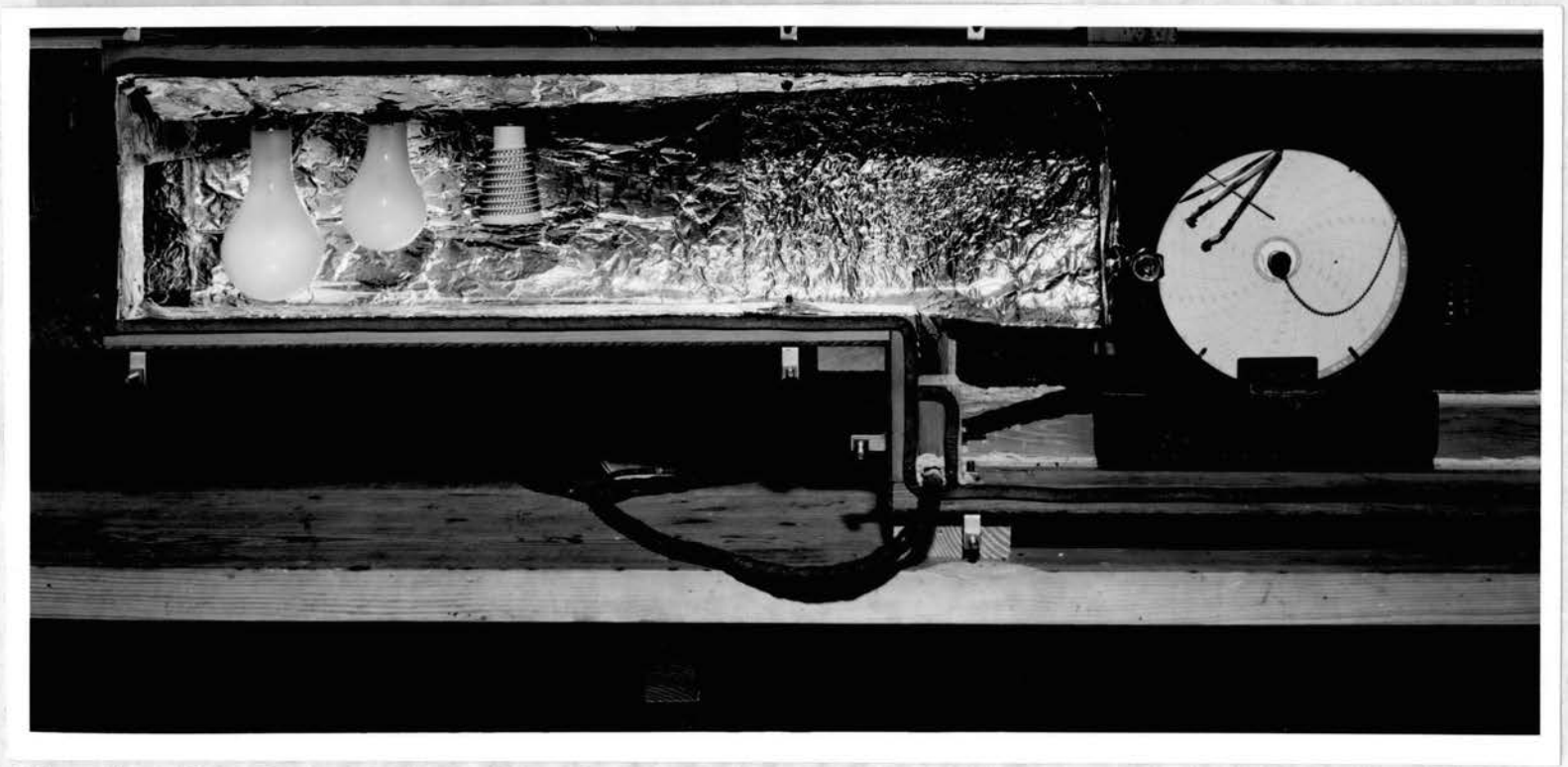

Fig. 1. Section of air tempering chamber showing location of heating elements and hygrothermograph.

end, were mounted. Finger tight application of wing nuts on ¼" bolts in the above combination was sufficient to prevent air leakage. Wood blocks secured the tempering chamber to the laboratory bench.

All joints were caulked to prevent air leakage. A 3/8" x 5/32" sponge rubber strip was placed along the edge of the surfaces adjoining the removable plywood section. Figure 1 shows the inside of the air tempering chamber with plywood face removed. The photo includes the hygrothermograph, mounted on the back of the chamber, and the heating unit. Porcelain receptacles, wired in parallel, comprised the heating unit, with the wire extending out through the chamber ceiling. Heat was supplied by any combination of 100 watt and 150 watt light bulbs or 600 watt heating elements. The reduced portion of the chamber was lined with two layers of asbestos paper and one layer of aluminum foil to provide protection against excess heat and to assist with the rate of heat flow.

Air was brought into the tempering chamber through a ¼" black pipe located 6 inches above the base and at the hygrothermograph end. A globe valve, pressure regulator, and orifice served as methods of controlling the incoming air velocity. The necessary size orifice was provided by three ¼" pipe caps having drilled holes 0.040", 0.081" and 0.099" in diameter, respectively. An inclined draft gauge, reading in 0.01" of water, was connected by a rubber hose to a ¼" pipe extending through the removable plywood section 4" into the tempering chamber.

Dry bulb temperature and relative humidity of the incoming air were recorded by a hygrothermograph.

Air tempering chamber temperature regulation was maintained by a vane type control millivoltmeter pyrometer having a 30 gauge iron-constantan temperature sensing element located at a point before the air entered the grain container cup (Fig. 2). Power was supplied to the heating elements through the millivoltmeter pyrometer.

From the heating unit, the air passed through the discharge hole up into the grain container (Fig. 3). The container was set in a piece of ¼" plywood, 4" square, having an inside diameter of 2.73" and an outside diameter of 2.95", with a depth of 5 5/8". A plastic screen was glued to the base. When empty, the container weighed 156 grams or 0.344 pounds.

The grain container was mounted over a discharge hole, with a diameter equal to the grain container inside diameter plus one thickness of lucite. Correct grain container position was assured by permanently fixing to the plywood surface a grooved right angle jig made from soft pine. Another right angle section was made removable. This section, along with a 1/8" x 1¼" steel clamp arrangement, held the container firmly in place. One end of the clamp had a ¼" slot, while the other end had a drilled hole for a ¼" bolt projection. The bolts were imbedded in a strip of 1" pine located beneath the plywood. Wing nuts were used for finger tight pressure application.

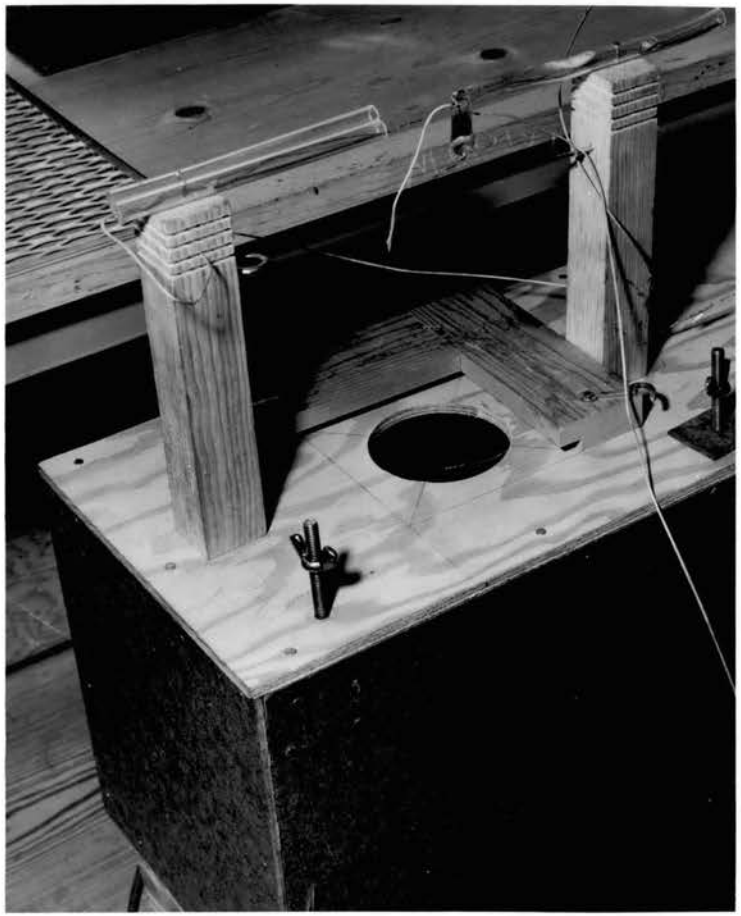

Fig. 2. Location of thermocouple junction for measuring the temperature of air entering the grain container.

Fig. 3. Mounted lucite grain container for holding grain samples.

The wet bulb temperature of the air leaving the grain was recorded by a circular chart potentiometer having a temperature sensing element located above the grain container cup (Fig. 4). Laundered cotton thread wicks were suspended from this thermocouple junction into a retainer cup containing distilled water. The design followed the principle suggested by Lorenzen.[14]

The wet bulb thermocouple junction was held in position by a holder, constructed from 3/8" diameter lucite tubing, mounted on a miniature column slightly above the grain container cup to permit sample removal. A portion of the lucite holder was heated and then bent and closed at one end to form a water cup. At the right angle bend, a groove was cut to allow the thermocouple junction to project through the tubing. Opposite the wet bulb thermocouple junction, there was a similar arrangement for the dry bulb thermocouple junction, except that a straight piece of lucite tubing was used. Dry bulb temperature of the air leaving the grain was recorded by a circular chart potentiometer.

Two other thermocouple junctions were located; one being in the grain, and the other midway between the grain and dry bulb and wet bulb thermocouples (Fig. 4). A 48 point indicating potentiometer measured the grain temperature and the temperature midway in the container.

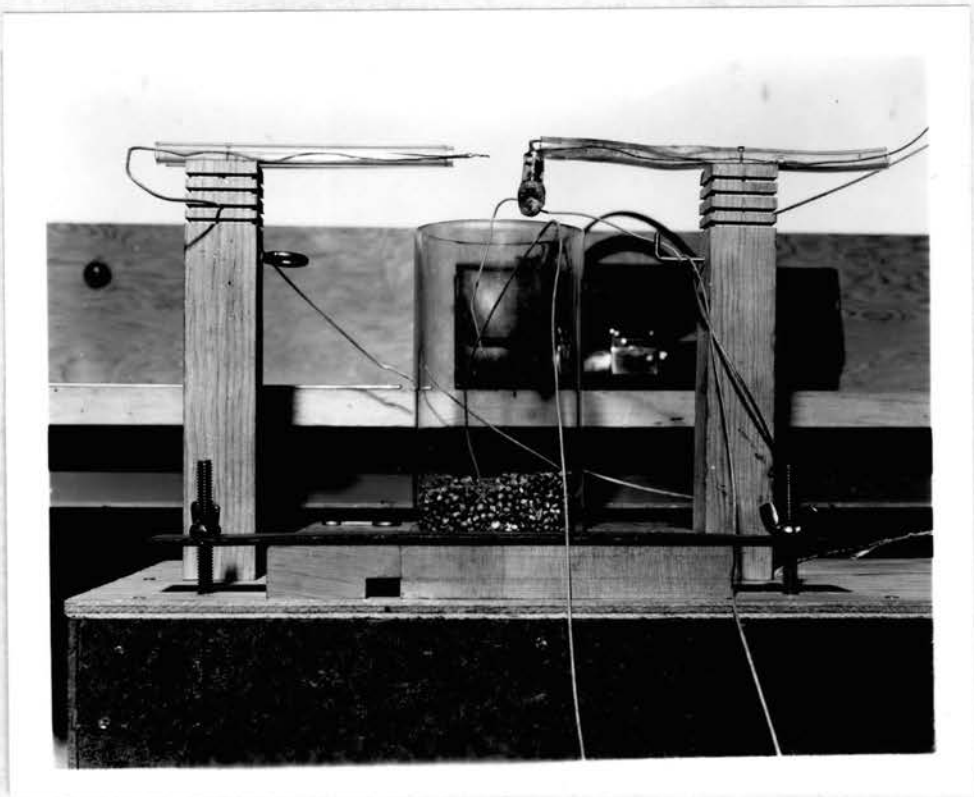

Fig. 4. Location of thermocouple junctions for grain drying tests.

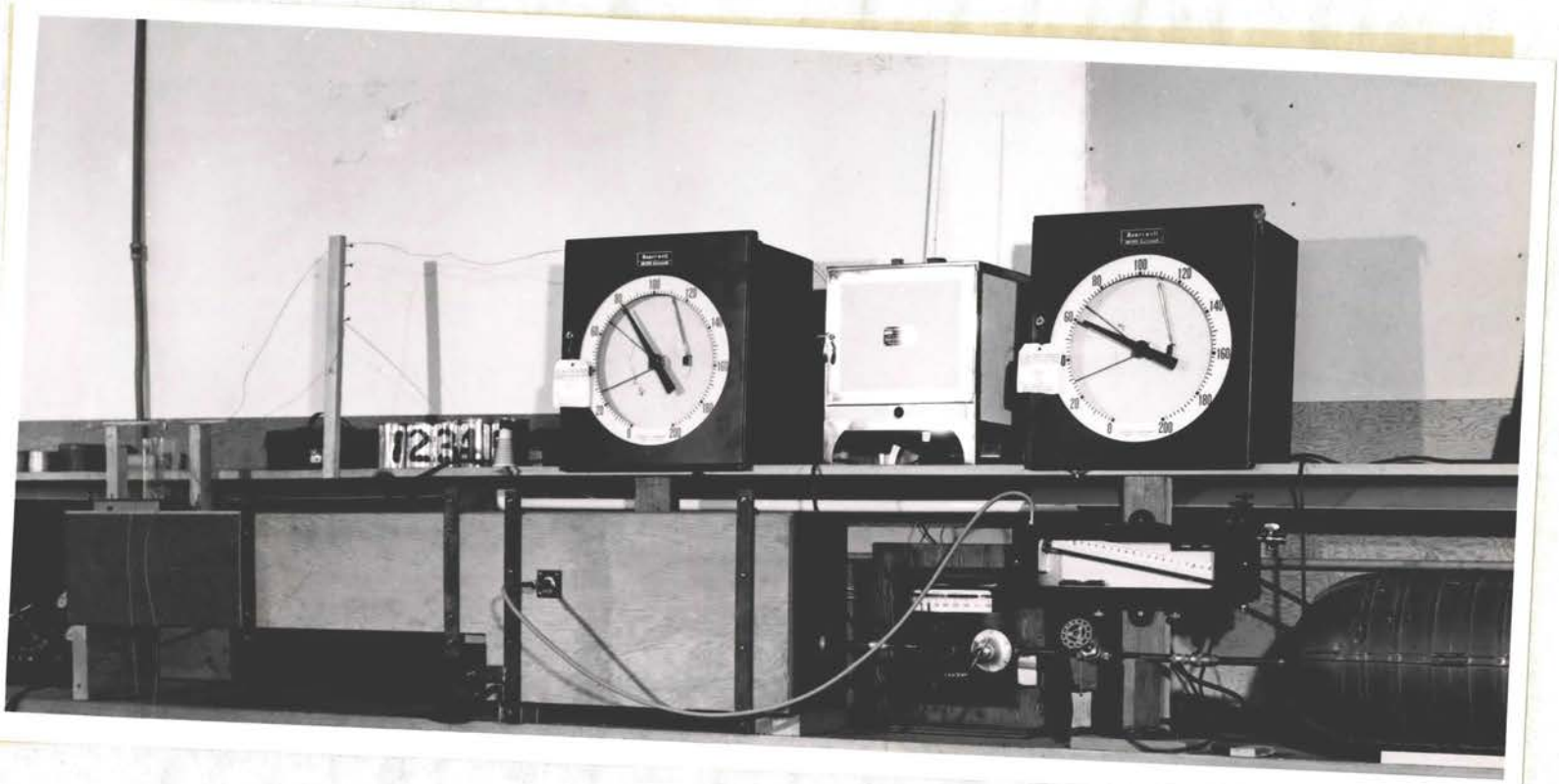

Fig. 5. Equipment arrangement for the laboratory grain drier air velocity calibration run.

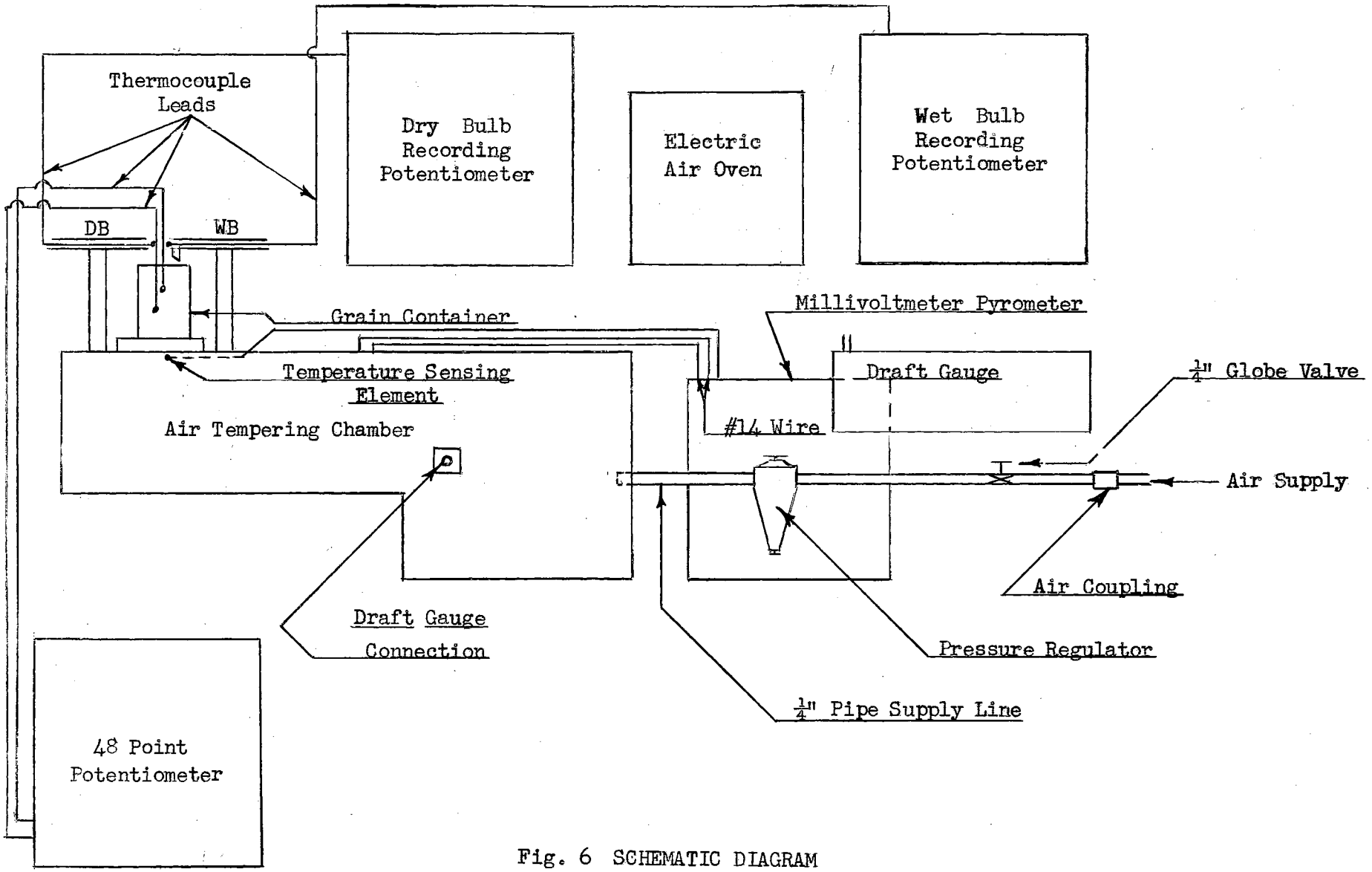

Fig. 6 SCHEMATIC DIAGRAM

LABORATORY GRAIN DRIER

Note: Use with Fig. 5.

Other Equipment

For flask and grain sample weighings, a Toledo Balance Scale was used. All grain drying runs were timed with a stop watch. Hygrothermograph accuracy and the temperature sensitivity of the dry bulb and wet bulb thermocouple junctions were checked with the hand aspirated psychrometer. Dry bulb and wet bulb temperatures of the air entering the compressor were also obtained with the hand aspirated psychrometer. For grain moisture content determination, samples were placed in the Fisher Junior electric air drying oven for a specified time interval. Grain was placed in numbered tin cans for identification purposes, but upon completion of the oven period the grain was transferred to waxed cardboard containers.

V. PROCEDURE

Grain Treatment

Redland Kafir grain sorghum was selected for the experiment. The grain had been dried previously by a large scale grain drier and natural means to a 12% or less moisture content. Therefore it was necessary to return moisture to the grain. Before this was done, the grain was cleaned to remove dirt, chaff, and cracked grain. The grain was then twice run through a Bates Laboratory Aspirator and sifted on a number 25 mesh screen. A Steinlite Moisture Test was made to determine the approximate moisture content of the grain.

The first method of moisture addition consisted of placing grain between layers of cardboard, saturated with moisture, in a circular metal container. Container dimensions were 8½" in diameter and 2" deep. The container was closed and the grain was allowed to absorb moisture for periods ranging from ½ hour to 8 hours. At the end of this time, it was found that the grain moisture gain was insufficient for the purpose of this study.

A more successful method of moisture addition was that of immersing the grain in water for periods ranging from one hour to three hours. Excess surface moisture was driven off by setting the wet grain on a wire screen and exposing it to room

temperature for approximately five hours. The moisture laden grain was then placed in a sealed cardboard container and allowed to set for a day. Due to the variation of the initial grain moisture content, the final grain moisture content after adding moisture varied from 19.8 to 31.6 percent.

Moisture Content Determination

Methods considered for moisture content determination were the All-Crop Moisture Tester, Brown-Duvel Moisture Tester,[5] Steinlite Moisture Tester, Tag-Heppenstall Moisture Meter,[6] and the electric air drying oven. Of the methods listed, the Tag-Heppenstall Moisture Meter and the Brown-Duvel Moisture Tester were unavailable. The All-Crop Moisture Tester, manufactured by the American Crop Drying Equipment Company, had an accuracy of 0.3 of 1% based on actual test, but there was a danger of burning the grain. The main disadvantage of this moisture tester was that continuous observation was required. The electrically operated Steinlite Moisture Tester provides a rapid method but results are inconsistent. The electric air oven is the official method for determining moisture content of grain. It is based on the assumptions that all the moisture is evaporated and that none of the other composite material of the grain is affected.[12] A long period of time is generally required with this method.

The electric air drying oven method was chosen for determining the moisture content of the grain used in the experiment. Grain samples were placed in the oven at a temperature

of 100 degrees Centigrade. To insure sufficient time allocation, a sample was checked hourly to determine whether or not moisture loss continued. When identical weighings were noticed, it was safe to assume that moisture loss had ceased. For convenience, a 12 hour time interval was selected.

Prior to placing the grain in the oven, the empty metal container weight was recorded. The metal container was a small tin can having a painted numeral for identification purposes. One hundred grams of grain was added and the new weight of the grain plus grain container recorded. The grain sample was placed in the oven and removed the following morning. Upon removal of the grain sample, the weight of the grain plus grain container was again recorded. The difference between the initial weight of the container plus grain and the final weight of the container plus grain is equal to the amount of moisture driven off. The percent moisture content, M_D, on a dry weight basis, was calculated from the following equation:[16]

$$\% M_D = \frac{\text{Wt. of Moisture}}{\text{Wt. of Dry Material}} \times 100$$

The following example illustrates the above procedure:

Data recorded for container #5.

Empty container weight----------	55.5 grams
Container plus 100 gms grain---------	155.5 grams
Container weight plus grain after removal from oven----------	137.5 grams
Moisture removed----------	18.0 grams

$$\% \text{ Moisture Content} = \frac{18}{82}(100) = 22\%$$

Equipment Calibration

Before a grain drying test was performed, a calibration curve showing the relationship between pressure in the air tempering chamber and air velocity through the 2.73" diameter grain container was plotted. A hundred grams of grain, on a dry weight basis, were placed in the grain container to simulate experimental conditions.

Equipment necessary for the calibration run is shown in Figure 5 accompanied by a schematic diagram explanation (Fig. 6). The compressed air flasks were filled to approximately 250 psig and the weights then recorded. An orifice restriction was placed on the ¼" pipe line and the pressure regulator set for a desired velocity. Draft gauge graduations were in 0.01" of water pressure. Pressures selected were 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.15, 0.20, 0.25, and 0.30 inches of water.

After the desired setting was established, the air supply was cut off at the globe valve and the flask uncoupled for weighing. This initial weight was recorded and the run then carried out for a period of ten minutes. The flask was then again weighed and the final weight recorded. At higher pressures, the time range was reduced to five minutes because of the higher quantity of air exhausted. The difference between the initial weighing and the final weighing was equal to the weight of air exhausted. Both gram and pound weights were used, but all calculations were in pound units. The total

amount of air exhausted, in pounds, divided by the length of run, in minutes, gave the air exhausted in pounds per minute. Conditions for the calibration run were that of the surrounding room temperature. Relative humidity and temperature of the incoming air were recorded by the hygrometer. With these two conditions known, it is possible to determine the remaining conditions from the psychrometric chart. In this particular case, the specific volume in cubic feet per pound of dry air was desired, being obtained by use of the following expression:[10]

$$v = v_a + \mu v_{as} \qquad (1)$$

where:

v = volume of moist air per pound of dry air, cubic feet per pound

v_a = specific volume of dry air, cubic feet per pound

μ = degree of saturation

v_{as} = $v_s - v_a$, the difference between volume of moist air at saturation, v_s, per pound of dry air, and the volume of the dry air itself, cubic feet per pound of dry air.

$$\mu = \frac{W}{W_s}$$

where:

W = humidity ratio of moist air, grains of water per pound of dry air.

W_s = humidity ratio, at saturation, weight of water vapor per pound of dry air, grains per pound.

or rewriting Eq. (1):

$$v = v_a + \frac{W}{W_s} (v_{as}) \qquad (2)$$

The air consumption, in pounds of dry air per minute, times the specific volume, in cubic feet per pound of dry air, gave the quantity of air handled in cubic feet per minute, Q. The relationship Q = AV was solved for V, where

A = Grain container area, square feet.

V = Cubic feet per minute per square foot.

The following example illustrates the above procedure. Data were as follows:

Draft gauge setting	0.06" water
Pipe cap orifice size	0.040"
Initial weighing - Final weighing	0.803 lbs.
Length of run	10 min.
Temperature of incoming air	89 degrees F
Relative humidity	28%

Designating M as the number of pounds of air, t as the time in minutes, and G as the air exhausted in pounds per minute, the following expression can be written:

$$G = \frac{M}{t}$$

or upon proper substitution:

$$G = \frac{0.803}{10} = 0.0803 \text{ lbs/min}$$

Consulting tables[11] for thermodynamic properties of moist air and a psychrometric chart, specific volume can be found:

$$v = 13.83 + \frac{0.008}{0.03017} (0.668)$$

$$v = 14.01 \text{ cu ft/lb dry air}$$

The quantity of air handled $Q = Gv = AV$.

$$Q = 0.0803 \text{ lbs/min} \times 14.01 \text{ cu ft/lb}$$

$$= 1.125 \text{ cfm}$$

Grain container area = 0.0406 sq ft

$$V = \frac{Q}{A} = \frac{1.125 \text{ cfm}}{0.0406 \text{ sq ft}} = 27.7 \text{ fpm}$$

In the above calculation, a correction factor must be applied to G. The amount of air expended in pounds per minute included both air and vapor, while the specific volume was in cubic feet per pound of dry air.

Mass Expended = 0.803 lbs (air plus vapor)
Air Conditions: 89 F Dry Bulb
V = 14.01 cu ft/lb dry air
Vapor in 1 lb of dry air (Psychrometric Chart) = 58 grains moisture/lb dry air or 0.008 lbs of moisture/lb of dry air

(Vapor plus air) /lb dry air = 1.008 lb/lb dry air

Lb dry air in 0.803 lb

$$\frac{0.803}{1.008} = \frac{x}{1}$$

$$x = 0.797 \text{ lb dry air}$$

Flow Rate = 0.797 x 14.01

= 11.18 cubic feet/10 min

or

1.118 cfm

$$V = \frac{1.118}{0.0406} = 27.55 \text{ cu ft/min/sq ft}$$

The results from plotting on ordinary coordinate paper velocities, v, against pressures, p, indicated that the relationship v versus p was not linear. When these same conditions were plotted on logarithmic paper (Fig. 7), an equation of the form $v = ap^b$ was obtained, or, on taking logarithms[8]

$$\log v = \log a + b \log p \qquad (3)$$

Values for log v and log p obtained from the calibration data may be found in Table 1.

Fig. 7 - AIR FLOW CALIBRATION CURVE FOR LABORATORY GRAIN DRIER

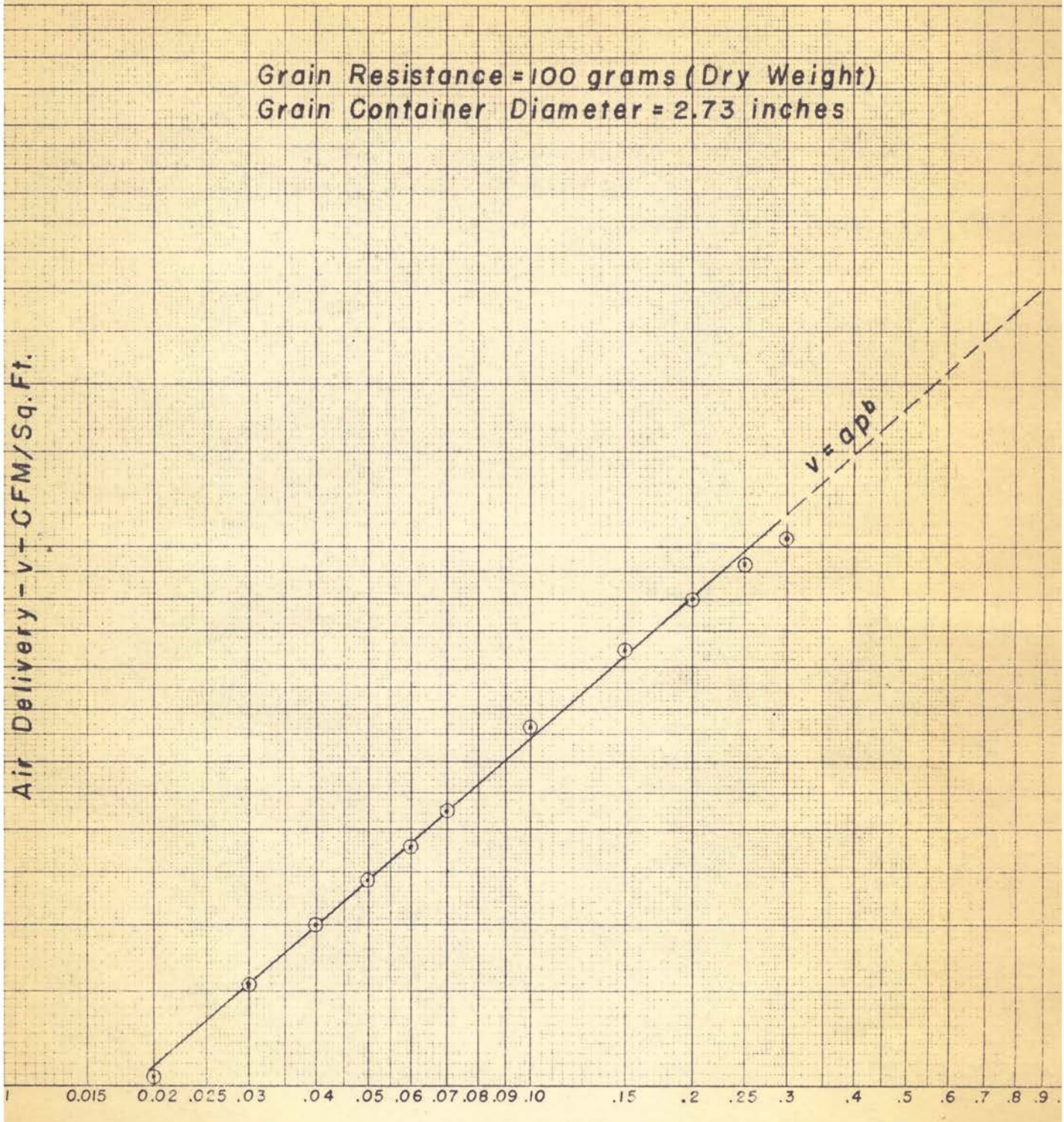

TABLE 1

CALIBRATION CURVE DATA

p, pressure in. water	v, velocity fpm	log p	log v
0.02	10.3	0.3010-2	1.0128
0.03	15.4	0.4771-2	1.1875
0.04	20.0	0.6021-2	1.3010
0.05	24.0	0.6990-2	1.3802
0.06	27.7	0.7782-2	1.4425
0.07	31.2	0.8451-2	1.4942
0.10	46.4	0.0000-1	1.6665
0.15	64.2	0.1761-1	1.8075
0.20	80.0	0.3010-1	1.9031
0.25	92.3	0.3979-1	1.9652
0.30	104.0	0.4771-1	2.0170

These values were substituted into equation (3) from which two expressions were written. Adding the first six equations and the last five,

$$7.8182 = 6 \log a + (0.7025\text{-}15)b \qquad (4)$$

$$9.3593 = 5 \log a + (0.3521\text{-}6)b \qquad (5)$$

Dividing Eq. (4) by 6 and Eq. (5) by 5,

$$1.3030 = \log a + (0.6171\text{-}2)b \qquad (6)$$

$$1.8719 = \log a + (0.2704\text{-}1)b \qquad (7)$$

which yield, on subtracting Eq. (6) from Eq. (7),

$$0.5689 = (-0.3467 + 1)b$$
$$0.5689 = 0.6533b$$
$$b = 0.872$$

Substituting for b in Eq (6),

$$\log a = 1.3030 - (-1.3829)\ (0.872)$$
$$\log a = 2.511$$
$$a = 325$$

Substituting a and b in $v = ap^b$, two points can be established for laying out the calculated calibration curve. For $p = 0.04$, $v = 19.8$ and for $p = 0.2$, $v = 80$.

Grain Drying Data

The air temperatures selected were increments of 20 degrees ranging from room temperature to 160 degrees Fahrenheit, while the air velocities were increments of 20 fpm ranging from 20 fpm to 80 fpm. During each drying run, the following data were collected:

Relative humidity and temperature of the air entering the air tempering chamber.

Air temperature before the air entered the grain container.

Dry bulb and wet bulb temperatures of the air leaving the grain.

Grain temperature.

Air temperature midway in the grain container.

Static pressure in the air tempering chamber.

Moisture content of the grain initially, during the drying run, and at the end.

Weight of the grain sample plus grain container at the beginning and end of the drying period.

Dry bulb and wet bulb temperatures of the air entering the air compressor.

Grain moisture content was figured on a dry weight basis. The initial weight of the grain sample before drying was 100 grams plus the equivalent weight in grams of the grain moisture content.

A continuous record of the dry bulb temperature and the relative humidity of the incoming air was maintained on the hygrothermograph circular chart. A like record was kept of the dry bulb and wet bulb temperatures of the air leaving the grain on the recording potentiometer circular charts. All other data were recorded at 15 minute intervals.

VI. DISCUSSION OF RESULTS

Data Compilation

The data presented in Table 2 represents the observed conditions of grain drying behavior for air temperatures ranging from room temperature to 189 degrees Fahrenheit, and at velocities of 20, 40, 60, and 80 fpm. In Table 2, a summary of the laboratory apparatus air conditions entering and leaving the grain has been compiled. The dry bulb and wet bulb temperatures for the air entering and leaving the grain container are given, and from these two conditions the absolute humidity, dew point, enthalpy, relative humidity, specific volume, and vapor pressure can be read directly from a psychrometric chart.

The initial condition of the air entering the tempering chamber was found on a psychrometric chart from the dry bulb temperature and relative humidity data recorded on the hygrothermograph chart. As the incoming air was heated to the desired temperature entering the grain container without a change in moisture content, a line of constant moisture was followed on a psychrometric chart to the corresponding dry bulb temperature of the air entering the grain container. The wet bulb temperature for the air entering the grain was then selected from this point. With the dry bulb and wet bulb temperatures established for the air entering the grain, the remaining

TABLE 2

SUMMARY OF AIR CONDITIONS DURING DRYING

Velocity Fpm	Avg Temperature of Air Entering Grain, F		Avg Temperature of Air Leaving Grain, F	
	Dry Bulb	Wet Bulb	Dry Bulb	Wet Bulb
20	82	55.5	72.5	56.0
40	80	58.5	70.5	58.0
60	74	57.0	68.0	55.0
80	77	56.0	72.0	58.5
20	115	69.0	89.0	64.0
40	116	75.5	90.0	68.0
60	117	63.2	98.0	68.0
80	116	69.3	86.0	64.0
20	139	77.5*	85.0	70.0
40	140	78.0*	94.0	68.0
60	141	78.0*	115.0	74.0
80	146	79.0*	125.0	82.0
20	164	83.0*	93.0	74.0
40	165	84.0*	111.0	74.0
60	165	84.0*	128.0	79.0
80	164	83.0*	144.0	84.0
20	187	88.0*	112.0	81.0
40	184	87.5*	126.0	84.0
60	189	88.5*	139.0	85.0
80	183	87.0*	148.0	85.0

* Estimated wet bulb temperature.

conditions could be found if required for further evidence. Because of the hygrothermograph temperature recording limitation, the described procedure could be followed only for air temperatures entering the grain container not exceeding 120 degrees Fahrenheit.

For air temperatures entering the grain container greater than 120 degrees Fahrenheit, an estimate was made of the wet bulb temperatures. This estimate was made by taking the average humidity ratio of the temperatures less than 120 degrees Fahrenheit. Values for humidity ratio were obtained from a psychrometric chart[1] using the dry bulb and wet bulb temperatures of the air entering the grain. The average humidity ratio was then used with the dry bulb temperatures of the air entering the grain greater than 120 degrees Fahrenheit to find the wet bulb temperature of the air entering the grain at the higher temperatures.

Throughout the grain drying tests, iron-constantan duplex 30 gauge thermocouple junctions were used as the temperature sensing element for the recording potentiometers, 48 point potentiometer, and the vane type millivoltmeter pyrometer. In the final grain drying tests, suspicion was aroused when an apparent higher temperature was observed in the grain than the temperature of the air entering the grain container. Upon checking the temperature sensing junctions at the vane type millivoltmeter pyrometer and in the grain container, a tempera- difference as high as 30 degrees Fahrenheit was observed. In

a few of the previous grain drying runs, there had been a slight temperature difference, but it was believed that this was due to the time lag between the heating elements and the temperature sensing element located before the grain cup. A thorough check was made of all thermocouple lead connections and junctions. Recleaning and reconnecting the thermocouples produced the same results. The thermocouples were then replaced with new thermocouple leads. It was thought perhaps there was a broken connection but the results were repeated. At this time it was decided to replace the thermocouple junction and leads to the vane type millivoltmeter pyrometer with a heavier, 20 gauge, wire. The new arrangement gave the correct results. It was concluded that a 30 gauge wire has too high a resistance for use with a millivoltmeter instrument.

After the instrument error had been found, a temperature correction was made for all the grain drying runs. This was accomplished by using another temperature sensing element connected to the 48 point potentiometer. The thermocouple junction was located before the air entered the grain container, at a point where the vane type millivoltmeter pyrometer thermocouple junction had previously been. Previous grain temperatures were duplicated at the various velocities from the data which had been recorded and the actual temperature of the air entering the grain container recorded.

Drying Rate

Figures 8 to 11, inclusive, show the effect of the drying rate at various velocities on the moisture content of grain. The drying rate for the Redland Kafir grain sorghum increased for the different grain moisture contents at all temperatures above 140 degrees Fahrenheit. The drying rate slowed down at the end of the two hour drying interval. This infers that the drying rate would decrease more as equilibrium moisture content was approached.

Air velocity apparently did not have much influence upon the rate of drying. An attempt was made to establish a relationship between grain moisture content removed and air velocity. Plotted curves gave no consistency. It was felt that insufficient evidence, within the range of studies, did not permit stating whether or not drying rate was independent of air velocity, but the laboratory tests tend to verify Hukill's work.[13]

As the purpose of this paper was primarily to develop and design a laboratory apparatus for grain drying studies, equilibrium moisture content was not approached. Using the laboratory apparatus, equilibrium moisture content could be observed by allotting a longer operational time for drying grain samples.

A better correlation of data could probably be obtained if a series of tests were made starting with grain having the same initial moisture content. For example, at a given air

Symbol	Average Grain Temperature	Entering Air Temperature
	Dry Bulb	Dry Bulb
—×—	74 F	82 F
—⊙—	101 F	115 F
—⊗—	117 F	139 F
—△—	136 F	164 F
—⁄—	157 F	187 F

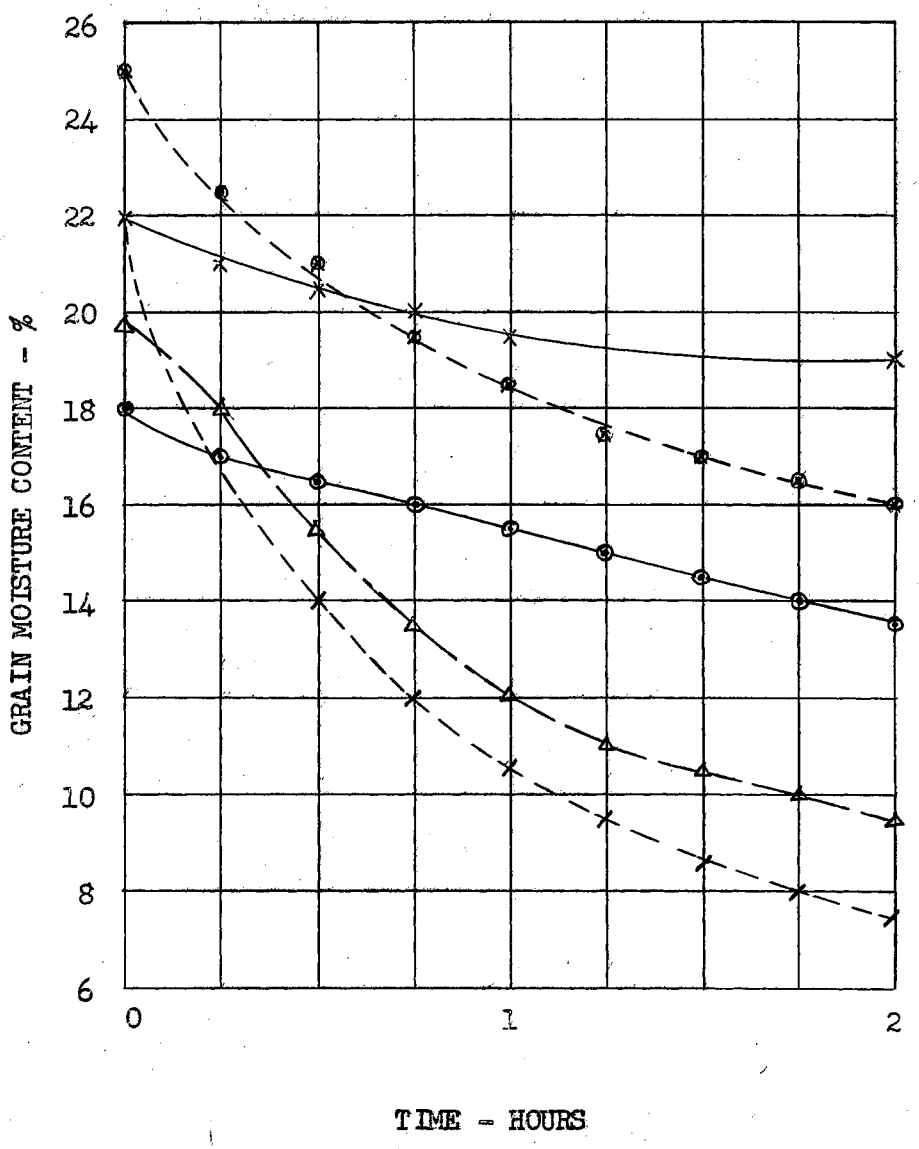

Fig. 8 GRAIN DRYING RATE CHARACTERISTICS
FOR AN AIR VELOCITY OF 20 F.P.M.

Symbol	Average Grain Temperature	Entering Air Temperature
	Dry Bulb	Dry Bulb
—×—	73 F	80 F
—⊗—	98 F	116 F
—△—	119 F	140 F
—⊙—	139 F	165 F
—/—	157 F	184 F

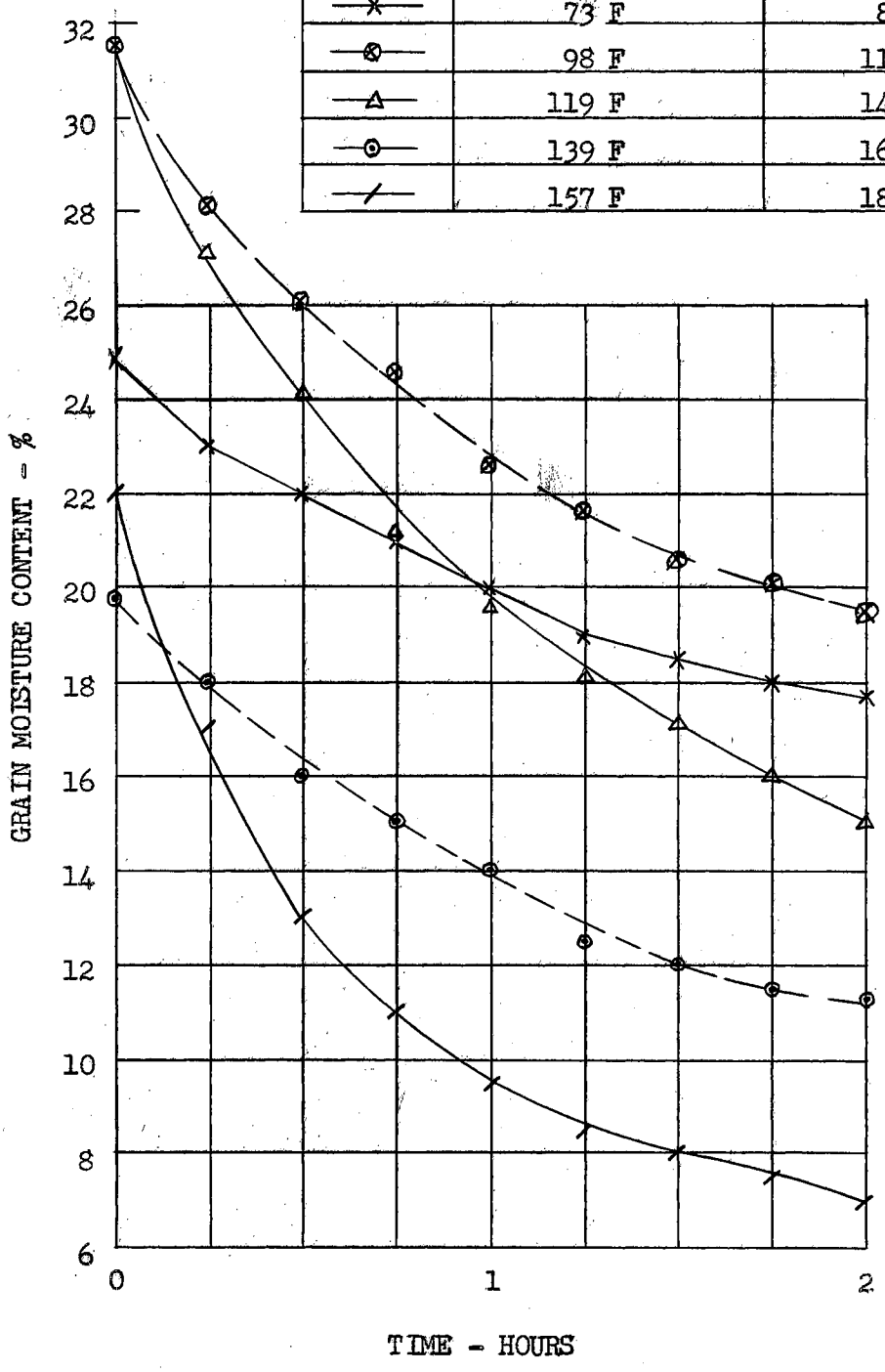

Fig. 9 GRAIN DRYING RATE CHARACTERISTICS
FOR AN AIR VELOCITY OF 40 F.P.M.

Symbol	Average Grain Temperature	Entering Air Temperature
	Dry Bulb	Dry Bulb
—⊙—	72 F	74 F
—×—	107 F	117 F
—⊗—	127 F	141 F
—△—	153 F	165 F
—/—	173 F	189 F

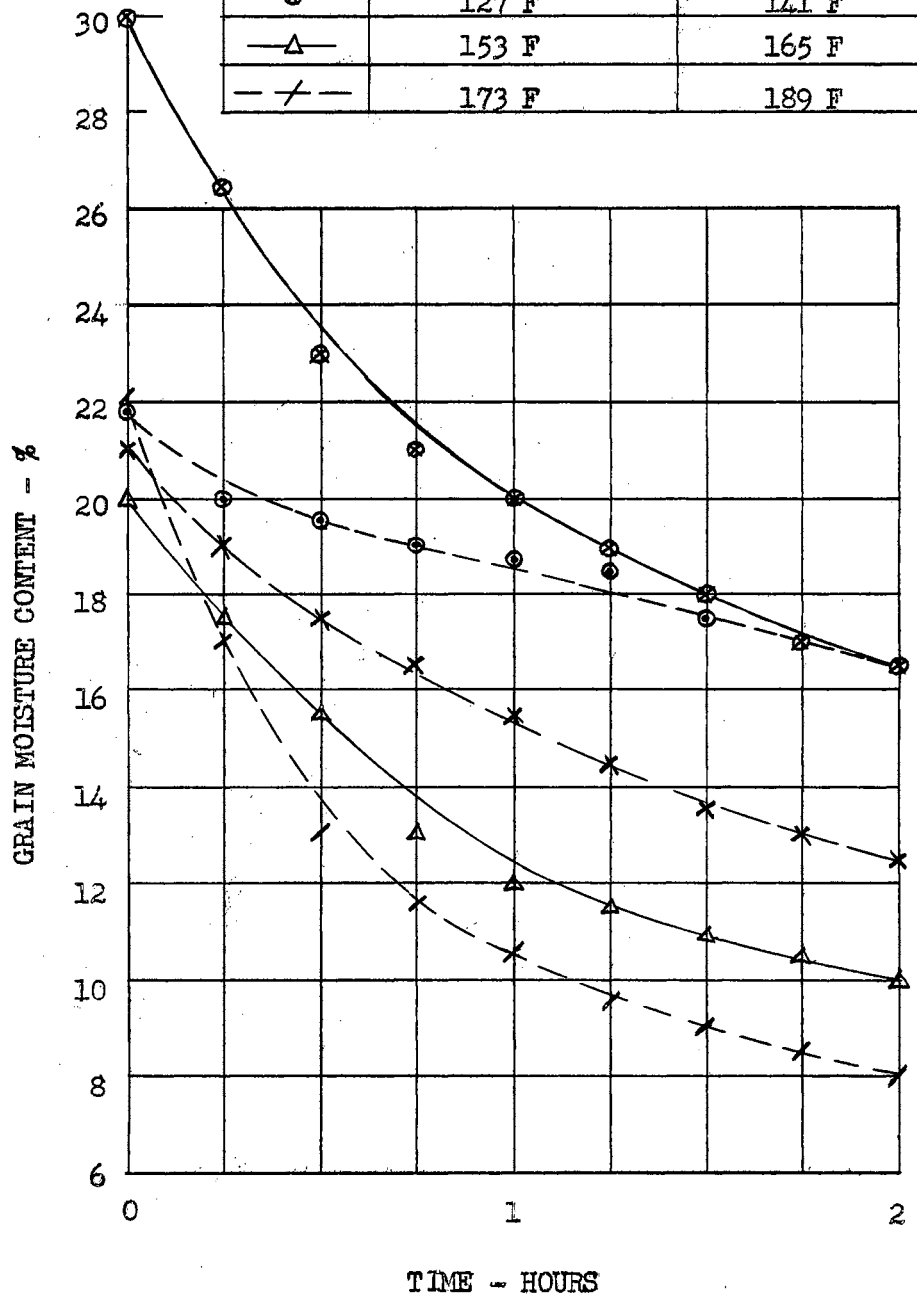

Fig. 10 GRAIN DRYING RATE CHARACTERISTICS
FOR AN AIR VELOCITY OF 60 F.P.M.

Symbol	Average Grain Temperature	Entering Air Temperature
	Dry Bulb	Dry Bulb
—×—	77 F	77 F
—△—	105 F	116 F
—⊗—	138 F	146 F
—+—	157 F	164 F
—⊙—	175 F	183 F

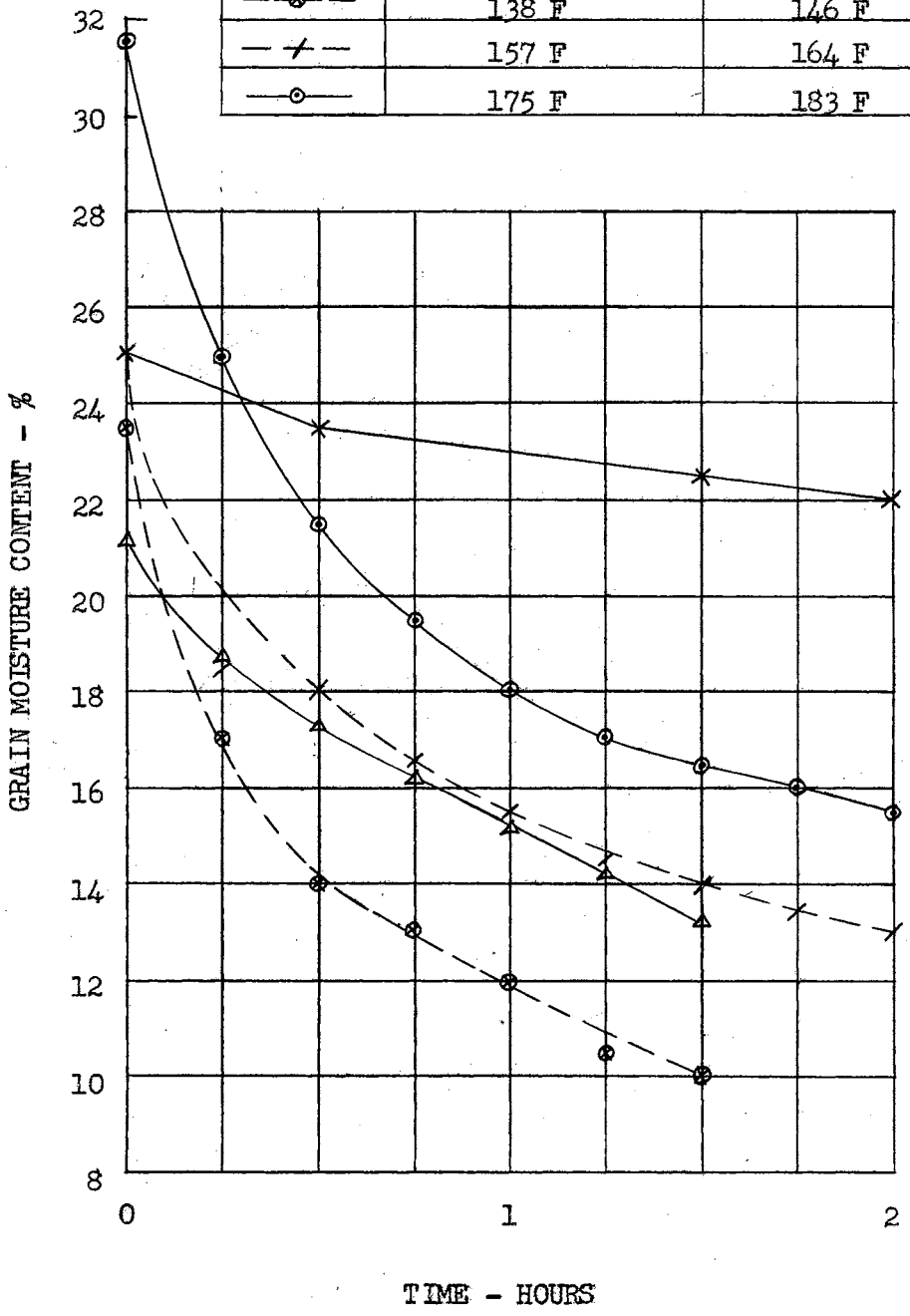

Fig. 11 GRAIN DRYING RATE CHARACTERISTICS
FOR AN AIR VELOCITY OF 80 F.P.M.

temperature entering the grain of 100 degrees Fahrenheit, grain having a 21 percent moisture content would be dried at velocities of 20, 40, 60 and 80 fpm. The same principle would be applicable when air velocity is made constant and the temperatures entering the grain varied. By following such a procedure, perhaps more conclusive evidence could be offered.

The affect of heat upon the grain quality itself was not studied, but at the 183 to 189 degrees Fahrenheit temperature grain drying tests, the dried grain, besides being warm, had a roasted appearance.

In the initial laboratory tests, the reduced portion of the air tempering chamber consisted of the original materials, masonite and soft pine. Trial laboratory grain drier runs indicated that there was a possible fire hazard from the heating elements. This hazard was reduced by relining the reduced portion of the tempering chamber with two layers of asbestos paper and one layer of aluminum reflective foil lining to provide insulation and to protect against charring.

In the original design, bakelite receptacles were used to hold the heating elements. At the higher temperatures, 160 and 180 degrees Fahrenheit, the bakelite receptacles began chipping due to the heat. The bakelite receptacles were then replaced by porcelain receptacles which served satisfactorily for all grain drying runs as high as 189 degrees Fahrenheit.

The advantage of placing the silica gel dehydrator unit between the globe valve and the pressure regulator was proved

by the hygrothermograph chart record. The moisture content line for the air entering the air tempering chamber was fairly uniform when the silica gel dehydrator was placed in the line. Without the dehydrator in the supply line, the hygrothermograph chart curve fluctuated up and down.

One of the precautions that must be taken with the silica gel dehydrator is that a valve should always be on the high pressure side to prevent the silica gel crystals from being blown out under pressure.

During one of the calibration runs, condensation occurred on the inside of the grain container. Such a condition was not repeated again during either the calibration runs or grain drying tests. The conclusion reached was that an exceptionally cold room had been the cause. To remedy such occurrences, a space heater was used to maintain room temperature on cold days.

One of the strange phenomenon with the laboratory grain drier occurred prior to the air velocity calibration run when mice chewed away the thermocouple connections. It was necessary to reconnect all thermocouple instrument connections and suspend the thermocouples in mid-air (Fig. 5).

In the final grain drying tests, the temperature control indicator on the vane type millivoltmeter pyrometer began sticking occasionally at a certain temperature. It led to the belief that either the instrument was at fault or that this method of temperature control should not be used in future grain drying runs.

When the air tempering chamber was first constructed, a 1" thick wood baffle was placed between the heating elements and the grain container. There was an inch clearance between the baffle and the reduced section base of the air chamber. The baffle restricted the heat transfer from the heating elements to the grain container, but there was heat flow toward the hygrothermograph. Removal of the baffle restriction helped to ease this problem.

Design Recommendations

One of the experimental problems had been a continuous air supply for high velocities. When the electric compressor and the gasoline engine compressor were arranged in a parallel hook-up, an air velocity of 80 fpm was maintained. Higher velocities than this were obtained if a reserve air supply was built up in the air compressor, but this condition lasted for a short duration. The gasoline engine compressor did not have a reserve tank but forced the air directly into the supply line.

One approach that may be taken toward maintaining a continuous air supply is the use of a blower in combination with orifice restrictions. After determining the blower operating velocity range, the equipment would be calibrated by the method explained previously under procedure. If ease of air velocity range control were considered, it appears that the blower arrangement would not be as advantageous as parallel compressors.

With the use of flask cylinders, the maximum calibration air velocity is 100 fpm. A much higher air velocity for calibration runs could be obtained by placing the compressed air bottle directly into the supply line. The scale for weighing the compressed air bottle would then not only have to be of sufficient size, but it should also have comparable accuracy.

There are two improvements which can be made if use of the hygrothermograph were to be continued in further experiments. The first is to take into consideration the time lag in response of the hair elements to relative humidity; and secondly, to make provision for measuring the air temperature of the air passing the hygrothermograph during high temperature drying runs. Although the air entering the tempering chamber is initially at room temperature, the heating elements radiate heat toward the hygrothermograph causing the 100 degree Fahrenheit temperature limit to be exceeded. A baffle, placed between the heating elements and the hygrothermograph, might safeguard against high temperature, but the baffle may also cause a restriction to air flow. If the latter did occur, it would probably be negligible as to its effect on grain drying operation. A better solution would be to place a thermocouple lead from the 48 point potentiometer to a point where the hygrothermograph is located in the air tempering chamber. The dry bulb temperature could then be recorded at 15 minute intervals with this temperature sensing element, while the

relative humidity could still be obtained from the hygrothermograph.

In redesigning the laboratory apparatus, each heating element should be controlled individually from outside the air tempering chamber by a series of manual switches. This would reduce the frequency of removing the plywood panel section to hygrothermograph chart changes and the replacing of burned out heating elements. It would also probably be best to place the porcelain receptacles on the tempering chamber floor instead of the chamber ceiling.

The grain container used for the experiment had a plastic mesh screen glued to its base. Continuous clamping and removal of the container caused the screening to occasionally tear loose. By placing another piece of 4" square plywood, identical to the one in which the lucite cylinder sets, over the container base, this trouble could be avoided. Another approach would be the use of a cylinder alone with screening at the base. The container would be set into a rubber gasket arrangement on the tempering chamber ceiling.

Probably as a point of interest, although the unit could be observed better, a removable panel section constructed from a transparent material could be used instead of plywood. The factor to consider here is that the material must be able to withstand grain drying temperatures.

If it were desired to thoroughly study the drying behavior of grain by forced air methods with this apparatus, a more

permanent design should be used, preferably one of a heavier material, or metallic construction.

VII. CONCLUSIONS

Studies made with the small scale laboratory grain drier support the following statements:

1. The small scale laboratory grain drier, with some modifications, can be successfully used in obtaining data on drying small grain samples with forced air.

2. Air flow calibration curves of air delivery, v, in cfm/sq ft, versus static pressures, p, in inches of water, for a given grain resistance and grain container diameter can be determined. For a grain resistance of 100 grams, dry weight, and a grain container diameter of 2.73", the equation of the line is $v = ap^b$ where $a = 325$ and $b = 0.872$.

3. Air entering the grain sample at temperatures of 140 to 189 degrees Fahrenheit will increase the grain drying rate compared to air entering the grain sample at lower temperatures.

4. No conclusive evidence was found to indicate whether or not grain drying rate is dependent upon air velocity.

5. By extending the time interval for drying grain samples, equilibrium moisture content studies could probably be undertaken.

6. Air from a compressed air supply has the advantage of a wide range of air velocity control by means of an orifice, pressure regulator, and globe valve.

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THESIS TITLE: DEVELOPMENT OF A LABORATORY APPARATUS FOR GRAIN DRYING STUDIES

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