

DRYING WHITE PEA BEANS WITH
HEATED AIR

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
Robert Leo Maddex
1953



This is to certify that the
thesis entitled

"Drying White Pea Beans with Heated Air"

presented by

Robert L. Maddex

has been accepted towards fulfillment
of the requirements for

M.S. degree in Agricultural
Engineering

Walter M. Carleton
Major professor

Date Oct 16 1953

DRYING WHITE PEA BEANS

WITH HEATED AIR

By

Robert Leo Maddox

A THESIS

Submitted to the School of Graduate Studies of Michigan State College
of Agriculture and Applied Science in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

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ACKNOWLEDGMENTS

The author wishes to express his gratitude to Dr. Carl W. Hall for consultation and advice on this project and for his help in conducting the series of tests run on the portable field unit.

Acknowledgment is due to William F. Brandt, Investigator on Pea Bean Research in the field of drying; to Dr. Herbert Pettigrove of the Farm Crops Department for the loan of the Steinlite Quick Moisture Tester and for his consultation on problems of harvesting and storing pea beans; and to Dr. Walter Carleton for suggestions and comments in the preparation of this thesis.

Sincere thanks is expressed by the author to the Commodity Credit Corporation for the financial support that made it possible to carry on this work, and to Judson A. Thompson, Grain Branch of the Production Marketing Association, for his interest and helpful suggestions in this project.

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AN ABSTRACT

Submitted to the School of Graduate Studies of Michigan State College
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Walter M. Carleton

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Michigan ranked second in the nation in total bean production in 1950, 1951, and 1952. Michigan harvested 378,000 acres of edible beans in 1951 and 340,000 in 1952. Michigan harvested 93% (3,782,000 - 100 pound bags) in 1951 and 94% (3,523,000 - 100 pound bags) in 1952 of the total pea bean production in the United States. Michigan also harvested 55% (72,000 bags) of the dark red kidney beans, 78% (80,000 bags) of the cranberry beans, and 48% (73,000 bags) of the yellow eye beans produced in the United States in 1952.

The climatic conditions are such that during many falls the pea beans must be harvested above 18% moisture content. The nature of the pea bean is such that it must be stored at a moisture content of 18% or less, if the pea bean is to remain in an edible condition for any length of time. It becomes necessary then to remove moisture by the circulation of forced air when pea beans are harvested above 18% moisture content.

Although extensive investigations have been made into the drying of various grain crops with both unheated and heated forced air, no investigation had been made into the drying of pea beans. Pea beans differed from other grains in that rapid evaporation of surface moisture caused a shrinking of the bean seed coat and a cracking of the bean. Cracked beans become cull beans so from an economical standpoint it is very desirable to prevent excessive cracking of the pea beans as they are being dried.

The Commodity Credit Corporation proposed the partial recirculation of the drying air as a means of controlling the drying rate and preventing

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excessive cracking. A portable field drying unit (bin and fuel oil heater) was loaned to the Agricultural Engineering Department for use. Five tests made with this unit used drying air at 100°F. and from 0% recirculation up to 75% recirculation.

Two laboratory units were built, one providing controlled recirculation and the other providing controlled humidity by introducing steam into the air stream. A total of 26 tests were run using the two laboratory units with temperatures ranging from 90° to 170°F., air flows ranging from 5 c.f.m./bu. to 35 c.f.m./bu., and recirculation from 0% to 75%. Five of these tests were made using controlled humidity (by addition of steam) to regulate the drying rate of pea beans.

High percentages of cracking occurred when the temperature of the drying air was above 130°F. and no recirculation or a low percentage of recirculation was used. The drying rate became slower as the amount of recirculation was increased but the amount of cracking was reduced. Cracking was held to a minimum by controlling the humidity in the air stream.

Tests indicated that drying temperatures below 130°F. with a recirculation of 50% of the drying air, or with drying air having a relative humidity of approximately 15% would prevent undue cracking of the pea beans.

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INTRODUCTION

Michigan produced approximately 93% of the pea beans produced in the United States in 1951 and approximately 94% of the total United States production in 1952.

Michigan ranked second in the nation behind California in total bean production in 1950, 1951 and 1952. In 1951 there were 378,000 acres of edible beans harvested in Michigan and in 1952 there were 340,000 acres harvested. The average yield in 1951 for Michigan bean production was 1,120 pounds per acre and in 1952 the average yield was 1,150 pounds per acre.

Figures furnished by Michigan Cooperative Crop Reporting Service show the total production of cleaned pea beans in the United States in 1951 was 4,072,000 (100 pound) bags, of which about 93% or 3,782,000 bags were produced in Michigan. In 1952 the total United States production was 3,753,000 bags of which about 94% or 3,523,000 bags were produced in Michigan. In addition Michigan produced 108,000 bags or 80% of the total dark red kidney beans produced in the United States in 1951 and 78,000 bags or 55% of total production in 1952. Michigan also produced about 85% or 72,000 bags of cranberry beans in 1951 and 78% or 80,000 bags in 1952, plus 41% or 60,000 bags of yellow eye beans in 1951 and 46% or 73,000 bags in 1952.

The five major states in order of cleaned bean production for the past three years are California, Michigan, Colorado, Idaho and New York. Climatic conditions in the western states make it possible to harvest beans at moisture contents near 16%. In Michigan the climatic conditions

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during many falls make it necessary to harvest beans above 12% moisture content. The nature of the pea bean is such that it must be stored at a moisture content of 12% or less if the pea bean is to remain in an edible condition for any length of time. When beans are harvested above 12%, moisture must then be removed by forced circulation of air through the grain either by 'on the farm' or commercial driers. There are relatively few 'on the farm' drying systems for handling pea beans and commercial drier installations now in use for bean drying were designed primarily for drying small grain. The use of the commercial equipment has resulted in high percentages of split beans because forced hot air is applied rapidly. Although the need for forced air drying systems for drying pea beans is definitely established, very little information has been available that can be used as a basis for design and selection of equipment for drying pea beans.

OBJECTIVES

The almost complete lack of information on drying pea beans made it necessary to first conduct several tests using a wide range of drying conditions. The results of these tests would be used to guide the investigations that would follow. The Commodity Credit Corporation had purchased especially designed equipment utilizing the principle of recirculation of the drying air at controlled humidity levels. This equipment had been used in a limited number of field demonstrations by inexperienced personnel and, although the principle and equipment appeared sound, extreme difficulty had been encountered by the field personnel in attempting to use the equipment. This equipment was made available to the Agricultural Engineering Department of Michigan State College for test work.

After the first broad objective was achieved using the field demonstration equipment, a laboratory unit that permitted controlled recirculation was designed to do further test work. After a number of tests were run on this laboratory unit, a second laboratory unit previously used in a hay-drying project was set up and a series of tests run using this equipment. The second laboratory unit made it possible to control the humidity of the air stream without recirculation.

Considering the entire scope of this project, the objectives were:

1. To determine the feasibility of drying beans by recirculation of moist air to prevent cracking of the beans.
2. To determine the effect of recirculation on the cracking of the beans.
3. To determine the optimum percentage of recirculation.

4. To determine the effect of air flow rates on the cracking and drying of the pea beans.
5. To determine the effect of temperature on the drying and cracking of the pea beans.
6. To determine the effect of controlled humidity on the cracking and drying of the pea beans.
7. To determine the static pressure required to force the air at various rates of flow through the pea beans at various depths.
8. To provide information to use in the design of a field unit for drying pea beans.

REVIEW OF LITERATURE

Much work has been done on the conditioning of grain with forced air, both using natural and heated air. Duffee (1) of Wisconsin reported on combing and drying grain in 1927 and Lehmann (2) of Illinois reported on drying and shrinkage problems in 1926. The National Research Council of Canada (3) compiled a rather extensive report in 1929 on studies made of the commercial driers being used at that time to condition the Canadian wheat crop. Many of these same driers are being used today with little change in their design. Investigations on the drying and storing of grain has centered primarily on wheat and corn; however, the drying of such crops as rice, sorghums, flax, peanuts, and grass and legume seeds has been reported in detail.

No investigations on the drying of pea beans were reported in the literature; however, many of the basic principles and problems of removing moisture from grain without damage to the grain itself apply to the drying of pea beans and will be cited herein.

The problem of controlling the drying rate was recognized early by Duffee (1) of Wisconsin in his work on the drying of seed corn. Duffee reported the recirculation of the drying air and the reversing of the air flow through the drying bins to control the drying rate and the evenness of drying.

Investigators who compiled the information for Report No. 24, "The Drying of Wheat" by the National Research Council of Canada (3) state:

The data reported support the suggestion that the safe limit for temperature probably varies with the moisture content of the grain. This suggestion is well founded in theory since it is well known that proteins become more easily changed with increase in the moisture content. Drying at high temperatures would tend to dry out the outer portions of the kernel while the inner portion was still close to the original moisture content. With decreased evaporation the temperature of the grain itself will tend to rise and the effect on the inner portion of the kernel will be similar to that in a steam-pressure cooker. The use of lower temperatures on the other hand will prevent too rapid drying of the outside of the kernel and will allow the moisture from the inner portions to be transferred to the outside and driven off.

These investigators concluded that there is probably a range of safe drying temperatures depending on the initial moisture content of the wheat, and that wheat of lower moisture content can probably be safely dried at a higher temperature than wheat of a high moisture content. Milling characteristics, loaf volume of baked samples, and official grading of the samples out of the driers were the means of determining the effect of drying on the samples.

In 1939 Kelly (4) reported that in drying wheat rapid drying took place while the surface moisture was evaporating followed by a slower rate of drying depending on the diffusion of moisture from the inside of the grain to the outside surface. Kelly tried applying the heat directly to the grain and obtained a faster drying rate which he attributed to a greater vapor pressure difference between the inside and outside of the grain causing the moisture to move out. Warming the inside of the grain caused the difference in vapor pressure. Kelly used natural air at a temperature of approximately 80°F. as a drying medium. In 1941 Kelly (5) reported on drying grain heated to temperatures in the range of 140° to 145°F. in a revolving drum oven. He found that 57 to 60 percent of the drying took place in the first minute and that 43 percent of the total temperature drop took place during the first minute. The drying

rate slowed considerably as the temperature of the grain fell. Natural air at temperatures of 78° to 81°F. were forced through the grain. The relative humidity of the drying air was 57 to 61 percent.

Several investigators have worked on the problem of drying rice. McNeal (6) reported that by redrying the rice three or four times at temperatures of 130°F. satisfactory milling characteristics and good germination was obtained. The use of high temperatures to dry the rice down to the desired final moisture content in one operation resulted in weight loss, poor milling characteristics, and poor germination.

Many investigators have found that in drying grain there is a 'zone of drying'. This zone is referred to by some as a layering or drying front. When drying air is forced through wet material the air picks up moisture from the wet material in the bin. The drying of the material begins where the drying air enters the bin and moves in the direction of air flow. The air reaches its moisture carrying capacity in a relatively short time of contact with the wet material and will then pass through the remainder of the wet material without absorbing any moisture from it. There is a lower limit below which a material will not give up moisture to drying air if the drying air is maintained at a constant temperature. The drying air then passes through the dried grain and absorbs moisture from the first wet grain with which it comes in contact. There results a zone of transition from dry to wet material which is called the 'zone of drying' and can be rather sharply defined by limits of specific moisture content.

Reporting on investigations in storing grain sorghums Fenton (7) says that the temperature of the grain is of greatest importance in affecting vapor pressure and that the temperature of the grain is the

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greatest single factor in grain drying. Fenton states:

Grain sorghums, like other grain, are hygroscopic in nature, in that 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 grain.

One of the most complete treatments of basic principle involved in drying grains is given by W. V. Hukill (8). Hukill states:

The drying rate for fully exposed grain¹ is a function of the air temperature and humidity and the grain moisture content. It is affected but slightly by the air velocity. At a given temperature, humidity and moisture content, each kind of grain dries at a characteristic rate, the smaller grains in general drying faster than the larger ones.

Hukill says that as air of a given condition is introduced into the grain the rate of drying of the very first grain with which it comes into contact is influenced very little by the rate of air supply. Tests on exposed drying rates showed that for each kind of grain exposed to air of a given wet-bulb temperature the drying rate (a) is independent of air velocity, (b) at a given relative humidity it is proportional to the difference between the grain moisture and the equilibrium moisture content (expressed on a dry basis) and (c) at a given grain moisture content it is proportional to the difference between the dry-bulb temperature of air and the dry-bulb temperature of air in equilibrium with the grain.

As air moves upward or downward through grain of uniform moisture content, the wet-bulb temperature of the air remains constant but the

¹The term 'fully exposed grain' is not explained by Hukill. The author believes fully exposed grain to mean clean grain in a drying chamber so designed that there is a flow of air around all sides of the grain kernel. In an improperly designed drying system there can be dead spots resulting in no air flow around some of the grain kernels or uneven air flow around some of the grain kernels.

dry-bulb drops approaching a temperature at which the air and grain are in equilibrium. At any point along its path the rate of evaporation seems to be about proportional to the amount by which the dry-bulb temperature exceeds its final equilibrium temperature.

Both Barre (9) and Fenton (7) emphasize that many of the problems of drying grain become clearer when approached from the standpoint of vapor pressures. Vapor pressure differences of the magnitude of 0.05 to 0.10 pounds per square inch are sufficient for effective drying. Favorable atmospheric conditions may occasionally be utilized to provide suitable vapor pressure differences. Heating a stored grain by using forced ventilation during warm periods and following with circulation of cold air can provide large vapor pressures naturally. It is often possible to utilize natural atmospheric conditions on such crops as corn that are harvested during the season when sharp temperature drops are most likely to occur. Pressure differences in drying with heated air are obtained by an increase in the vapor pressure of the grain and not by a decrease in that of the surrounding air. Removal of moisture from the grain results because the grain is heated and not because the air is heated.

More heat is needed to evaporate water from grain than from a free water surface, reports Hukill (10). It is necessary to supply the latent heat of vaporization to evaporate moisture from grain. The amount of moisture evaporated from grain is proportional to the amount of heat supplied to the grain by the drying air. The heat available for evaporating the grain moisture is the difference between the initial dry-bulb temperature and wet-bulb temperature of the air providing there is no loss or gain of heat to or from the grain through which the air passes.

It is seldom that full utilization of this heat is realized.

An English publication (11) points out that for air and grain at the same temperature, a definite relationship exists between the grain (wheat) moisture content and relative humidity of the intergranular air. This relationship (Table I) is such that a condition of equilibrium exists between the two. Table I shows that with increasing atmospheric relative humidity, we get increasing grain moisture, particularly when the relative humidity is above 71%.

TABLE I
RELATIONSHIP OF GRAIN MOISTURE CONTENT
TO RELATIVE HUMIDITY OF SURROUNDING AIR²

Air Relative Humidity	Grain Moisture Content
64% is in equilibrium with	14%
71% " " " "	15%
78% " " " "	16%
83% " " " "	17%
88% " " " "	19%
90% " " " "	22%

In discussing the use of heated air for drying grain the publication states:

While any grain being dried is really wet, with say 30% moisture content, free evaporation can occur at its surface: as quickly as surface moisture is evaporated more moisture

²The author assumes this Table is based on a temperature of 77°F. which is the standard temperature used in computing equilibrium moisture contents of grain. This fact is not stated in the English publication.

diffuses to the surface from inside. So long as this happens the rate of removal of moisture is constant and is dependent not only on the air temperature and humidity but also its velocity. The grain acquires the wet-bulb temperature of the air.

After a time however, as the grain dries, moisture no longer diffuses to the surface as quickly as it can be evaporated. The rate of drying falls continually in proportion to the residual moisture still in the grain; the drying rate is less and less dependent on air speed, and the grain cannot use all the heat supplied for evaporation and so its temperature rises above the wet-bulb value.

If the drying capacity of the air is too great during this phase, the outer layers of the grain will be baked or 'case hardened' and the rate of diffusion of internal moisture will be further retarded. If the temperature and volume of the drying air is too high the grain may get too warm, and its germination power will be reduced. The shrinkage, which accompanies all drying, may be too fast and the grain will acquire a shrivelled appearance and will become brittle or even cracked internally.

Henderson and Perry (12) use the following equation to define equilibrium moisture curves:

$$1 - rh = e^{-KTM^N}$$

rh = equilibrium relative humidity, a decimal

M = equilibrium moisture content, dry basis, percent

T = temperature, °R.

K, N = constants (some constants are given by Henderson and Perry)

Henderson and Perry point out that the equilibrium moisture curves are affected somewhat by a change in temperature, an increase in temperature shifting the curve downward which gives a lower grain moisture content for a given equilibrium relative humidity. However, the effect is not sufficiently pronounced to be considered in most engineering work.

They state:

The equilibrium moisture properties of materials are important in storage and drying. If the relative humidity of the air in contact with a material is higher than the equilibrium relative humidity of the material at its current moisture content, the material will increase in moisture content, the moisture content at the relative humidity being approached. An air relative humidity lower than the equilibrium will cause the moisture content to decrease.

DRYING EQUIPMENT IN USE

Farm Driers

In the fall of 1951 several farmers in the Thumb area of Michigan adapted their hay or grain drying equipment to drying pea beans. As far as the author was able to determine five installations were built using natural air as the drying medium. There was some question by bean growers in the area where the farm driers were built as to whether or not the beans dried in these drying units would remain in condition through the following spring and summer.

In the winter of 1952 the author took a quart sample of pea beans from two farm drying bins. Both samples were harvested in early October 1951 at close to 23% moisture by elevator test. The drying equipment in the bin from which the sample shown on the left in Figure 1 was taken was turned on four times and operated for a total of approximately 30 hours



Fig. 1. Bean Samples Taken from Farm Drying Bins

during the early part of October. The drying equipment was run for several hours after an elevator test showed the moisture to be just over 18%. The rate of air flow was approximately 25 to 30 c.f.m./bu. The sample on the right in Figure 1 was taken from a bin where the drying equipment was operated during intervals of warm weather until the farmer decided by the feel of the beans that the moisture content was low enough for safe storage.

The samples were placed on a cabinet in an office in the Agricultural Engineering Building with the can lids turned down tightly and remained there for 20 months. The average temperature in the office was in the neighborhood of 72°F. After several months the beans in the jar from which the sample on the right was taken began to discolor and mold growth appeared. Samples from the two jars were dried in the oven in July 1953. The sample on the left in Figure 1 had a moisture content of 14 $\frac{1}{2}$ % while the sample on the right had a moisture content of 20%.

On the farm drying can be done if the farm operator will follow recommended drying practices and take the trouble to check moisture contents. This information is included here, not from the standpoint that it was a part of the research work of this thesis problem, but from the standpoint of background information of on the farm drying.

Commercial Driers

Eight elevators that were using commercial equipment for drying beans were visited by the author during the fall of 1951 and the fall of 1952. This equipment was designed and installed primarily for the drying of wheat or ear corn. None of the elevator operators that the author talked with expressed a desire to handle wet pea beans, especially when moisture con-

tents were such that more than two percent of moisture had to be removed. However, since there are many years when it is impossible to harvest pea beans at moisture contents safe for long storage, the elevator operators have learned by trial and error how best to use the drying equipment they have to remove excess moisture from pea beans.

The three types of drying equipment observed are shown in Figures 2, 3 and 4. These are simplified drawings of the commercial drying units. The author talked with the elevator operator and the person responsible for operating the drying equipment when visiting each elevator. Their method of operation was recorded and is given on the following pages. The methods of operation by the elevators having similar equipment were very much alike even though they had arrived at these methods through their own experience.

Other types of commercial drying equipment may be in use in Michigan elevators which the author did not visit.

Hess Grain Drier. This drier consists of a cooling chamber, a heating chamber, a centrifugal blower, dust work and steam coils. The air is pulled through the cooling section, into the blower, and passes over steam coils before entering the pressure chambers. The air passes through the grain sections into exhaust chambers that either release it to the outside or force it up through the holding bin that serves as a preheat chamber. The drier is operated as a batch drier when it is used for pea beans. None of the operators of the Hess driers with whom the author talked knew the temperature of drying air or the rate of air flow through the beans. Drying was regulated by controlling the steam pressure in the coils and varying the time the beans were in the drying units for different initial moisture contents. The information recorded on the operation of the Hess drier is as follows:

P - Pressure
E - Exhaust
S - Suction
G - Grain Column

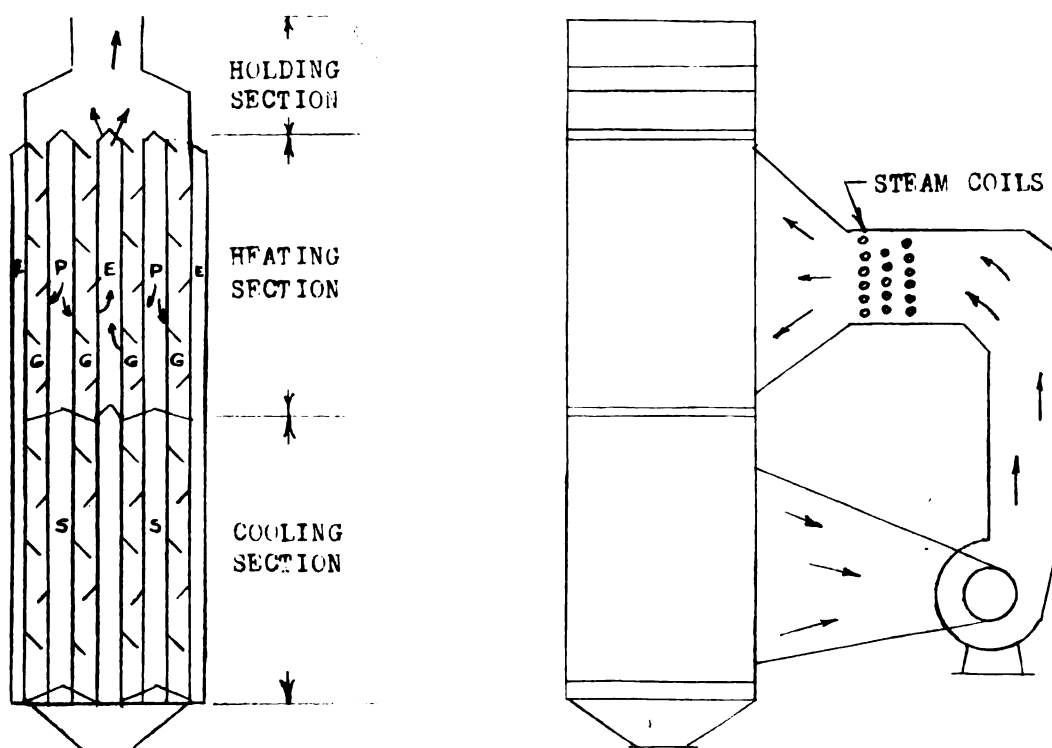


FIG. 2. HESS GRAIN DRIER

- Steam pressure - 10 psi for beans and 60 psi for corn
- Operated as - batch drier with preheating chamber, drying chamber, and cooling chamber. Slide doors manually operated to control grain movement.
- Time beans held - 21% held 20 to 25 minutes
25% held up to 60 minutes
- Capacity - 50 bushels in each chamber
- Percent cracks - negligible cracking occurs with correct drier operation; attempting to speed up drying by using higher steam pressures to produce higher air temperature results in cracking several percent of the beans.

Schanzer Grain Drier. This drier is operated as a continuous drier. The unit has a drying and a cooling section and heat is supplied by an oil burner. The products of combustion of the fuel oil are forced through the grain by a centrifugal blower and a second fan supplies air to the cooling section. A smaller burner is used for drying beans than is used for drying other crops. The movement of the grain through the drier is controlled by varying the speed of the auger which removes the grain from the bottom of the drying column. Door dampers separate the heating and cooling sections. No preheating is done with the moist warm air. The information recorded on the operation of the Schanzer drier is as follows:

- Temperature of heated air - 115°F.
- Drier operated as - continuous drier
- Time required - 21% beans require 30 to 60 minutes to dry down to 16% moisture content
- Capacity - 400 bushels per hour maximum
- Percent cracks - Operated to give negligible cracking
- Fuel rate - 3 gallons per hour maximum

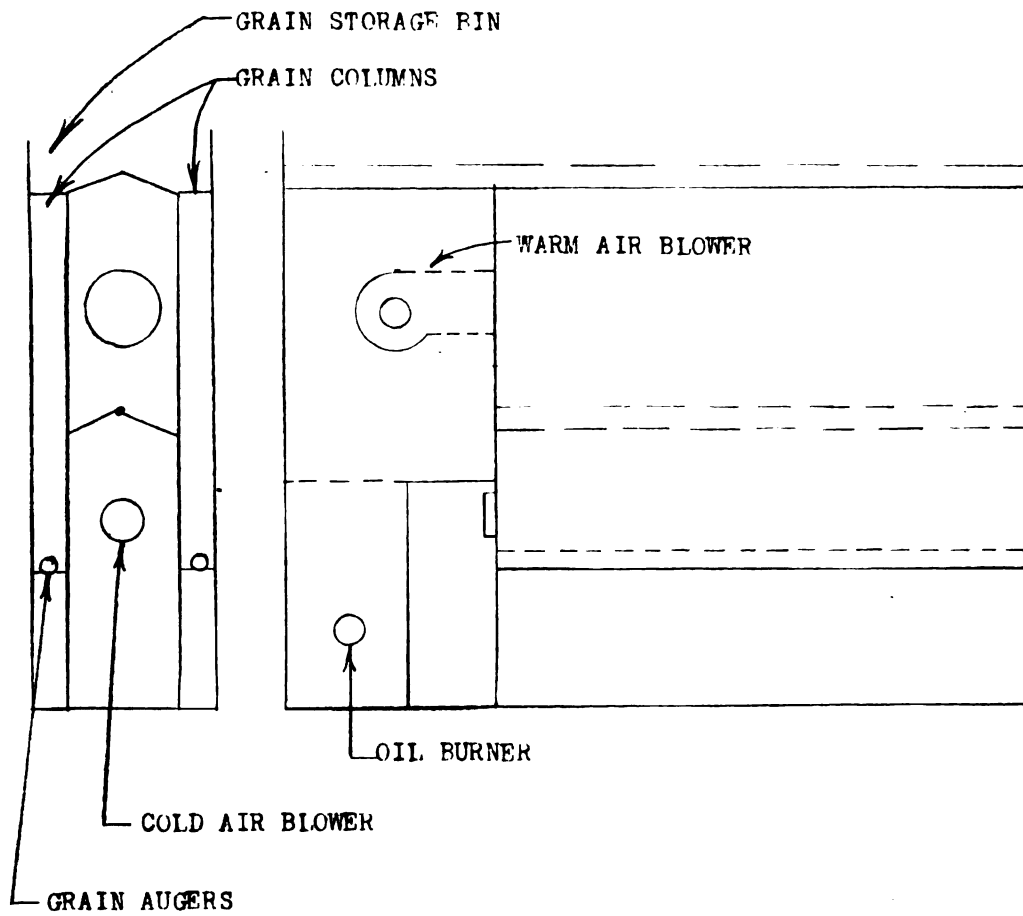


FIG. 3. SCHANZER GRAIN DRIER

Arid-Aire Drier. This drier is operated as a continuous drier.

The unit has a heating and a cooling section with the products of combustion being forced through the grain by a centrifugal blower. A second blower supplies the cooling air. An oil burner supplies the heat. A smaller burner is used for drying beans than is used for drying other crops. The grain is carried through the drier on a horizontal belt. A fire wall separates the heating and cooling chambers. No preheating of the grain takes place although the operator of this drying unit suggested preheating of the beans as a method to reduce the cracking occurring in this unit. The information recorded on the operation of the Arid-Aire Drier is as follows:

Temperature of the drying air - 150°F.

Drier operated as - continuous drier with beans 4 inches deep on belt

Time required - 4% moisture removal requires 18 to 21 minutes, 12 to 15 minutes in heating section and 6 minutes in cooling section. Two runs are made on high moisture beans.

Capacity - 75 to 80 bushel per hour removing 4% of moisture

Percent cracks - up to 12% with splits occurring when beans first come into contact with the heated belt. Percentage of cracks becomes greater as moisture goes below 18%.

Fuel rate - 6 gallons in 10 hours

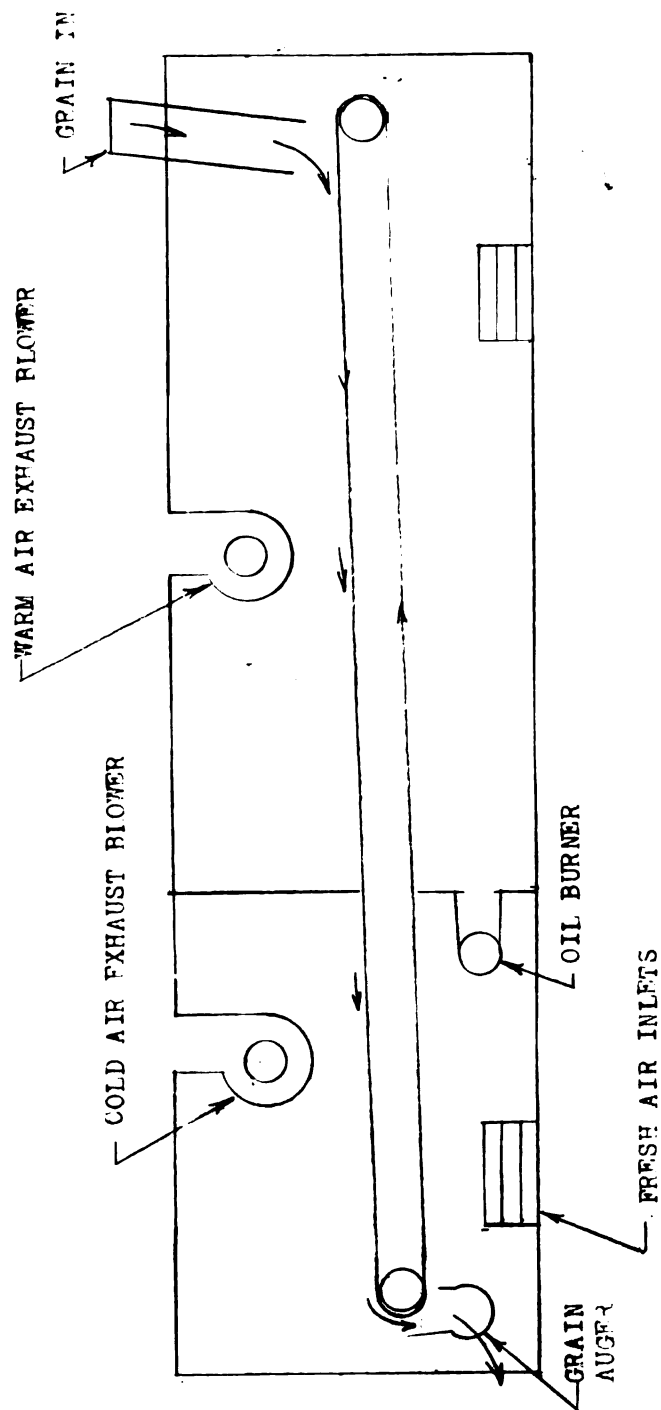


FIG. 4. ARID-AIRE (CONTINUOUS) GRAIN DRIER

EXPERIMENTAL APPARATUS AND EQUIPMENT

Three separate sets of tests were run during the time the experimental work was being done. Different equipment was used in each series of tests and will be discussed separately.

Field Unit Using Recirculated Air

A portable field unit made up of a drying bin, burner and blower, owned by the Production Marketing Administration, was made available to the Agricultural Engineering Department in the fall of 1951 to conduct research tests on drying pea beans. This unit was made up of the two trailers shown in Figure 5.



Fig. 5. Portable Drying Unit

The two-wheeled trailer on the left houses the oil burner, centrifugal blower, and a generator which was not used in these tests. The blower was driven by a stationary engine. The four-wheeled trailer to the right of the picture is the drying bin and was connected to the heater and blower unit by metal ducts.

A thermostat with an operating range from 100° to 125°F. is located in the hot air stream and controls the oil supply to the burner. Relay type controls are used to guard against ignition failure and overheating. An American centrifugal blower, series 550 E, furnished approximately 8000 cubic feet of air per minute to the drying bin during the tests.

The bin had an inside floor area of 7 feet by 10 feet and was designed to hold about 3 feet of beans or approximately 150 bushels. The floor was made of perforated steel sheet with a small flight conveyor running the length of the bin. There was about one foot of air chamber space under the entire floor. The drying bin was completely enclosed, with two air-tight doors provided, so that air could be recirculated.³

Five tests were run using this equipment, three using recirculation of a part of the drying air and two without recirculation. Recirculation was controlled by manual operation of the dampers shown on the upper return duct in Figure 6. Air flow was computed using the duct area and air velocity as determined with a vane-type velocity meter (anemometer). An indicating hair hygrometer and a wet-and-dry bulb thermometer was used to determine the humidity of the air.

³ A more complete explanation of this equipment is given in a research report by C. W. Hall (13). Several changes were made in the drying unit by Agricultural Engineering technicians before the unit was used in the drying tests. The technicians also assisted in running tests on the equipment to determine operating characteristics and operating procedures for the equipment before it was used in the drying of the pea beans.

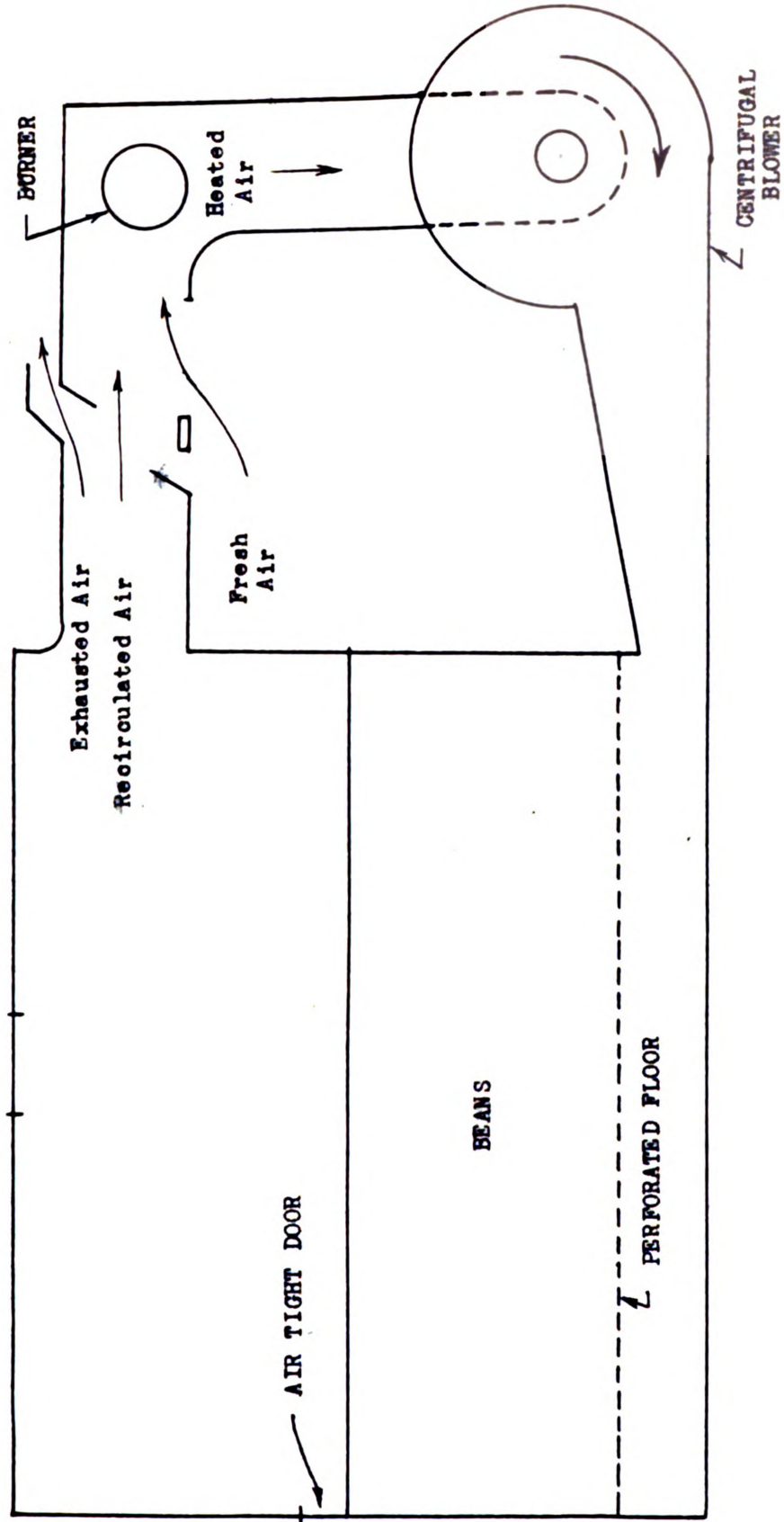


FIG. 6. ARRANGEMENT OF DRYING BIN, DUCT, AIR CHAMBERS, BURNER AND BLOWER

A standard grain sampler shown in Figure 7 was used to take the samples every 30 minutes. This sampler permitted getting a sample from different depths. The bean samples were weighed, percentage of cracks determined and recorded, then the samples were oven dried to determine the moisture content (wet basis).

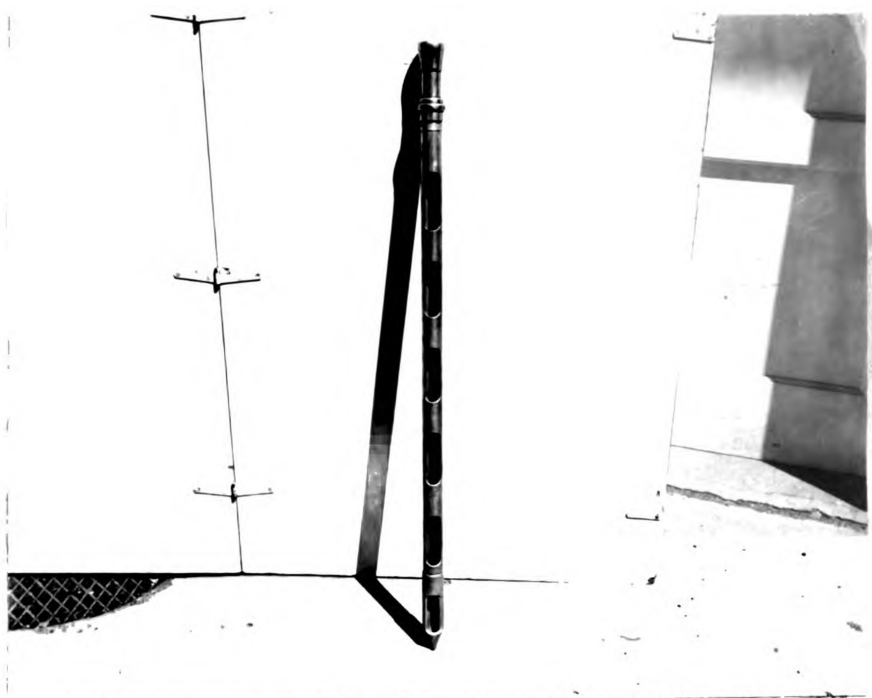


Fig. 7. Grain Sampler Used to Take Bean Samples

Laboratory Drying Unit for Controlled Recirculation

The use of the large portable drying unit to run a number of tests was not desirable because of the quantity of pea beans that had to be handled, and because a high air flow had to be maintained or the oil burner would not operate correctly, so a laboratory unit was designed and built in August 1952.

The laboratory unit shown in Figure 8 was made up of a drying bin, heating section, small centrifugal blower, galvanized vent pipe, and orifice plates. The control equipment shown on the table in the left side of Figure 8 was connected to the heater section to provide temperature control. A schematic diagram of the drying unit is shown in Figure 9.

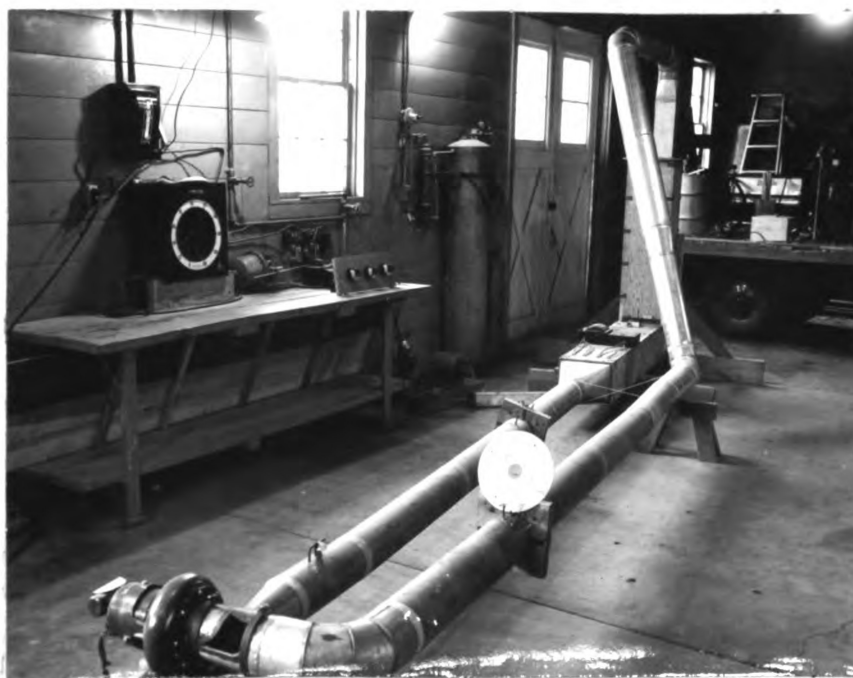


Fig. 8. Laboratory Drying Unit for Controlled Recirculation

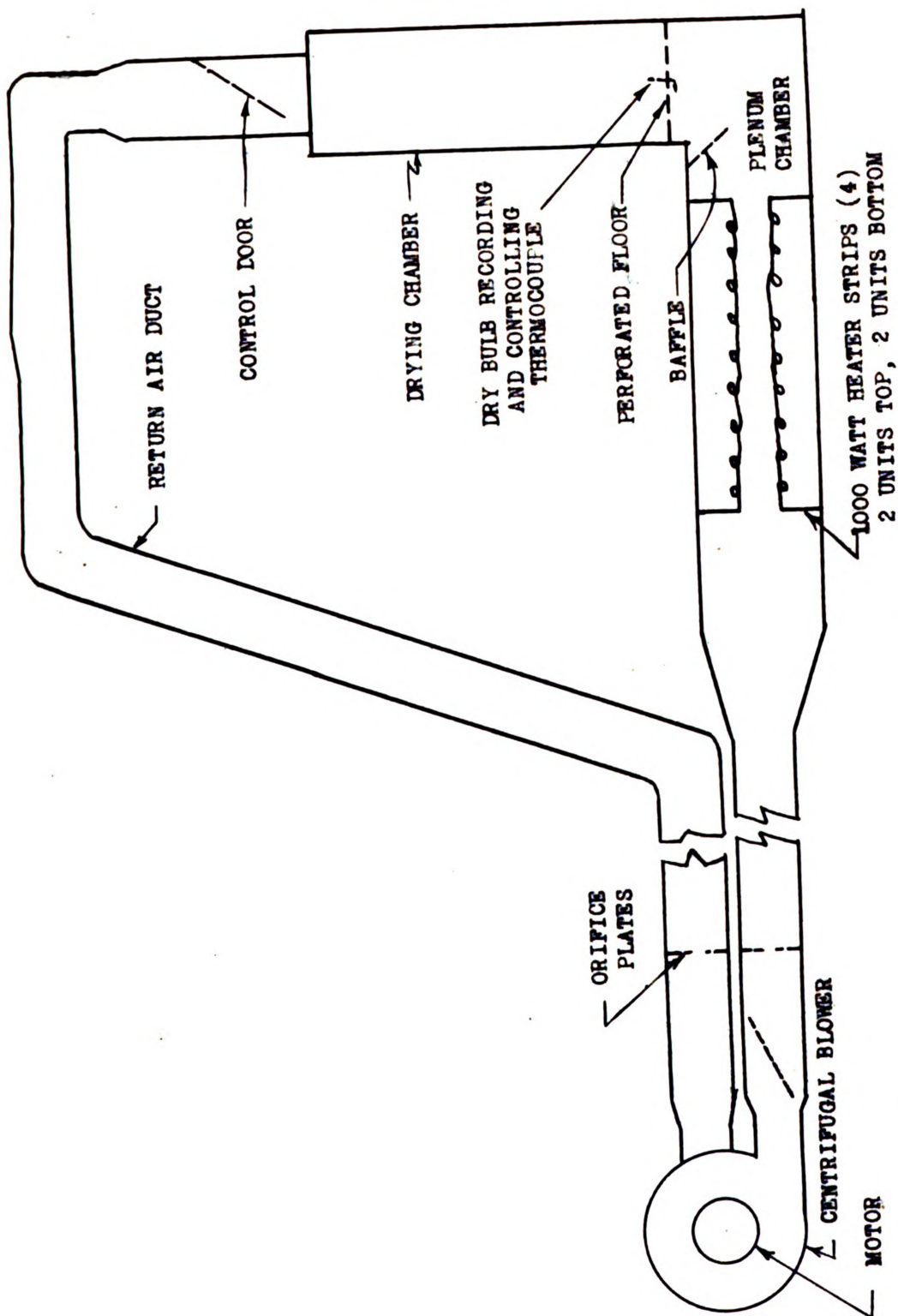


FIG. 9. LABORATORY DRYING UNIT FOR CONTROLLED RECIRCULATION

The drying bin was one foot square on the inside and made of plywood. The bin section, Figure 10, was three and one-half feet deep but only two feet of pea beans were used in the drying tests run with this unit. The second section of the drying bin sitting on the floor in Figure 10, was three feet deep and bolted to the lower section when placed on top. The upper section was used in determining the static pressure required to force air at various rates of flow through pea beans up to seven feet deep. A perforated floor made of thin steel supported the beans and allowed air to move up through them. A thermocouple used to record dry-bulb temperatures and to supply the voltage potential to the control equipment was located in the center

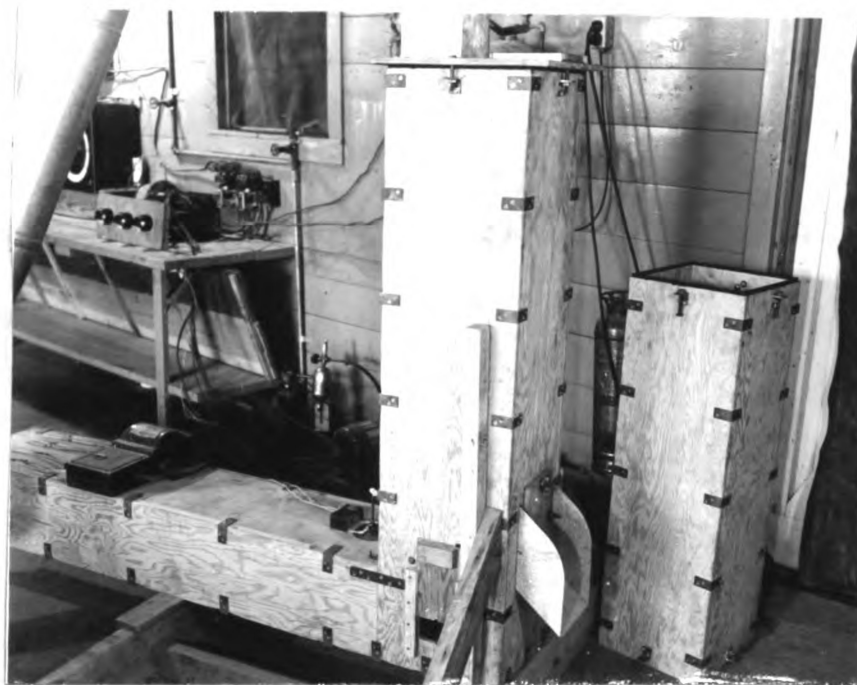


Fig. 10. Drying Bin and Heater Section

of the drying bin two inches above the perforated floor. The beans were emptied from the lower bin section through the door shown in Figure 10.

Bean samples were taken at first with the sampler shown in Figure 7. The sampler was inserted through a slide door opening in the bin cover. For the second series of tests using this unit, a tube sampler was developed that could be inserted through a small opening cover by a slide door on the side of the bin. This opening was two inches above the perforated floor and located on the side of the drying bin next to the wall as it is shown in Figure 10. The tube sampler is shown in Figure 17.

Four 1000 watt strip heaters were mounted in the heater section shown in the lower left side of Figure 10. The units were 1 inch wide, $\frac{1}{4}$ inch thick, and 30 inches long and were mounted approximately four inches from the plywood walls. In order to give maximum flexibility to the control unit two of the heater strips were wired in parallel and two heater strips were wired individually to the control mechanism. Fuse protection was provided to the strip heaters in the switch boxes shown on the top of the heater section.

An 11 $\frac{1}{2}$ blower, series 7 $\frac{1}{2}$ HP, driven with a $\frac{1}{4}$ horsepower motor, was used to supply the air for drying. The amount of air supplied for drying was controlled by the position of a slide cover over the intake of the blower and by a damper in the pipe ahead of the outlet of the blower. Both the slide cover and the damper can be seen in Figures 8 and 11.

Six inch galvanized vent pipe was used for air ducts. The joints were covered with masking tape to prevent air leakage.

The air was measured using orifices made from thin plates and a well-type manometer. An orifice plate with center orifice is shown on the duct in Figure 8. The multi-range, differential, well-type manometer connected to vena contracta taps on either side of an orifice in the return air duct is shown in Figure 11. The percent of recirculated air was adjusted by measuring the air flow through the supply and return ducts of the drying unit.

The formula for determining the pressure differential for various air flows and the location of the vena contracta taps is given by Severns and Degler (14). Curves developed by Brandt (15, 16) for thin plate orifices of one inch, two inch, and three inch diameters on associated research work on the drying of pea beans were used. These curves show the differential static pressures for various air flows.



Fig. 11. Measuring Air Flow in Return Duct

Drying Unit for Controlled Humidity

Several problems encountered in recirculating the air in the laboratory unit pointed to the fact that it might be more satisfactory for practical application to control the humidity of the air with the use of steam, than to build up the humidity of the air by partial recirculation.

At the higher percentages of recirculation, it was difficult to prevent air leakage into the return duct to the fan. Extra labor was required to remove the return duct each time a new batch of beans were put into the drying bin. Seals on the pipe joints were broken and the system had to be resealed for each test. It was also difficult to measure accurately the percentage of recirculated air. Few of the commercial drying systems in use today or even new commercial units lend themselves to recirculation without major rebuilding to collect and return the drying air as it discharges from the beans and it would be difficult to determine the percentage of recirculation.

Using an air duct that was previously constructed for use on a hay drying research project, a unit was built up that permitted controlling the humidity of the drying air by introducing steam into the air duct. This unit consisted of a drying bin, a single duct, having a heating section and a steam section, and a centrifugal blower. The heaters were connected to the same control equipment used with the laboratory drying unit for controlled recirculation. A thermocouple connected to the control equipment served as the dry-bulb thermometer and a mercury thermometer with a wick was used for the wet-bulb thermometer. Figure 12 shows a schematic drawing of the unit, and Figure 13 shows the unit assembled in the laboratory.

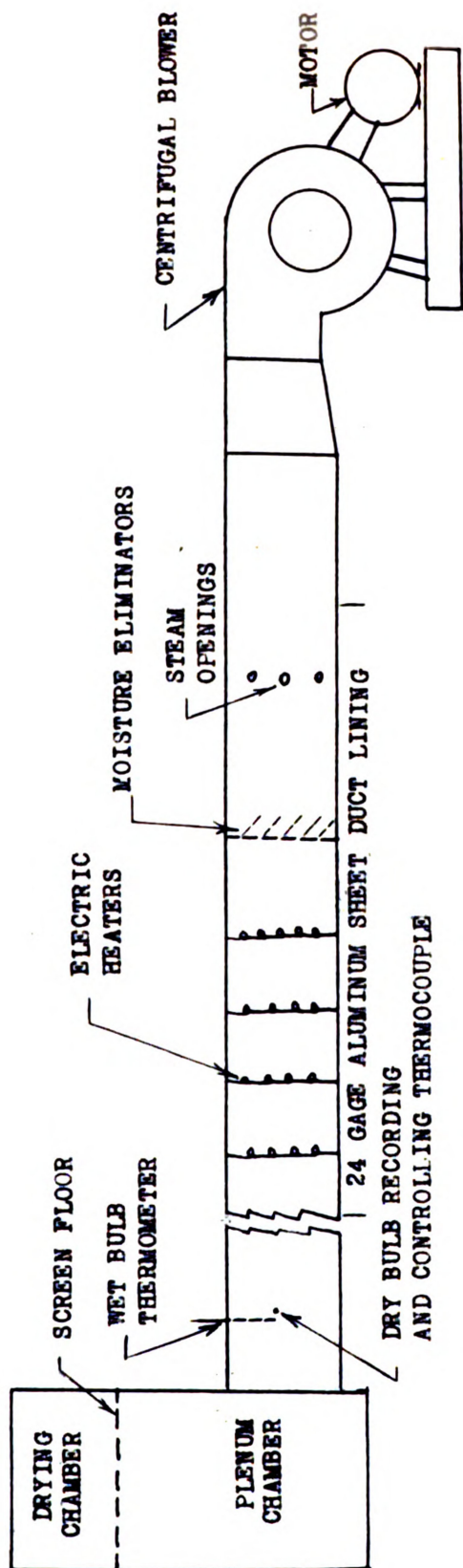


FIG. 12. LABORATORY DRYING UNIT FOR CONTROLLED HUMIDITY

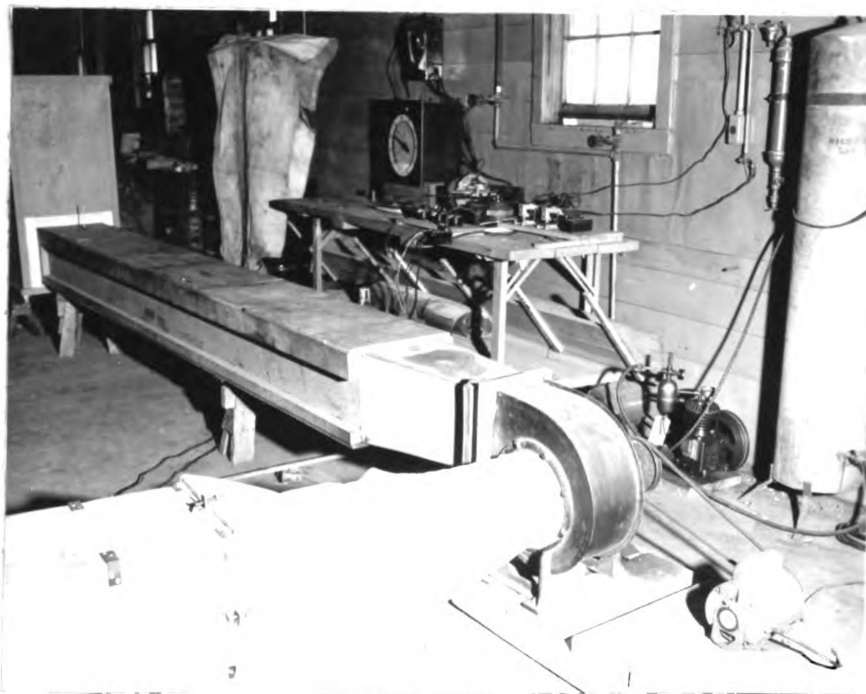


Fig. 13. Drying Unit for Controlled Humidity

The drying bin was two feet square and had a floor made of hardware cloth covered with door screen. All samples dried in this bin were one foot deep. A door was provided on the back side of the bin for removing the beans after a drying run.

Nichrome wire was used in the heating section of the duct shown in Figure 14. Four sections of wire were connected to the control equipment. The heater section from the recirculating unit was fastened to the fan intake, Figure 13, and used as an air preheater for two of the tests run with the unit.

Steam was introduced into the air duct through $\frac{1}{8}$ inch holes in a section of $\frac{1}{2}$ inch pipe. For the first two tests using this unit a small copper tube perforated with a number of small holes was used but the small tube did not supply sufficient steam for a higher temperature so it was

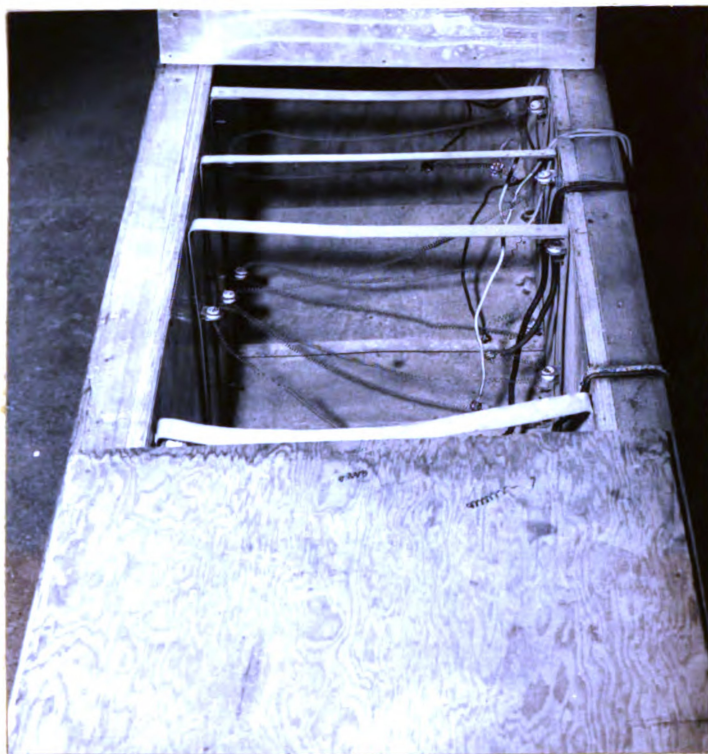


Fig. 14. Heater Section of the Humidity Controlled Unit

replaced with the $\frac{1}{2}$ inch pipe. A steam by-pass was provided and manual control was used to adjust the amount of steam allowed to escape into the air duct. Figure 15 shows the steam entering the air duct. Baffles in the air duct removed most of the free water droplets from the air stream.

A Clarage centrifugal blower driven by a one-half horsepower electric motor provided the drying air. The rate of air flow was regulated first by partially covering the opening into the fan, and then by a damper in the pipe ahead of the air preheating section.

The relative humidity of the air used in the tests was determined in the air duct just before the air entered the plenum chamber of the drying



Fig. 15. Steam Entering the Air Duct

bin. The thermocouple and the recording thermometer of the control equipment served as the dry-bulb thermometer and a mercury thermometer with a wetted wick served as the wet-bulb thermometer. Using the wet-and-dry bulb readings obtained, the relative humidity was read from a psychrometric chart. Figure 16 shows the thermocouple and thermometer in the air duct.

Bean samples were taken with a tube sampler as shown in Figure 17. The sampler entered the bin two inches above the screen floor.

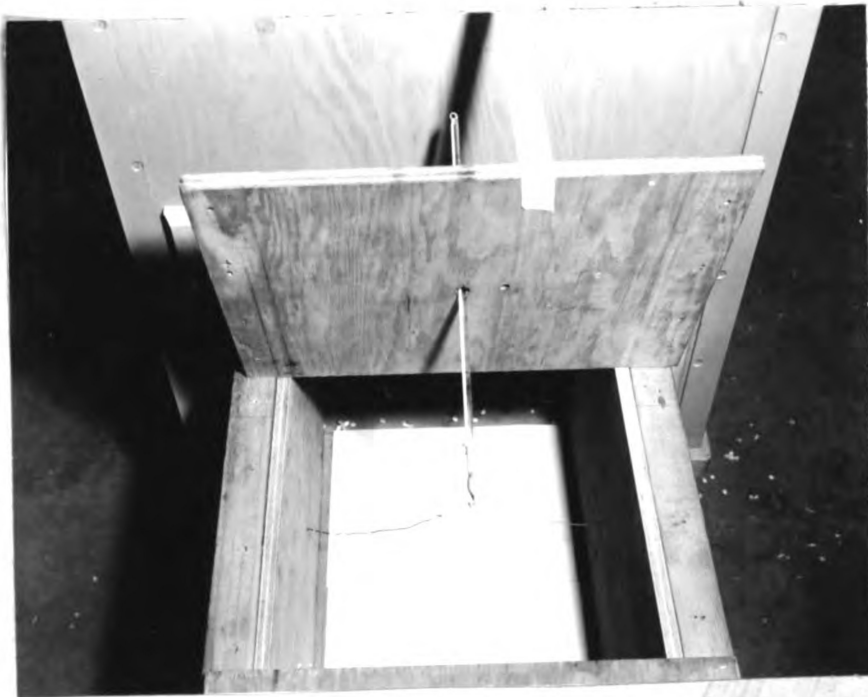


Fig. 16. Thermocouple and Thermometer Used
for Determining Relative Humidity

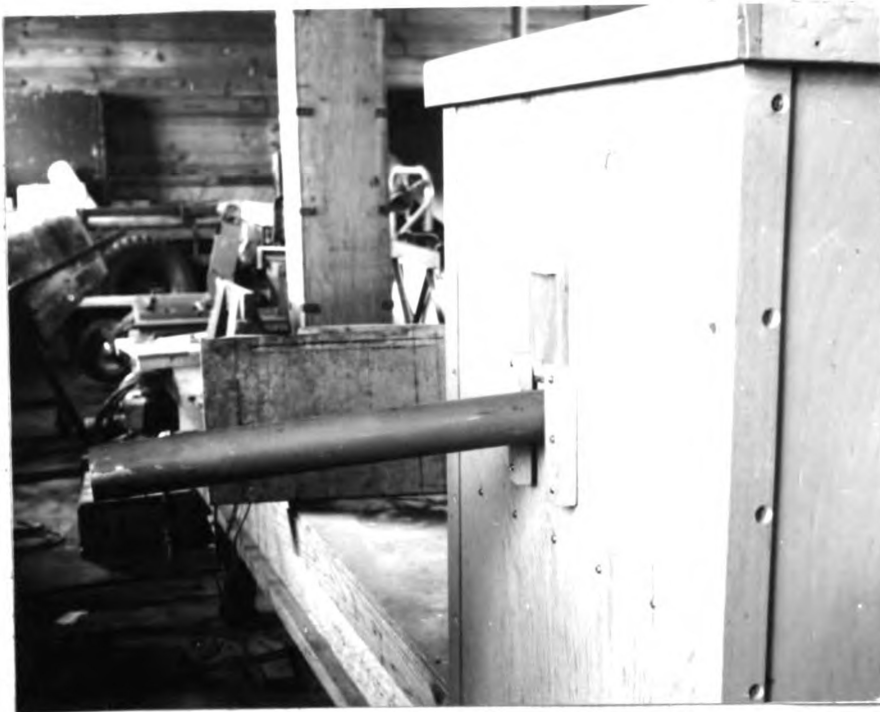


Fig. 17. Obtaining Sample with Tube Sampler

Temperature Control Equipment

Temperature control for laboratory units was provided by a Brown Air-O-Line Controller and associated equipment shown in Figure 18.

The Controller is designed for use in industrial applications to maintain desired temperature in continuously flowing liquids or gases. The unit was adapted for use on a hay drying research project by previous workers. A certain amount of experimenting and some minor repair was necessary to adapt the unit as the temperature control device for drying tests on pea beans.

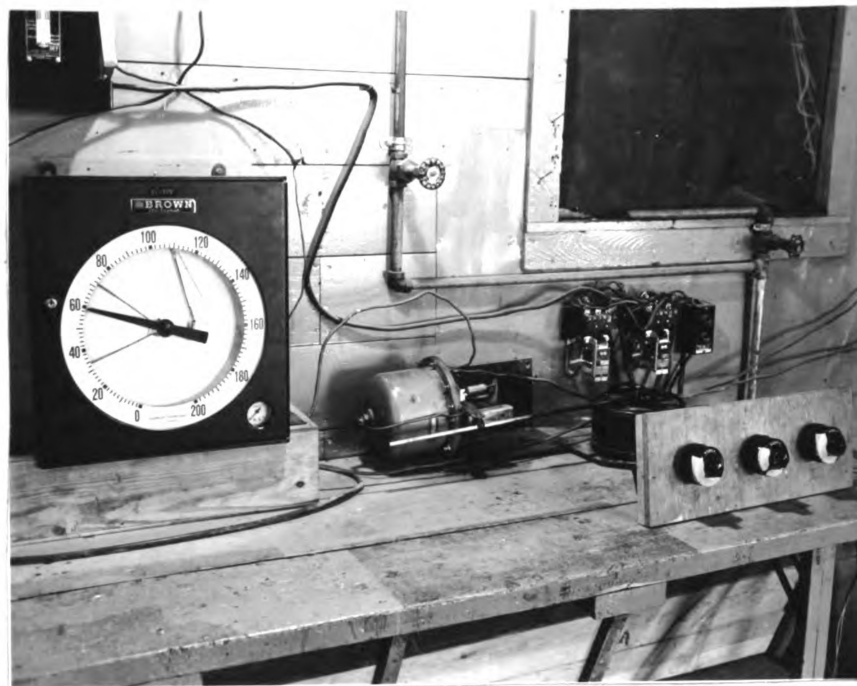


Fig. 18. Brown Air-O-Line Controller, Grad-U-Motor, Variac, and Magnetic Switches

A block diagram showing the Brown Air-O-Line Controller and the associated equipment is shown in Figure 19.

The detecting and balancing system of the Brown continuous balancing system is a pyrometer measuring circuit connected to the Brown continuous balance unit. The pyrometer circuit is made up of a thermocouple, slidewire resistance and battery. The continuous balance system is made up of a converter, which changes the unbalance in the D. C. circuit (pyrometer) to a proportional A. C. voltage, transformer, voltage amplifier, power amplifier, and balancing motor. The slidewire connector, pen, and pointer are linked directly to the balancing motor so that a continuous balance is maintained. An unbalance in the pyrometer circuit caused by a difference in voltage across the thermocouple and slidewire resistance is detected and amplified by the continuous balance system actuating the balancing motor and causing movement of the slidewire connector, pen and pointer.

The control index setting mechanism provides a connection between the measuring element (continuous balance system) and Air-O-Line control unit through mechanical linkages. The linkage is so designed that a movement of the pen with respect to the control index will rotate the actuating lever of the Air-O-Line control unit. When the pen and control-index are superimposed the actuating lever remains in a fixed position regardless of the setting of the control index.

The movement of the actuating lever is transmitted to bellows in Air-O-Line control unit and amplified by the bellows. The action of the bellows exerts pressure on air in the line to the Grad-U-Motor and controls the positioning of the diaphragm of Grad-U-Motor.

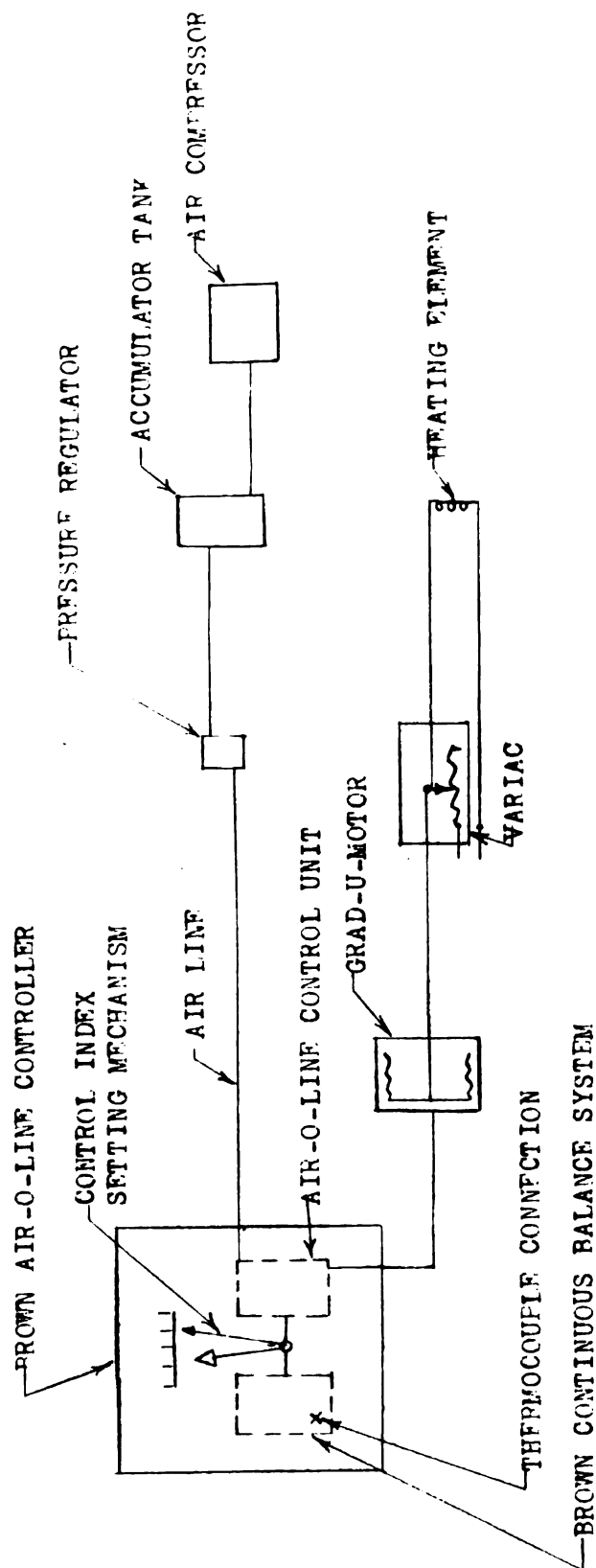


FIG. 19. BLOCK DIAGRAM OF BROWN AIR-O-LINE CONTROLLER
AND ASSOCIATED EQUIPMENT

The diaphragm of the Grad-U-Motor is linked to an extending arm causing a linear motion of this arm, which is welded to the gear assembly of a Variac. Linear motion of the Grad-U-Motor arm causes a rotation of the Variac gear assembly and brush connector of the Variac.

The Variac is so connected to the line voltage that 115 volts are connected across the full winding on the line side. The voltage on the load side of the Variac varies from 60 to 115 volts depending on the position of the brushes. This variation of voltage across the heating element provides the desired temperature control as called for by the Air-O-Line Controller.

The air supply for the Air-O-Line Controller is provided by the air compressor through the accumulator tank and pressure regulator.

After some experience with the control mechanism, it was adjusted to give very close temperature control. The temperature was controlled within a plus or minus two degrees during several tests and within a plus or minus eight degrees for all the tests. The time during which the temperature of the drying air was greater or less than the selected temperature was in the order of two to four minutes. Both the amplitude and frequency of the cycling of the control mechanism was adjustable. The temperature given in each test in Appendix III is the average temperature for that test as read from the continuous recording temperature chart.

METHODS OF TESTING MOISTURE

The pea bean samples collected in the tests using the portable field unit, and in the series of tests using the laboratory unit where the beans were rewet in the laboratory, were oven-dried to determine the moisture content. A Steinlite Moisture Tester was used to give a quick check on moisture content for the first series of tests made using the laboratory unit for controlled recirculation. In October 1952 a Tag-Heppenstall Grain Moisture Meter was purchased by the Agricultural Engineering Department. The moisture determination on all test samples after October 1952 was made by using the Tag-Heppenstall Meter. This included the series of tests run in both laboratory units using field harvested high moisture beans.

The procedure outlined in a leaflet published by the United States Department of Agriculture was followed in drying the bean samples in the oven. This leaflet is headed: United States Department of Agriculture, Agricultural Marketing Service, Service and Regulatory Announcements No. 147. The bean samples were placed in the oven for 72 hours, weighed and returned to the oven for 24 hours. At the end of 96 hours the beans were weighed again. If the weight loss was greater than 0.1 percent moisture the samples were returned to the oven for another 24 hours and weighed the third time. The oven was set at a temperature of 212°F.

The Steinlite Moisture Tester was borrowed from the Farm Crops Department of Michigan State College. This tester was used primarily to give a quick check on the moisture content of the bean samples, so that the progress of drying could be determined. It was found that the Steinlite tests, when carefully made, gave moisture contents very close to the oven determination when like samples were used. The Steinlite determination was less accurate when the moisture content of the sample was below 18%. The Steinlite Moisture Tester is an electric tester that measures the resistance to an electric current as it passes through the sample. The sample is not crushed or put under pressure. A uniform sample by weight is used.

The Tag-Heppenstall Moisture Tester, Figure 20, is the only rapid electric moisture tester approved for use by the United States Department of Agriculture for beans. This tester is made up of two corrugated rolls driven by a 1/3 horsepower motor, and a high resistance ohm meter. The material is crushed as it passes between the rolls insuring good contact between the particles of the material being tested for moisture. The ohm meter measures the resistance to flow of an electric current between the corrugated rolls. Charts for each grain furnished by the manufacturer were used to convert the meter readings into moisture percentages.

Hlynka and others (17) found the Tag-Heppenstall Moisture Tester to be the most accurate of ten meters tested. Hlynka also reported the Tag-Heppenstall Tester to be the most accurate in tests made previous to 1949.

The author realizes that some error will occur in determining the moisture content of rapidly dried samples without allowing sufficient



Fig. 20. Tag-Heppenstall Moisture Tester

time for moisture equalization within the beans. A number of samples of pea beans were oven-dried, and it was found that the moisture contents as determined by the Tag-Heppenstall Tester were generally within 0.3% of the oven-dried samples. For some samples the moisture of the oven-dried samples was higher than the moisture determination of the Tag-Heppenstall Tester and for some samples the oven-dried samples showed a lower moisture content. Since the problem of drying pea beans is primarily one of preventing cracking, which was accurately determined, the author feels that the moisture determinations made during the drying tests were of sufficient accuracy.

STATIC PRESSURE DETERMINATION

The static pressure developed in pea beans to the resistance of forced air flow through the beans was not available in the literature. Although static pressure determinations were not necessary for the work conducted on this thesis problem, it was felt that static pressure determinations should be available as a basis for selecting fans for the drying of pea beans, so determinations were made using the laboratory unit for controlled recirculation.

The air flow through the pea beans was measured using the thin orifice plate and the differential well-type manometer shown in Figure 11. A static pressure tap was located in the plenum chamber of the drying unit and the static pressure determined for various air flows within the limits of the fan and motor. The static pressure was measured as beans were added to the bin to a depth of six feet, and as beans were removed from the bin. Tests were repeated several times and the average reading of static pressures for the various air flows at various bean depths were used to plot the curves in Figure 21. The beans used in the tests were below 18% moisture content.

Figure 21 shows the static pressure developed for different air flows through beans from one foot to six feet in depth.

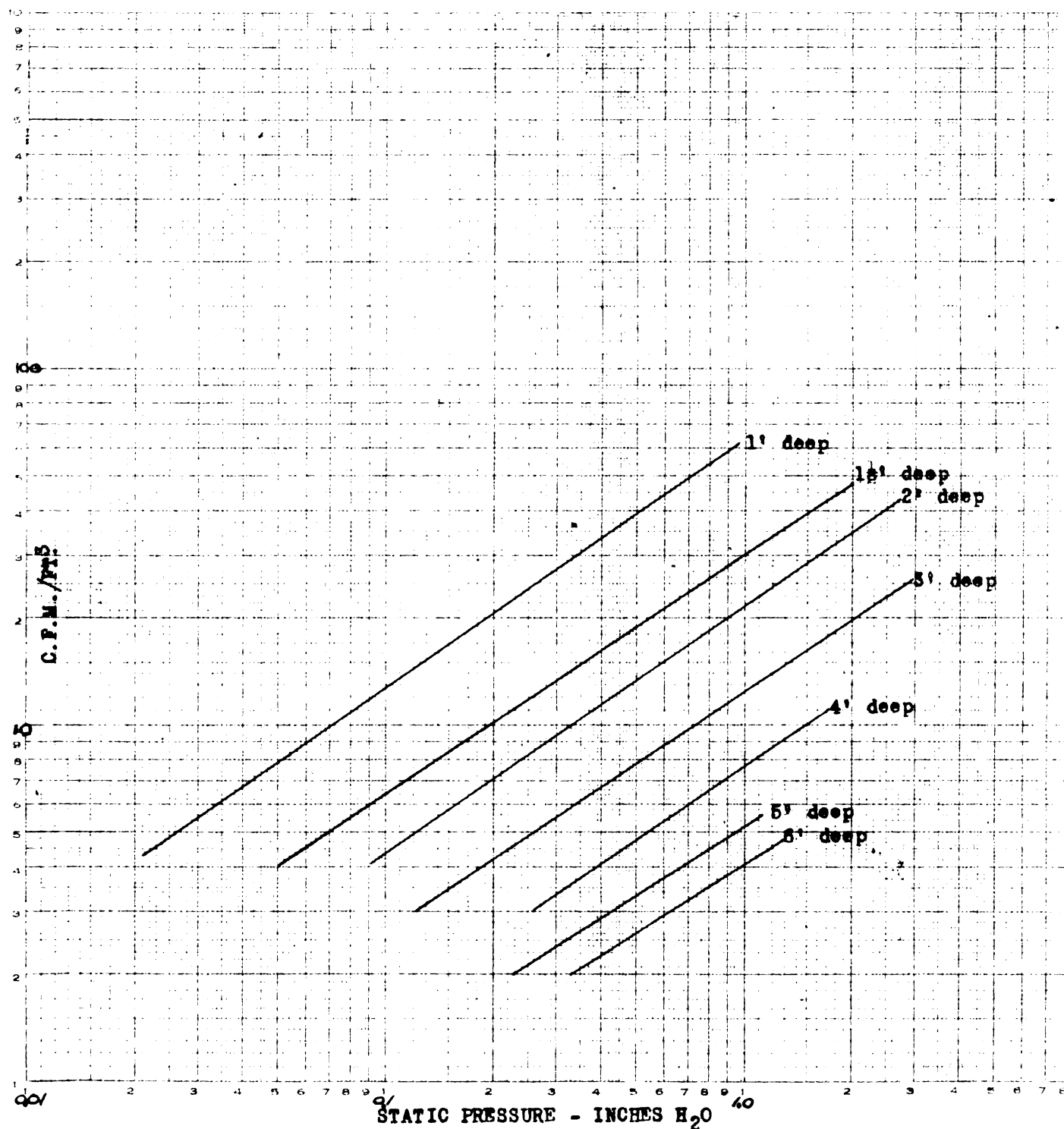


FIG. 21. AIR FLOW THROUGH CLEAN, DRY PEA BEANS

PRESENTATION AND ANALYSIS OF DATA

Drying Tests with Field Unit

To determine the feasibility of drying beans by recirculation of moist air five drying tests were run using the portable field unit, Figure 1. Table II lists the conditions of the five tests.

TABLE II
DRYING TESTS RUN WITH PORTABLE FIELD DRYING UNIT

Test No.	Initial ^a Moisture	Final ^a Moisture	Air Temp.	Air Flow c.f.m./ft ³	Percent Re-circulation	Percent Cracks
1	20.0	13.2	102°F.	60	0	18 bottom 12 top
2	24.92	15.8	100°F.	100	50	1.75
3	22.6	16.0	100°F.	100	75	1.25
4	22.4	16.6	98°F.	100	25	2.5
5	22.0	18.0	99°F.	100	0 ^b	5 bottom 1 top

^aAll moisture contents determined on 'wet basis'.

^bTurner on $\frac{1}{2}$ hour, off $\frac{1}{2}$ hour.

These tests showed that the recirculation of the moist air reduced the amount of cracking with the least cracking occurring when the highest percentage of air was recirculated. The time required to remove a percent of moisture from the beans increased as the percent of recirculation increased. This is in accord with Kelly (4), Fenton (7), and Barre (9) in their discussion of vapor pressure in relation to drying. Maintaining high vapor pressure in the drying air by recirculation slows the evapora-

tion of the surface moisture from the bean and warming the beans causes a more rapid transfer of moisture from inside of the bean to the outside. The slow surface drying prevents rapid shrinking of the skin coat and reduces the cracking.

The layering effect as previously discussed by the author was particularly apparent in the first drying test. The moisture content of samples taken approximately six inches from the bottom of the bin approached the final moisture content before there was much reduction in the bean samples from the top of the bin or approximately twenty inches from the bin floor. It was also noted that the temperature near the bottom of the bin increased rapidly until the temperature of the incoming heated air was reached while temperatures in the top layer of the beans increased very slowly.

As the temperature in the top layer of beans increased the relative humidity of the air leaving the bin became less, and the temperature of the air increased. This relation of temperature and relative humidity is in accord with Hukill's (8) discussion on the rate of evaporation of moisture in relation to the dry-bulb temperatures of the drying air.

In the tests made with no recirculation, more cracking occurred in the bottom layer of beans than in the top layer, while in the three tests made where recirculation took place there was no noticeable difference between the cracking in the bottom and top layers. This was apparently due to the rate at which the beans gave up their moisture to the drying air resulting in a more even drying throughout the depth of the beans. As the vapor pressure differences between the beans and the drying air were less where moist air was recirculated, there was a slower diffusion of moisture from the beans to the drying air. This resulted in a more

uniform absorption of moisture from the beans throughout the depth of the beans, and a reduction of cracking. Curves showing the percent of cracking vs. drying time, temperature of the bean layers vs. drying time, and the humidity of the air leaving the drying bin vs. drying time are included in Appendix I. These curves, drawn from the data recorded in the drying tests listed in Table II, were prepared and included in the Research Project Report for 1951 (13).

Drying Tests Using Laboratory Unit for Controlled Recirculation

Two series of tests were run using this unit. In the first series of tests dry pea beans (below 18% moisture) were raised in moisture content and then redried in the laboratory unit. The second series of tests were run using beans harvested at a high moisture content.

Bean Sample Rewet in Laboratory. The dry beans were spread out on trays to the depth of 1 to $1\frac{1}{2}$ inches. The trays were wood frame with hardware cloth supporting the beans. The trays were placed in an insulated box. Immersion heating elements placed in a small, open water tank maintained a temperature in this unit in the range of 105°F. to 115°F. with a relative humidity above 90% providing a high vapor pressure in the chamber. Beans placed in the chamber for 4 to 6 hours reached moisture contents as high as 22% although most of the samples that were redried were between 20% and 21% moisture when taken from the insulated box.

A Steinlite Moisture Tester was used to give a quick check on the moisture content of the beans. Twelve tests, Numbers 6 through 17 in Table III, were run using the wetted beans. No recirculation was used in these tests, except Test No. 17, as it was desired to determine the effects of drying temperatures on cracking at varying rates of air flow.

TABLE III
PEA BEAN DRYING TESTS

Test No.	Temperature of Air -°F.	Air Flow c.f.m./ft. ³	Recirculation Percent	Rel. Humidity of Drying Air
1	100	60	0	
2	100	100	50	
3	100	100	75	
4	100	100	25	
5	100	100	0 ^a	
6	90	5	0	
7	105	5	0	
8	130	5	0	
9	90	20	0	
10	105	20	0	
11	130	20	0	
12	90	35	0	
13	105	35	0	
14	130	35	0	
15	150	5	0	
16	150	20	0	
17	150	20	33	
18	150	35	50	
19	120	35	50	
20	150	35	0	
21	170	35	50	
22	90	35	50	
23	150	35	75	
24	150	35	25	
25	150	15	33	
26	150	15	0	
27	100	10		50%
28	100	10		30%
29	140	10		40%
30	140	10		15%
31	160	10		40%

Tests 1 through 5 - Field Unit; Tests 6 through 16 - Laboratory Unit for Controlled Recirculation; Tests 27 through 31 - Laboratory Unit for Controlled Humidity.

^aHeat on $\frac{1}{2}$ hour, off $\frac{1}{2}$ hour.

Figure 22 shows the drying rate using an air flow of 5 c.f.m./ft.³ and temperatures of 90°, 105°, 130°, and 150°F. Figure 23 shows the drying rate using an air flow of 20 c.f.m./ft.³ and temperatures of 90°, 105°, 130°, and 150°F. Figure 24 shows the drying rate using an air flow of 35 c.f.m./ft.³ and 90°, 105°, and 130°F. The drying rate curves by themselves do not present a complete picture of the drying problem. The curve, Figure 22, showing the drying rate using an air flow of 5 c.f.m./ft.³ at 150°F. has a steep slope at the start of the drying but levels out rapidly. This may be the result of changes within the structure of the bean resulting in a 'case hardening' effect (11). Drying rate curves for oven-dried samples, Appendix II, have a fairly constant slope indicating a fairly constant drying rate from 25% moisture to below 15% moisture. Using the oven drying rate as a basis, all the curves in Figures 22, 23 and 24 show some effects of 'case hardening'.

Several beans from the samples taken during the drying tests were cut with a razor blade and examined with a magnifying glass to see if any physical differences in the cross-section of the bean could be determined that would indicate a hardened layer. As far as the author could see, there was no ring or layer of greater hardness in the bean cross-section. The bean cross-section had the same physical appearance regardless of the drying temperature used. No attempt was made to check the chemical structure of a bean cross-section.

More information on the drying process within the bean itself could be of great value in designing drying systems.

The curves in Figure 22 show a slower drying rate when drying air at 130°F. and 150°F. was used than when 90° or 105°F. air was used.

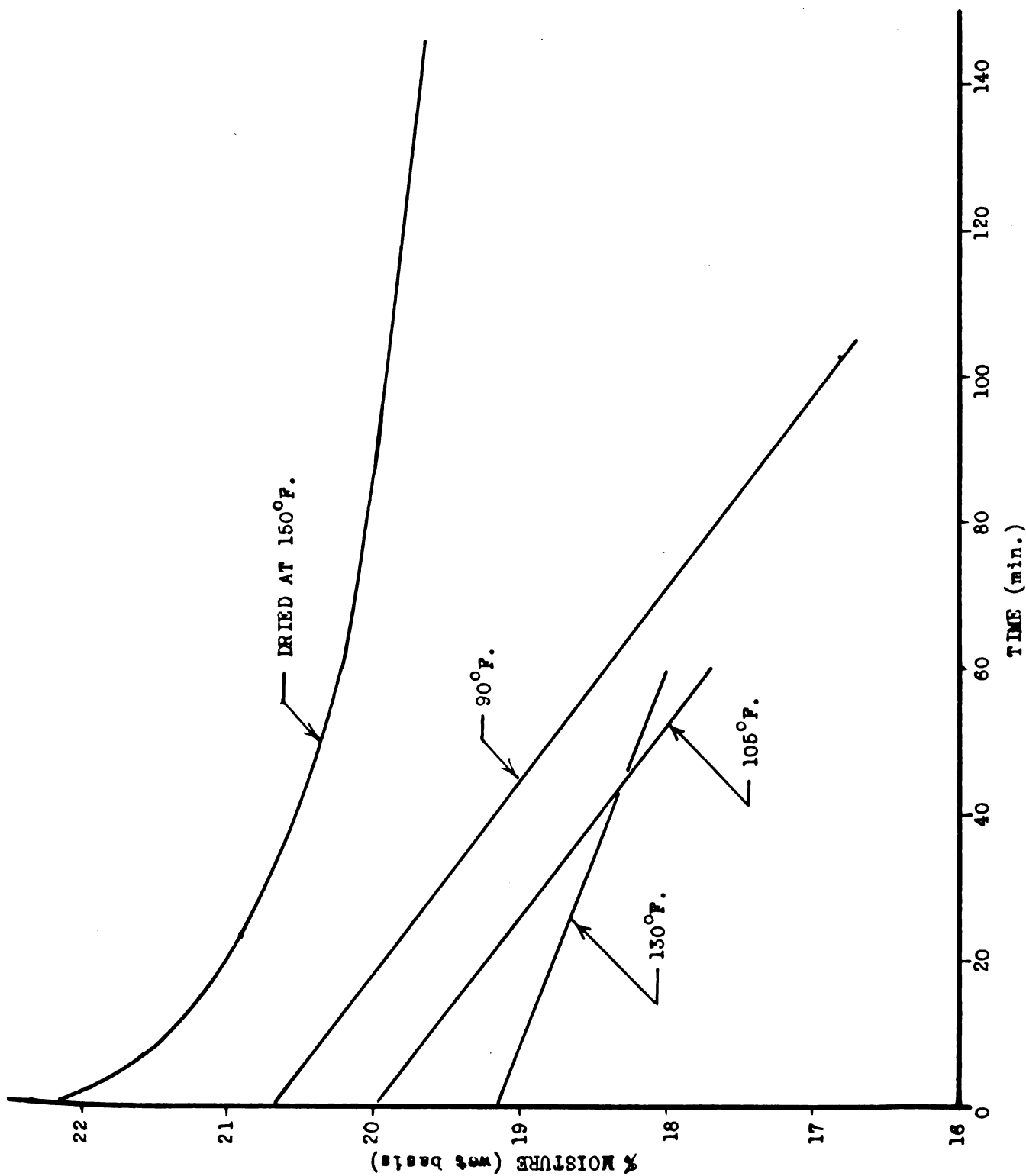


FIG. 22. DRYING RATE OF PEA BEANS (REWET) AT 5 C.F.M./FT³

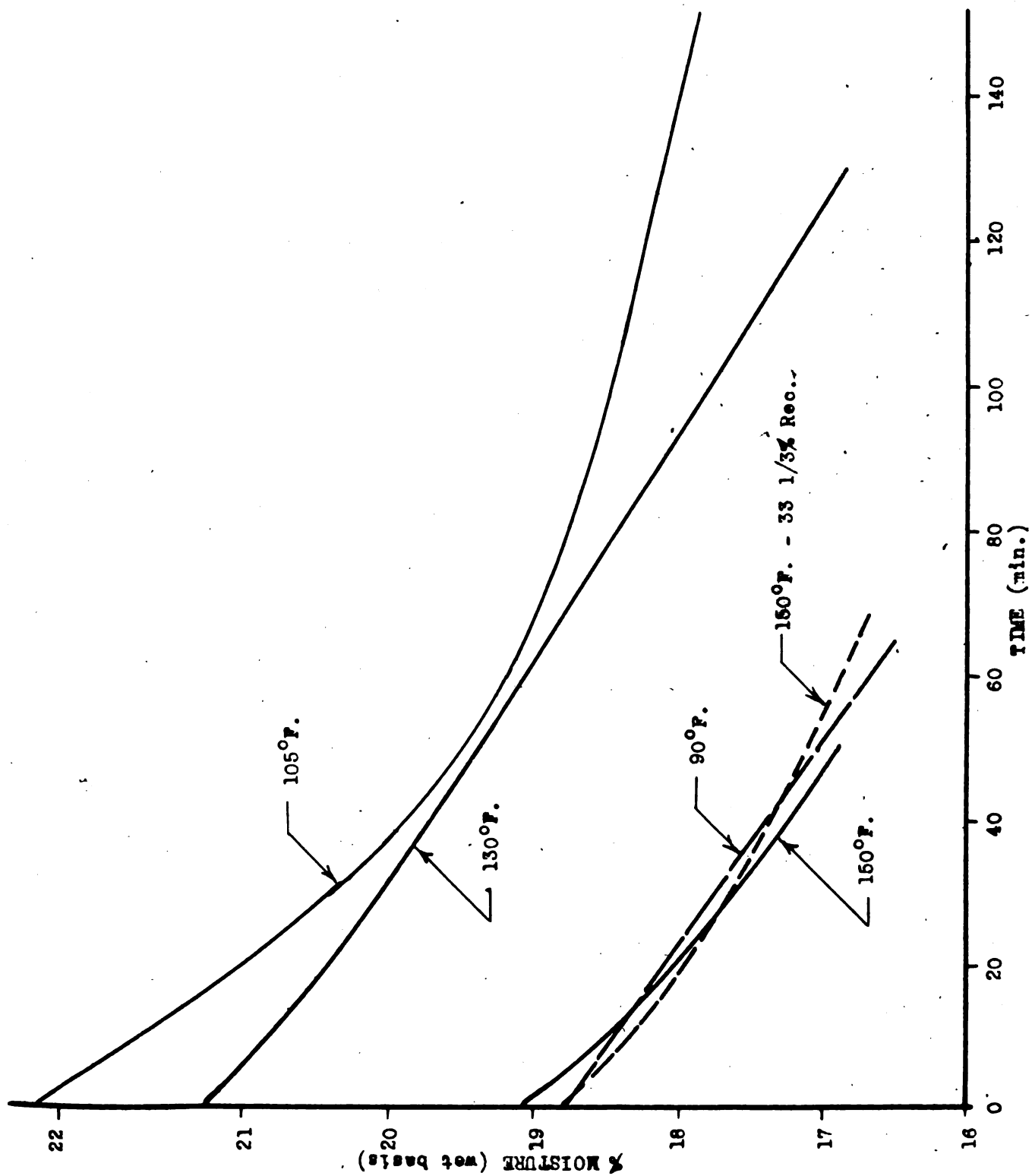


FIG. 23. DRYING RATE OF PEA BEANS (REWET) AT 20 C.F.M./FT. 3

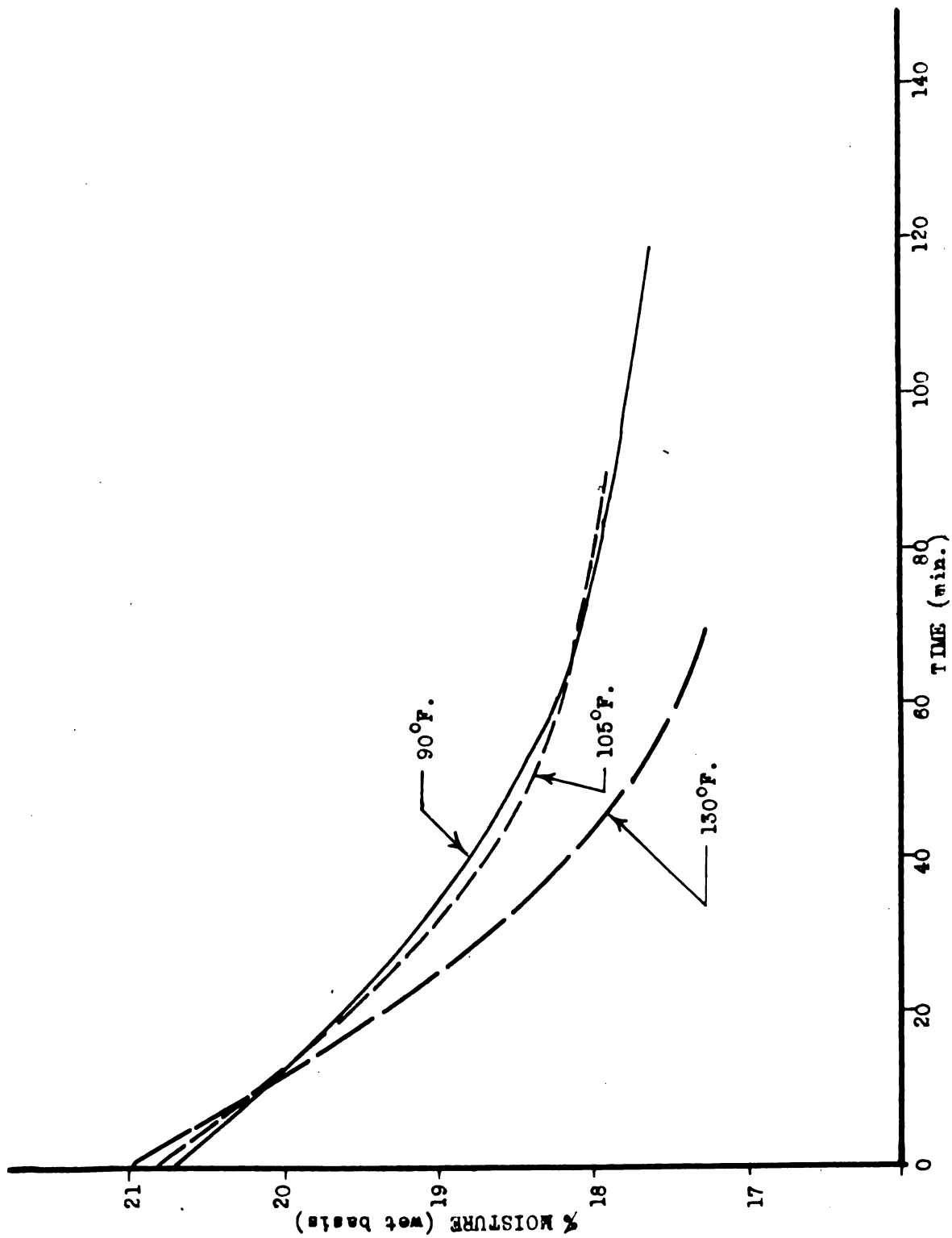


FIG. 24. DRYING RATE OF PEA BEANS (REWET) AT 35 C.F.M./FT.³

The curve for 150°F. in Figure 22 has a steep slope in the early stages of the drying period but flattens out rather quickly before the moisture content is down to 20 percent. The theory of 'case hardening' would explain this happening. Rapid evaporation of the surface moisture results in an internal change in the bean structure and even though the internal vapor pressure of the beans remains relatively high, the diffusion of moisture to the outside surface becomes very slow resulting in a slow drying rate.

In Figures 23 and 24 the curves show a flattening for the lower temperatures used. As the moisture is evaporated from the bean, the internal vapor pressure becomes less resulting in slower diffusion of moisture to the outside of the bean and a slower drying rate. Although the curves for 150° in Figure 22 and for 90° and 105° in Figure 24 have approximately the same shape, the flattening of the curves was for different reasons. Where the drying rate slows because of the 'case hardening' effect, the moisture and vapor pressure within the bean remains relatively high but diffusion of moisture is slow. Where there is no 'case hardening' effect, the drying rate slows because the lower internal moisture content and vapor pressure result in a decreasing rate of moisture diffusion to the bean surface.

The slope of the drying rate curves in Figures 22, 23 and 24 are not as steep as the slope of the drying rate curves in Figure 26, even though no moist air was recirculated. Two factors may have contributed to these results: (a) Beans used for Drying Tests 6 through 17 (Table II), upon which the drying curves in Figures 22, 23 and 24 are based, were dry beans that were subjected to a wetting process. The characteristic drying rate of the beans may have been changed by this process. The drying

rate curves shown in Figure 26 were made using high moisture beans as they were received from the elevator. (b) The moisture samples for Tests 6 through 17 were taken with the grain sampler shown in Figure 7. The average depth of these samples were five to six inches above the perforated floor. The moisture samples, with one exception, for Tests 18 through 26, upon which the drying rate curves of Figure 26 are based, were taken with the tube sampler, Figure 17, two inches above the perforated floor.

For the sake of comparison between and among curves, the drying rate curves of Figures 22, 23 and 24 are based on readings of the Steinlite Moisture Tester. The Tag-Heppenstall Moisture Tester was used to determine the moisture of bean samples for all later drying tests starting with Test Number 18 (Table III).

The percentage of cracked beans resulting for air flows of 5, 20, and 35 c.f.m./ft.³, as the temperature of the air was increased, is shown in Figure 25. The increase in amount of cracking that occurred was very great at temperatures above 130°F. The rate of air flow had a very small influence on the extent of cracking for this series of tests.

Figures 22, 23, 24 and 25 show that for drying conditions similar to these tests an air flow of 35 c.f.m./ft.³ at a temperature of approximately 125°F. would be desirable.

Using an air flow rate of 20 c.f.m./ft.³ the cracking was reduced one fifth by recirculating 33% of the moist air as compared to no recirculation of air. A greater reduction in cracking could have undoubtedly been achieved if a greater amount of air had been recirculated.

All bean samples dried in these tests were placed in the laboratory unit at a temperature from 90° to 100° F. The initial temperature of the drying air was room temperature in the range of 68° to 72°F.

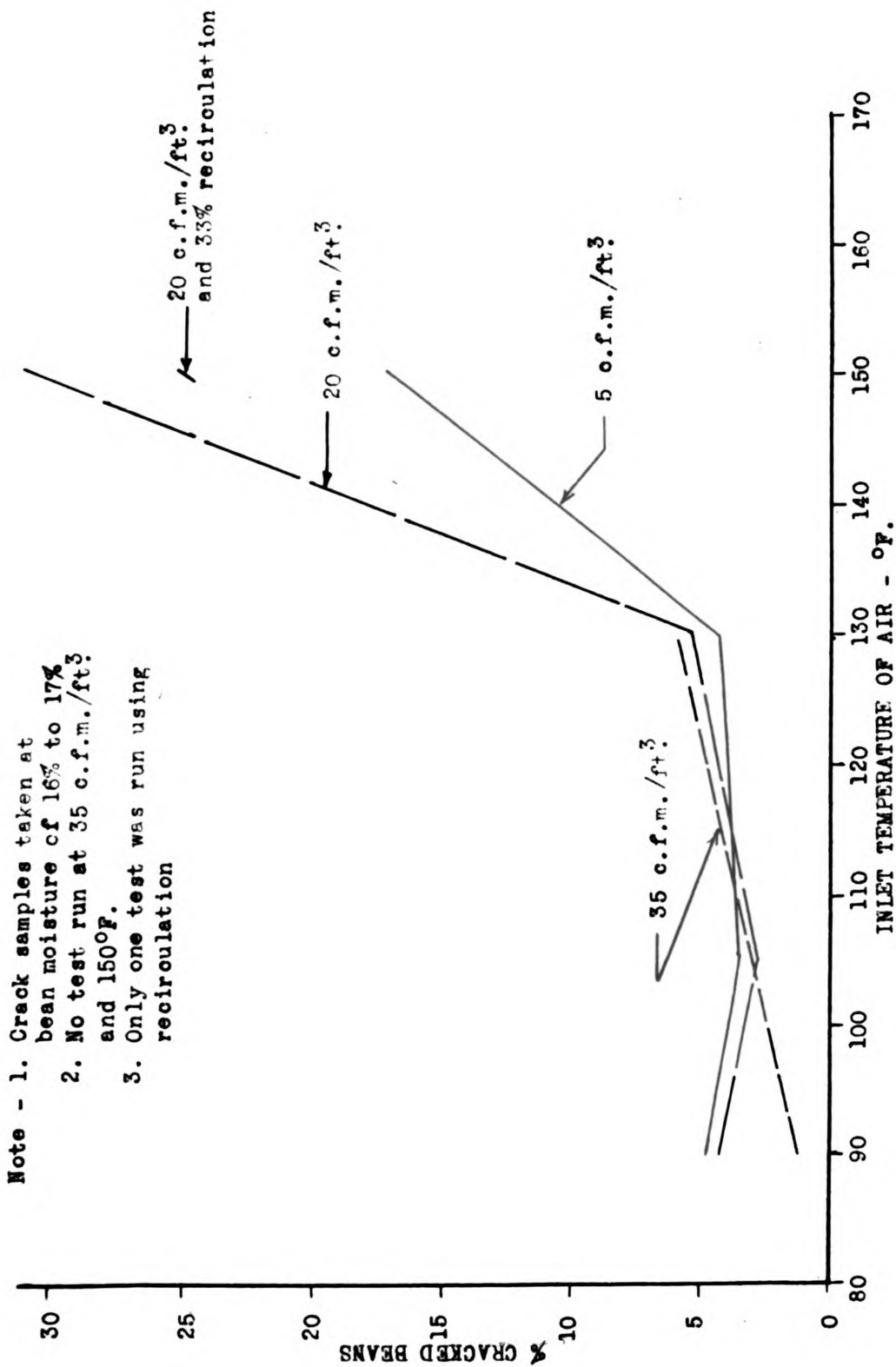


FIG. 25. PERCENTAGE OF CRACKED BEANS RESULTING FROM AIR FLOWS OF DIFFERENT TEMPERATURES

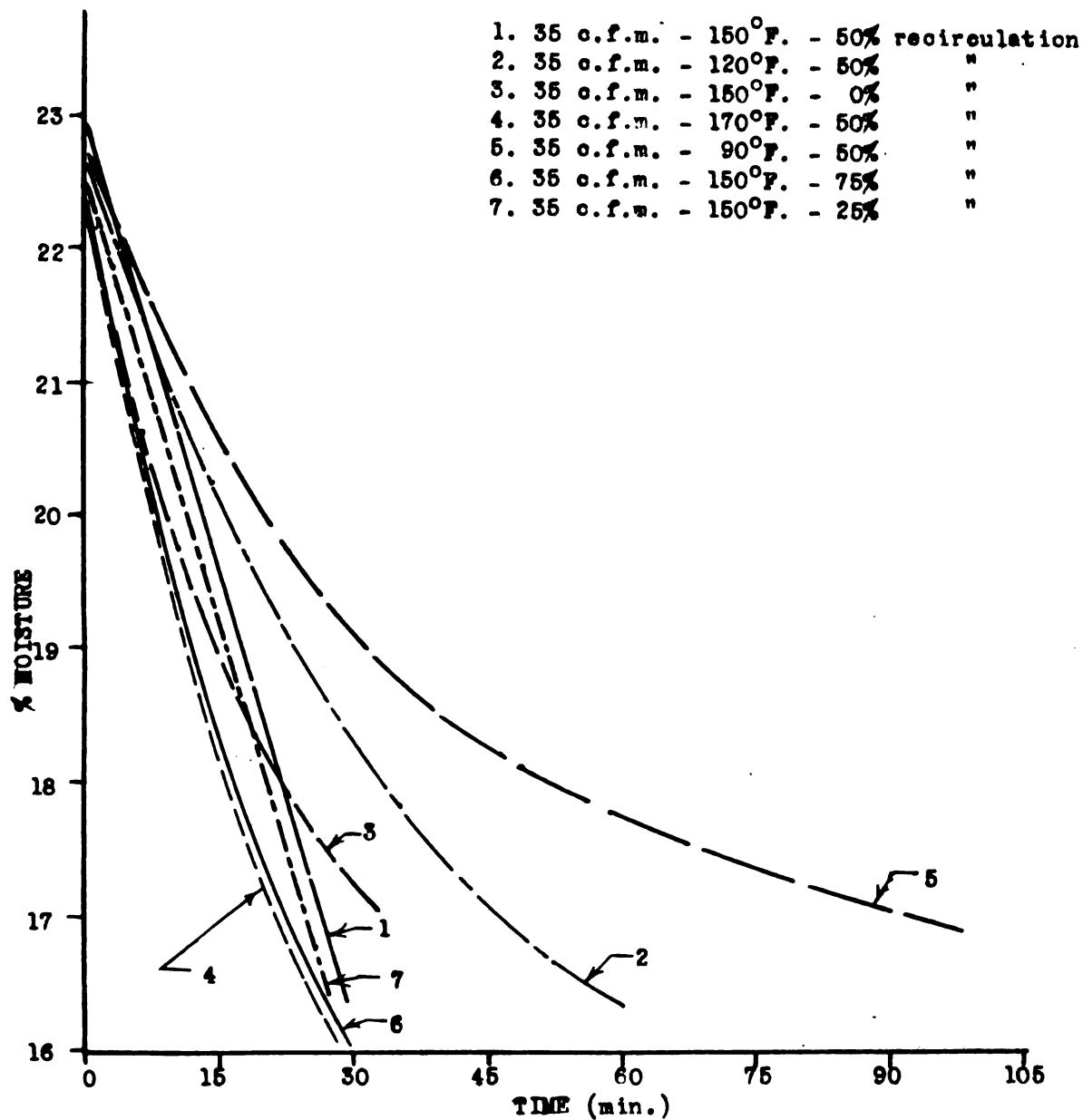


FIG. 26. DRYING RATE OF HIGH MOISTURE PEA BEANS - 35 C.F.M./FT.³

High Moisture Bean Samples. The weather during the fall of 1952 was such that pea beans were down to 18% moisture or below before they were harvested in the field. It was not until the middle of November that a batch of high moisture beans was obtained. These beans tested just under 23% moisture when they were received at the Agricultural Engineering Department. The beans were placed in a walk-in cooler and held at 42° to 45°F. They were at this temperature when placed in the laboratory drying unit. Many fall beans would often be harvested near these temperatures.

A rate of air flow of 35 c.f.m./ft.³ was used for Tests 18 through 24 (Table III) while the temperature of the drying air and percent of recirculation were varied. The results of these tests are shown graphically in Figures 26 and 27.

Figure 26 shows the drying rate of the pea beans. In general the curves have a steep and constant slope with the slopes being steeper than the curves in Figures 22, 23 and 24.

Conditions shown in Figure 26, Curve 5, where 90°F. air and 50% recirculation were used, resulted in the slowest rate of moisture removal. The next slowest rate of moisture removal was for the conditions of Curve 2 where 120°F. air and 50% recirculation were used. Curve 3, representing the conditions of 150°F. air and no recirculation also tends to flatten out. The slopes of Curves 2, 3 and 4 show that both temperature of the air and the amount of moisture in the drying air affect the rate of drying. The slopes of the curves for the tests where 150°F. air and some recirculation was used are about the same.

Figure 27 shows the rate of cracking of the pea beans. The rate of cracking tends to increase as the beans get dryer, indicating that it

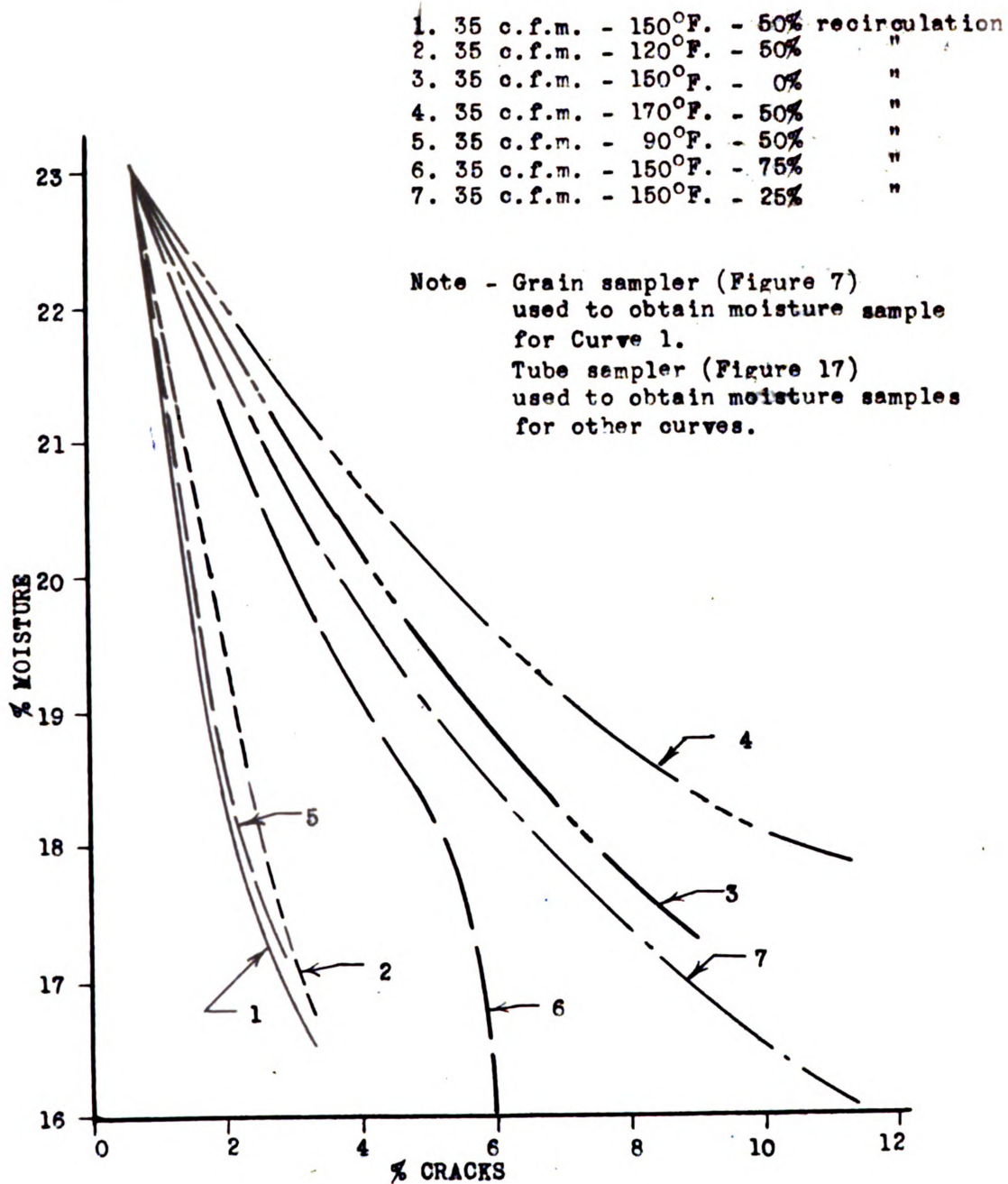


FIG. 27. CRACKING VS. PERCENT MOISTURE - PEA BEANS

would be desirable from the standpoint of cracking, to end the drying at the highest moisture content safe for bean storage. These curves indicate an increase in the rate of cracking at approximately 1% moisture.

The change in the slope of Curve 5 in Figure 27 at a moisture content of slightly above 1% can be accounted for by mechanical difficulties encountered while running this test. Recirculating 75% of the drying air apparently caused a substantial increase in velocity of the air through the ducts because the entire drying unit warmed up several degrees. The ducts were warm to the touch of the hand, and the temperature of the beans, as measured by a mercury thermometer placed in the bean chamber, was several degrees higher than for the other tests. As the velocity of the air increases, it remains in contact for a shorter time with the first beans with which it comes in contact. Less sensible heat is given up to the beans in the bottom of the bin and more heat is carried to the beans in the upper part of the bin and into the return duct. As the drying process continues, less and less moisture is evaporated from the beans in each layer, and more and more of the sensible heat remains in the air stream. Introducing the factor of velocity caused an increase in the bean temperature resulting in a change in the vapor pressure relationship of the drying air to the inside of the bean. The higher vapor pressure within the bean caused by the higher temperature, probably produced a more rapid transfer of moisture from the inside of the bean to the outside, and a more uniform drying even though the rate of drying decreased somewhat below 1% moisture.

Curve 1, Figure 27, does not fall as expected in the series of curves. Curve 1 represents conditions using an air temperature of 150°F. yet shows less cracking than the air temperatures of 90° and 120°F. using the same rates of air flow and of recirculation. The method of sampling is probably

responsible for the misplacement of Curve 1. The grain sampler shown in Figure 7 was used to obtain the sample so that the average sample depth above the perforated floor was five to six inches. It was difficult to force the grain sampler down through the beans to the perforated floor, so, after the test represented by Curve 1 was finished, the tube sampler shown in Figure 17 was devised. For the remaining tests the samples were taken by the tube sampler at a height of two inches above the perforated floor. The difference in the height of samples would account for the lower percentage of cracks shown by Curve 1.

Figures 26 and 27 show that the conditions that produce the most rapid drying also result in more cracking of the beans, and conditions that produce slower drying rates result in minimum cracking of the pea beans. In selecting the optimum drying conditions it becomes necessary to compromise between speed of drying and amount of cracks resulting. Since minimum cracking is desirable, the optimum conditions for drying, as based on Figures 26 and 27, would be an air flow of 35 c.f.m./ft.² at a temperature of 120°F. with approximately 50% recirculation.

Figure 28 is a comparison of data having the same percentages of recirculation but using different air temperatures and different rates of air flow. One set of data is from tests on the field unit (100°F., 100 c.f.m./ft.³) and the other data from tests on the laboratory unit. The data would be more comparable if the tests had been made using the same drying unit; however, the curves do show that (a) as the percent of recirculation increases, the amount of cracking decreases, and (b) more cracking of the pea beans can be expected when air of higher temperature is used for drying.

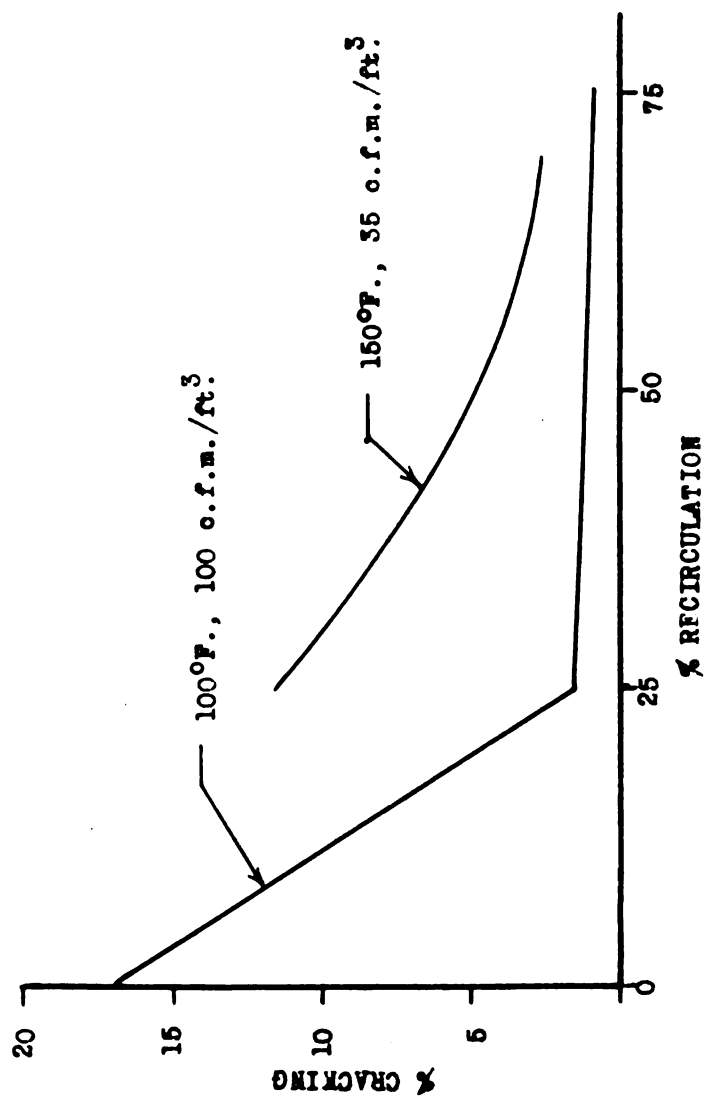


FIG. 28. EFFECT OF TEMPERATURE AND AIR FLOW ON CRACKING
PERCENT RECIRCULATION CONSTANT

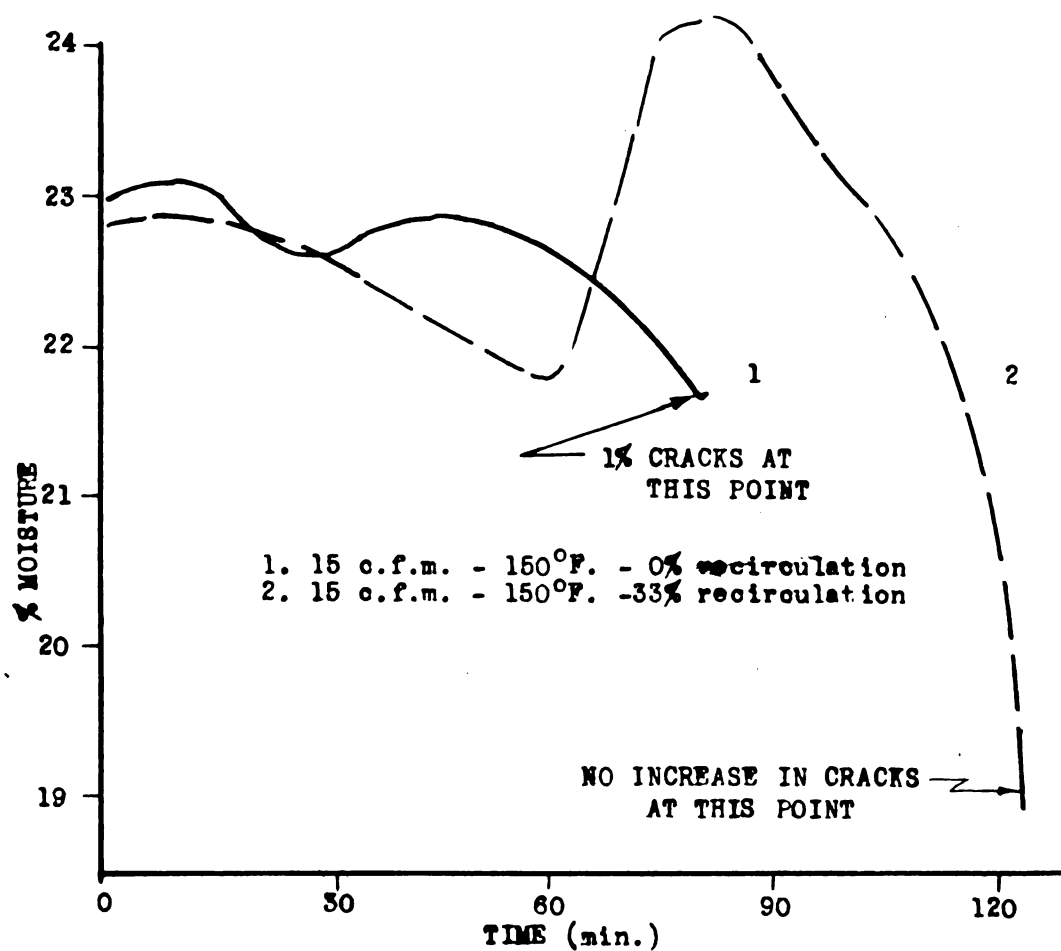


FIG. 29. DRYING RATE OF HIGH MOISTURE PEA BEANS - 15 C.F.M./FT.³

Figure 29 shows the drying rate of cold beans when using low air flows and high temperatures. An air temperature of 150°F. and an air flow of 15 c.f.m./ft³ was used in the two tests with no moist air being recirculated in one test and 33% of the moist air being recirculated in the other test.

The zone of drying is shown very distinctly in these drying rate curves by the second peak. The peaks are a result of surface moisture on the beans, to which the Tag-Heppenstall Moisture Tester is very sensitive. The drying zone was moving up much more rapidly, as shown by Curve 2, when no moist air was recirculated. Drying conditions such as these that result in large quantities of free water being deposited in the bean layers would not be desirable or efficient.

A comparison of Figures 23 and 29 show drying rate curves distinctly different in shape even though the conditions of air flow, temperature of drying air, and percent of recirculation are about the same. The initial bean temperature in the tests represented by the curves in Figure 23 was close to 100°F. while the initial temperature of the beans in the tests represented by the curves in Figure 29 was 42° to 45°F. The higher bean temperature would permit the drying air to discharge at a higher dry-bulb temperature carrying the moisture with it while the lower bean temperatures coupled with the low air flow caused the dry-bulb temperature to drop rapidly resulting in condensation of moisture onto the beans and a very thin layering or drying zone.

Drying Tests Using Laboratory Unit for Controlled Humidity

Tests made up to this time showed conclusively that the cracking of pea beans could be reduced by recirculating a part of the moist air through the beans as they were being dried. Recirculating moist air in effect raises the humidity of the vapor pressure of the drying air. As the drying air increases the temperature of the beans in the drying chamber, there results a more even diffusion of moisture to the outside of the bean and a slower rate of evaporation of the moisture from the surface of the bean. These conditions are desirable because they prevent the rapid shrinking of the seed coat which causes cracking.

The mechanics of providing for and controlling recirculation, however, could be burdensome to an elevator operator. Another approach to this problem seemed possible. This approach was the introduction of steam to the air stream to raise the humidity of the drying air to the point where cracking of the bean would be prevented.

In Tests 27 through 31, Table III, steam was introduced into the air stream. With the equipment used it was not possible to duplicate the air flows used in the previous tests. Two tests were run using air temperatures of 100°F., air flows of 10 c.f.m./ft³, and relative humidities of 50% and 30%. No cracking was apparent in the beans under these conditions. Three tests were run using temperatures of 140° and 160°F. The results of these tests are shown in Figure 30.

The curves in Figure 30 and 31 show that cracking can be reduced by increasing the relative humidity of the drying air. Although only a limited number of tests were run, the tests indicated that relative humidities in the range of 12% to 15% would reduce cracking to a minimum. Drying air with a relative humidity of 40% prevented cracking beyond

140°F.; however, the drying rate for 40% relative humidity air was much slower than when 15% relative humidity air was used. It required three hours to remove one percent of moisture using the 40% relative humidity air while two and one-half percent of moisture was removed in one hour using 15% relative humidity air. Even though the relative humidity of the drying air was held constant, the absolute humidity or the amount of water vapor in the drying air increased rapidly (Appendix III). In tests made with the field unit, the cracking increased very sharply when the relative humidity of the air dropped below 12%, Figure 31.

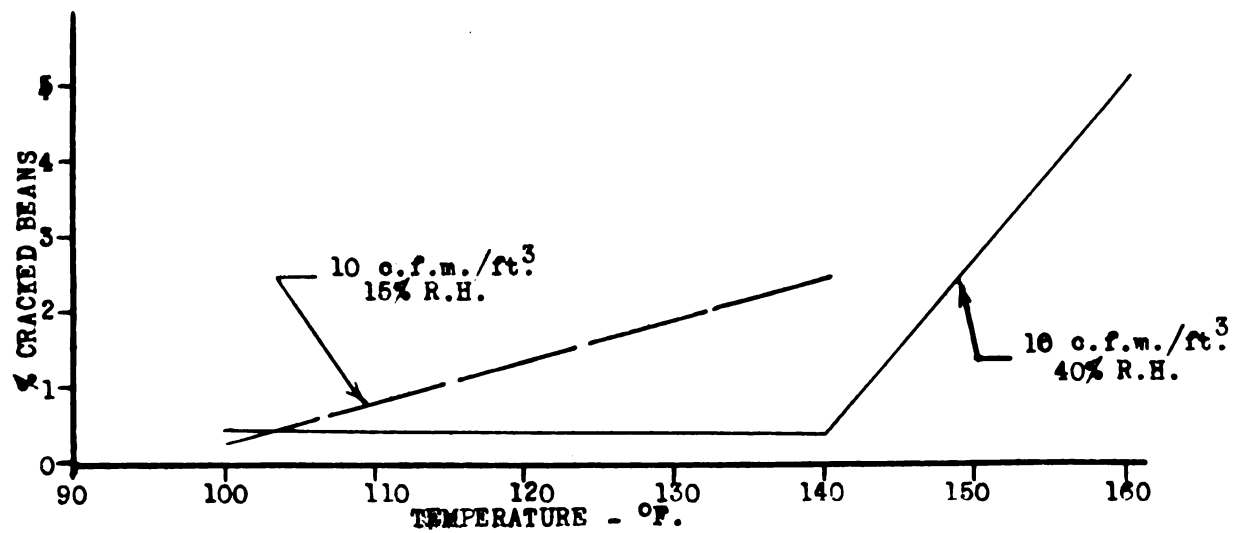


FIG. 30. CRACKING VS. TEMPERATURE - CONTROLLED HUMIDITY

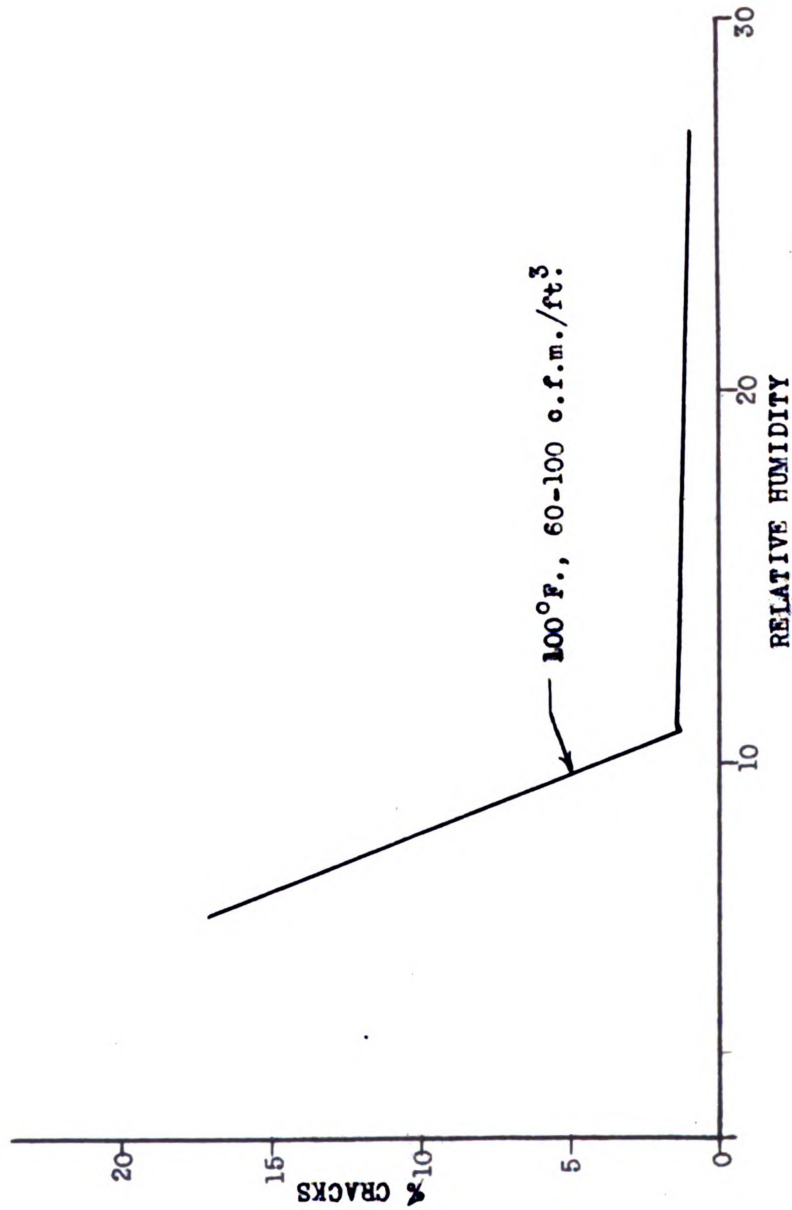


FIG. 31. CRACKING VS. RELATIVE HUMIDITY - FIELD UNIT

CONCLUSIONS

1. Partial recirculation of the drying air reduces the cracking of pea beans.
2. As the amount of recirculated air is increased for a given temperature and air flow, the amount of cracking decreases and the rate of drying decreases.
3. A drying temperature of 125°F. with a recirculation of 50% of the drying air at an air flow of 35 c.f.m./ft³ are the optimum conditions within the limits of these tests. As the drying rate is increased by use of higher air flows the temperature will have to be lowered or a greater amount of cracking will result.
4. The rate of air flow does not influence the drying rate of pea beans nearly as much as the temperature and humidity of the drying air.
5. Drying air at temperatures above 130°F. causes excessive cracking and should not be used.
6. Rapid drying of the pea beans at the start of the drying period produced a change within the structure of the bean. This change resulted in slow diffusion of moisture from the inside to the outside of the bean. The longer drying period required to remove the excess moisture resulted in more cracking of the beans.
7. Cracking of the pea beans occurs through the entire drying period, but increases in severity as the moisture content goes below 18%. Pea beans should not be dried to moisture contents lower than necessary for safe storage to prevent cracking during drying and handling.

8. Moisture can be removed from pea beans using heated air without recirculation if care is exercised in selecting the temperature of the heated air. The temperature of the drying air cannot be as high as when partial recirculation of the drying air is used. Tests indicated that the temperature probably should be 20° to 30° above the temperature of the beans as they are put into the drier.

9. Controlling the humidity of the drying air by introducing steam into the air stream is a suitable method of controlling the drying rate of pea beans.

SUGGESTIONS FOR FUTURE INVESTIGATIONS

Further investigations to determine the relative humidity of the air required to maintain a uniform drying rate that would prevent cracking are desirable.

The development of a heated air drying unit that would permit only a 20° to 30° rise in temperature would be of special benefit to the farm drying unit. A drying unit with a limited temperature rise would eliminate many management problems that are present when high temperature drying air is used.

Investigations that would show the process of moisture diffusion within the beans and how the moisture diffusion is affected by the temperature and humidity of the drying air, would be of great help in determining optimum drying conditions.

Future laboratory tests should be made in a laboratory unit having a cross-sectional area of approximately four square feet and a bean depth of eight to twelve inches. A unit of this design would permit more even drying through the bean depth and a smaller amount of the beans would be dried below 18% moisture where an increase in the rate of cracking occurs.

STATUS OF THE FIELD UNIT

The portable drying unit that is presently available for drying is shown in Figure 32. The drying unit, which is a direct fired unit, uses

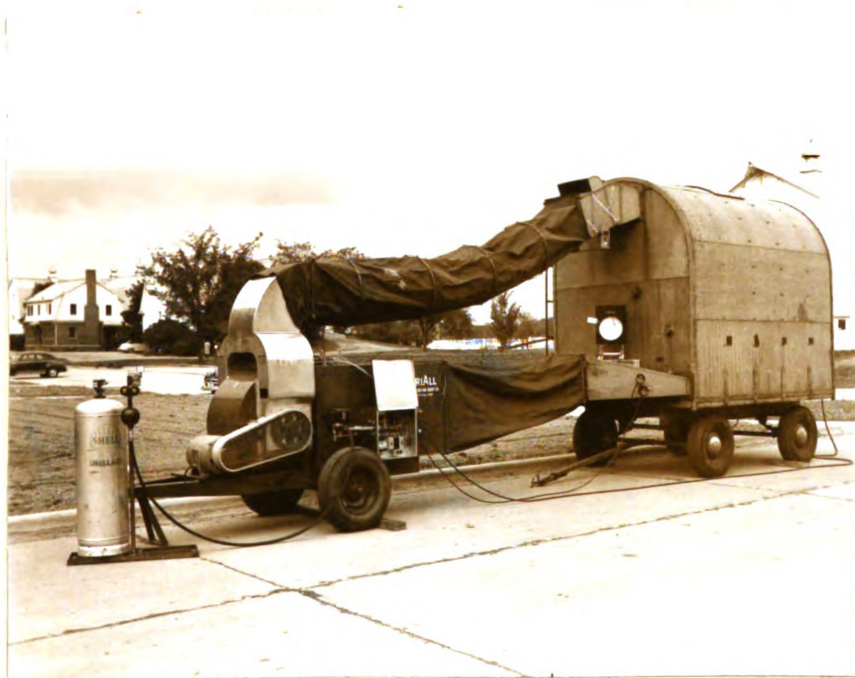


Fig. 32. Portable Drying Unit with Gas Type Heater

bottled gas as a source of heat. The bottled gas burner is adjustable for a wide range of heat output with a satisfactory operating cycle. This is possible because of the wide adjustment on the amount of bottled gas furnished to the burner. One of the main reasons for selecting this unit was the very desirable characteristic that permits the wide adjustment of the total heat output.

Sheet metal ducts were fabricated and mounted on the drying unit so that the air supply to the fan could be controlled. Canvas ducts were used between the drying unit and the bin. A more complete description of this unit and instructions for operating the unit are given by Brandt (16).

Some changes were made in the drying bin in the fall of 1952 to increase the plenum chamber beneath the perforated floor and to facilitate the unloading of the pea beans.

Only one test was run using this unit in the fall of 1952. Excellent conditions for field drying lasted until late October and only a very few wet beans were harvested. No high moisture beans were available for field demonstrations.

SUGGESTIONS FOR DESIGNING A DRYING UNIT

A heated air drying unit and bin should provide the following conditions when designed for drying pea beans:

Temperature range - 60° to 130° F. with a maximum variation of 10° at the selected temperature

Air flow - 35 to 100 c.f.m./ft³; speed of fan varied by using a variable speed drive or changing pulleys

Recirculation - Up to 50%; adjusted by manually controlled dampers

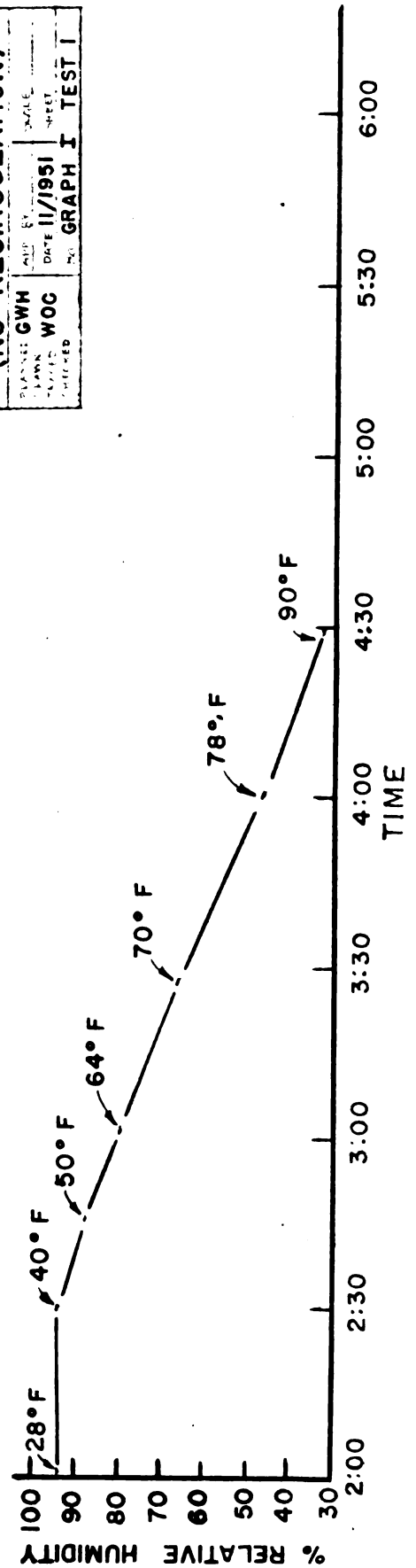
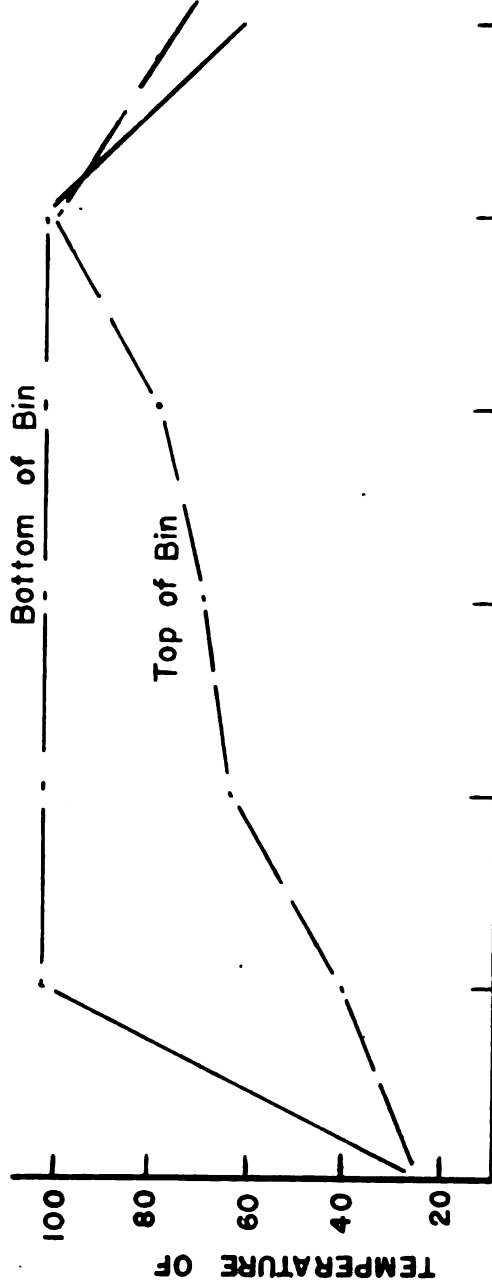
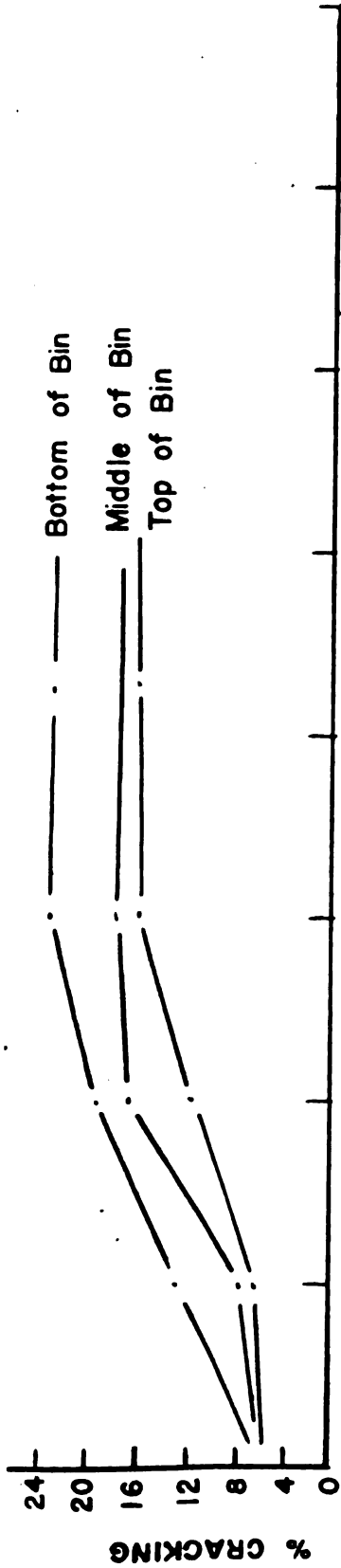
Drying bin - Column type with a maximum width of 12 inches. An auger type unloading device at the bottom of the column would be desirable.

APPENDIX I

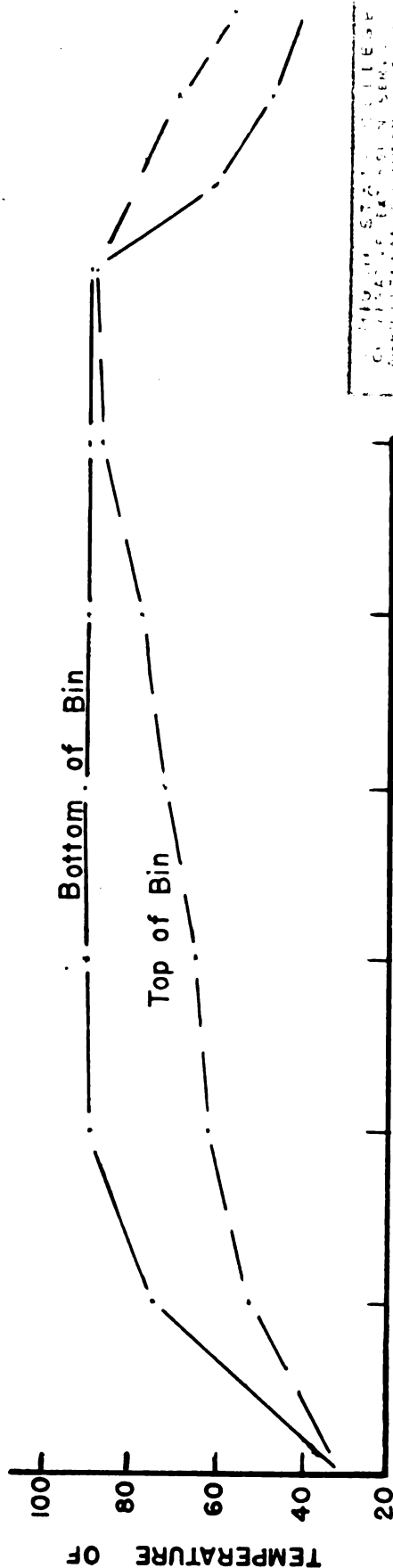
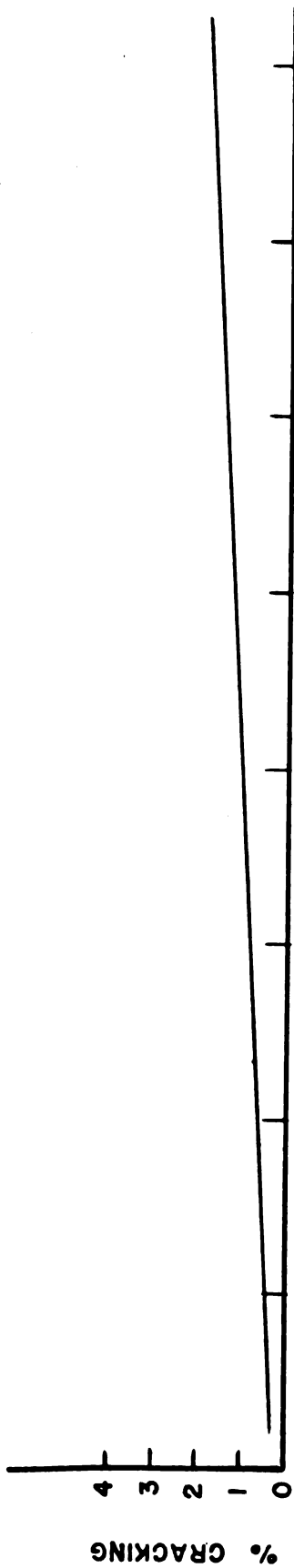
Curves for Tests 1, 2, 3, 4 and 5, Table III, showing:

1. Percent of Cracking vs. Drying Time
2. Temperature of Bean Layers vs. Drying Time
3. Humidity of Air Leaving Bin vs. Drying Time

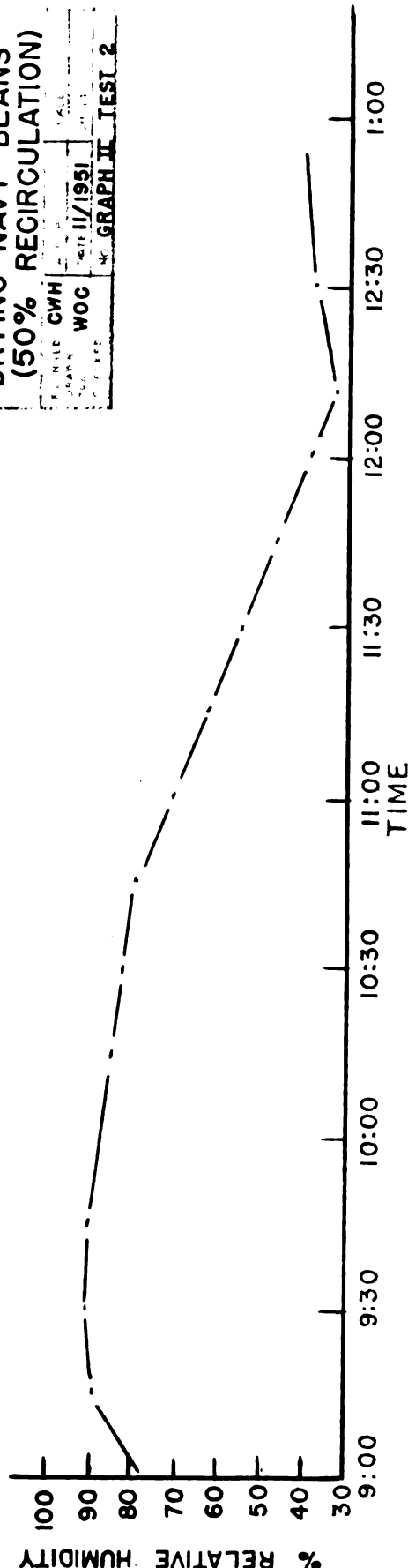
These tests were run using the portable field unit furnished to the Agricultural Engineering Department by the Production Marketing Administration. The conditions for these tests are given in Table I.

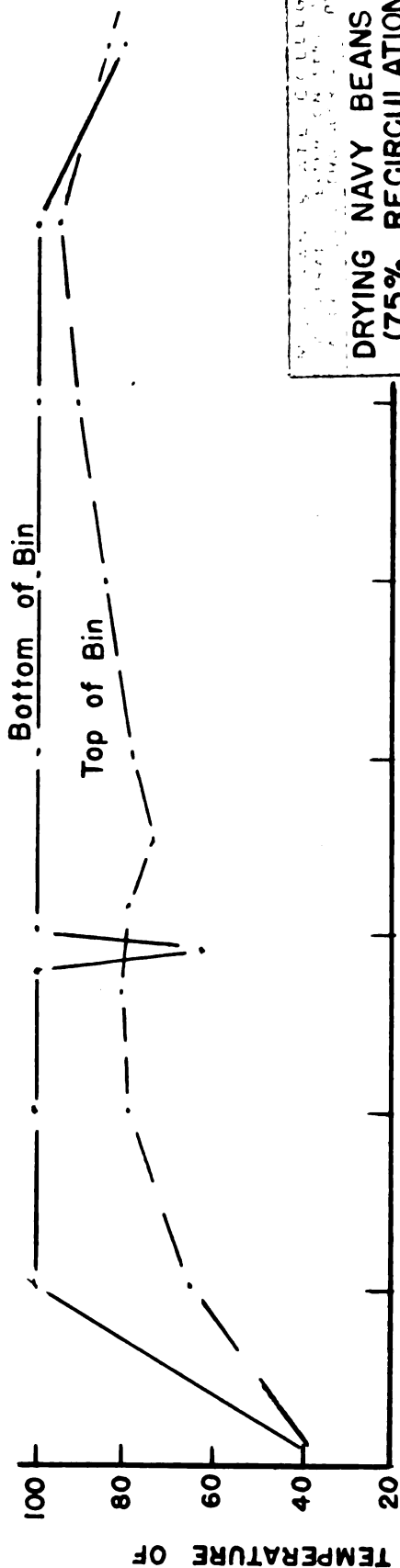
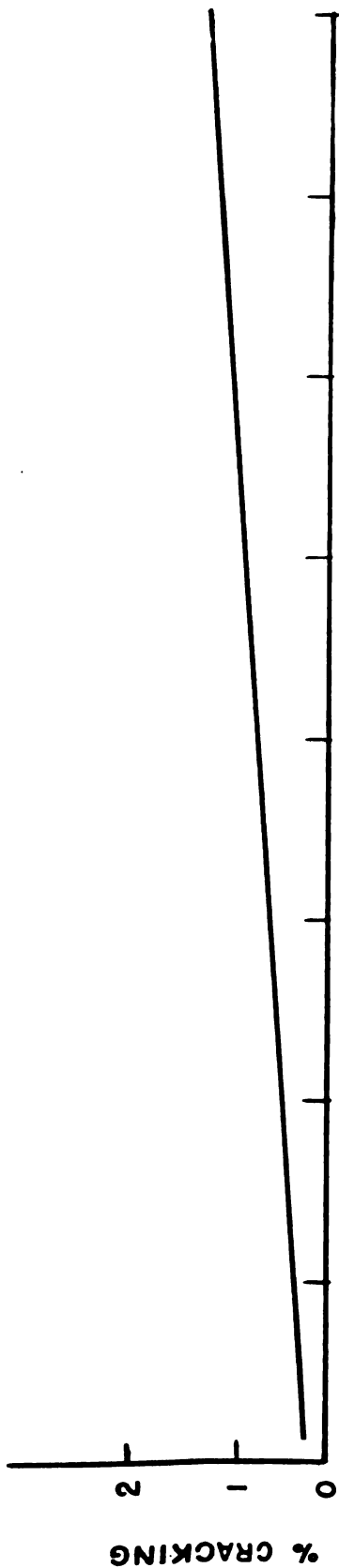


MISSISSIPPI STATE UNIVERSITY COMPUTATIONAL ENGINEERING		DATE 11/1951		SHEET	
PLANNED: GWM	APPROVED: WOC	DATE 11/1951	SHEET	NO. GRAPH I TEST I	
DRYING NAVY BEANS (NO RECIRCULATION)					

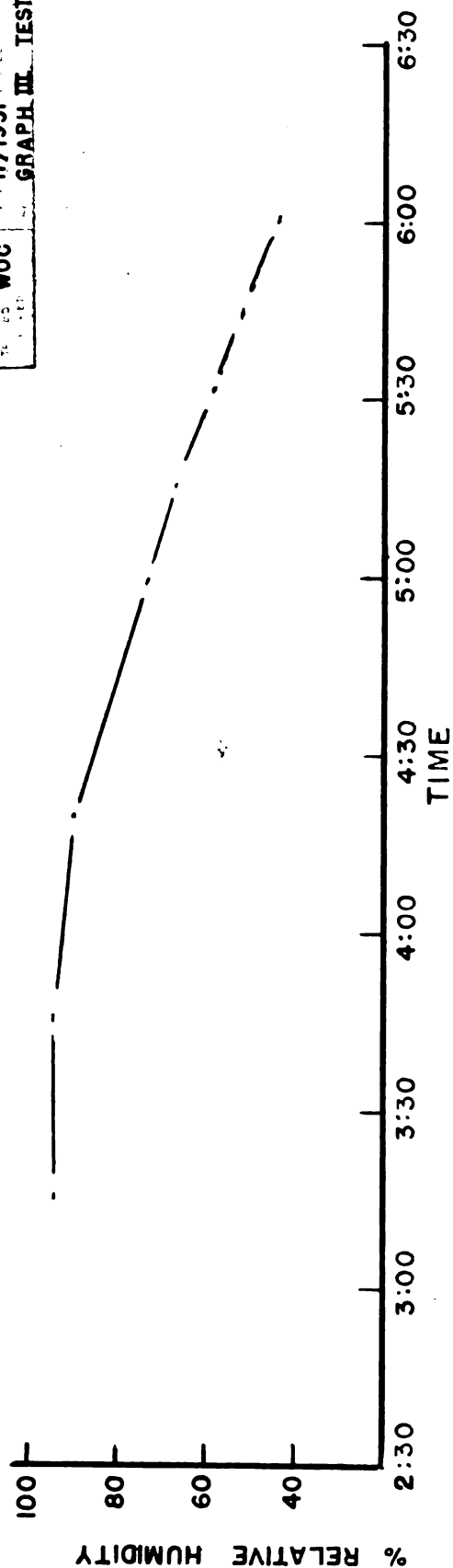


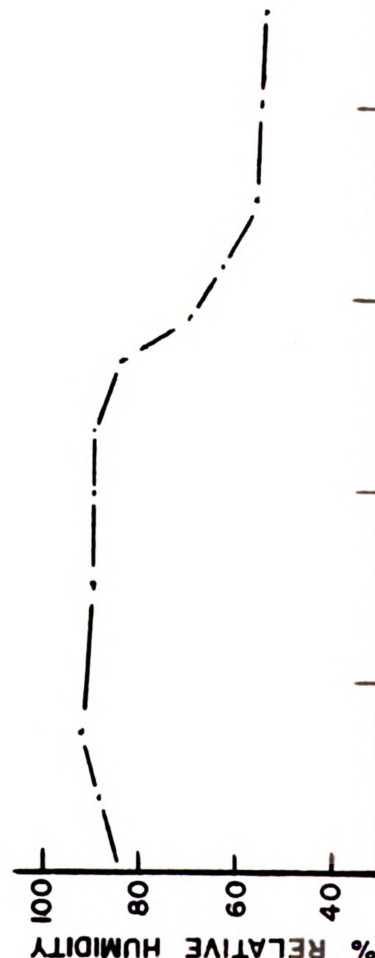
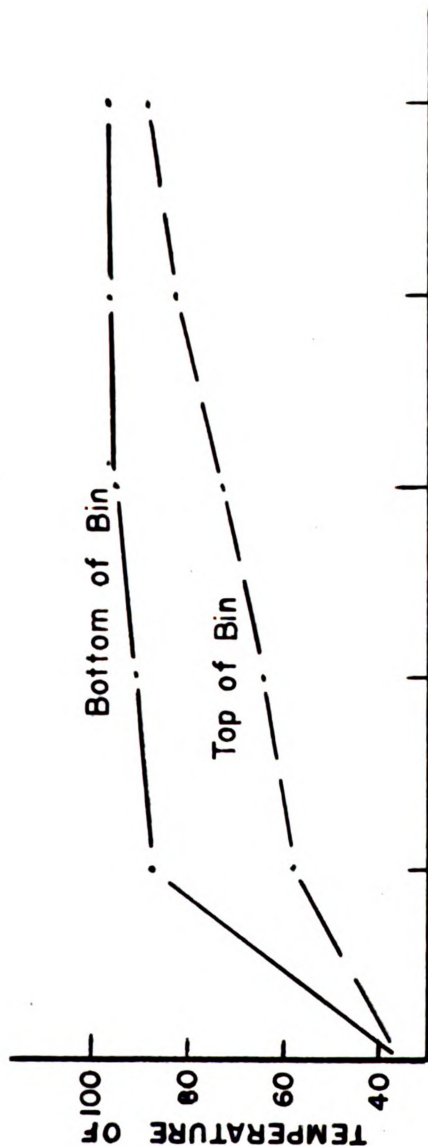
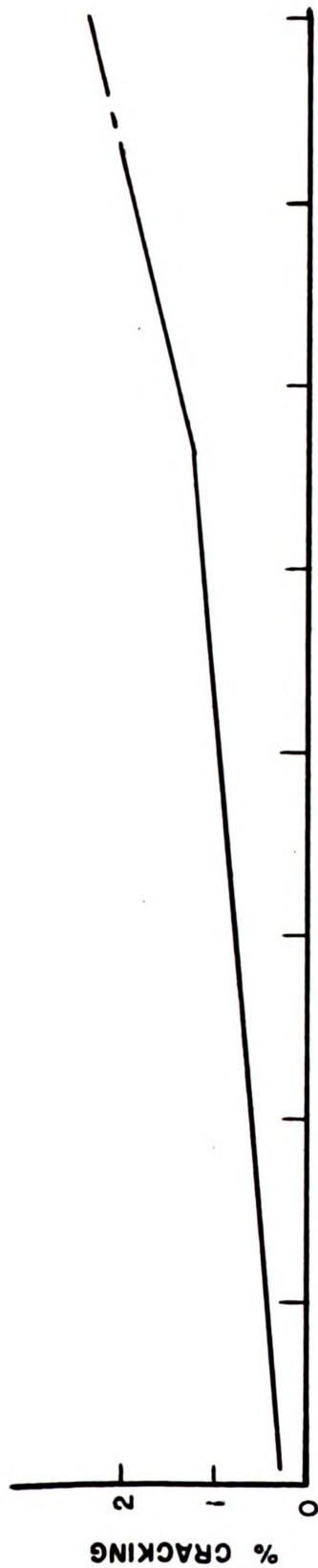
UNITED STATES GOVERNMENT OFFICE OF THE SECRETARY OF THE ARMY WASHINGTON, D. C. 20315	
DRYING NAVY BEANS (50% RECIRCULATION)	
PROJECT DRYING NAVY BEANS	DATE 11/1951
FILE NO. GWH	FILE NO. WOC
NO. GRAPH TEST 2	



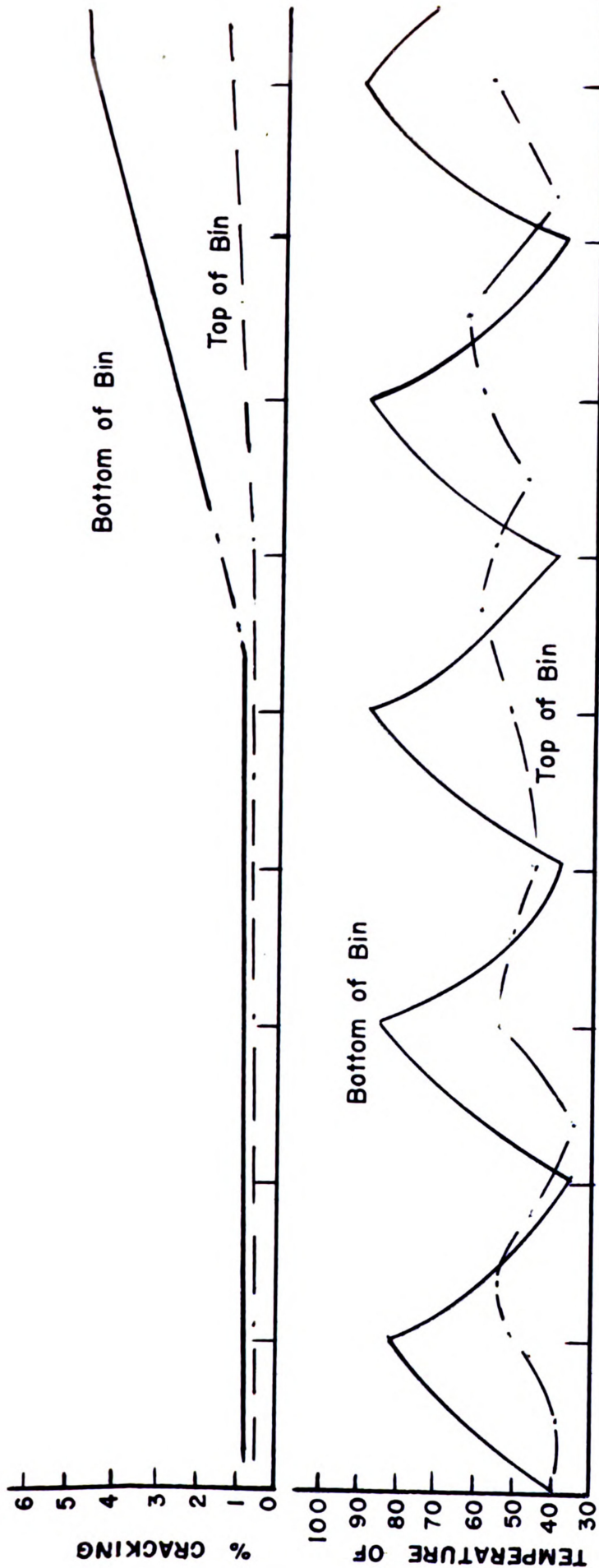


NAVY BEANS
 DRYING NAVY BEANS
 (75% RECIRCULATION)
 PLANT: CWH
 DATE: 11/1951
 TEST: WOG
 GRAPH III TEST 3

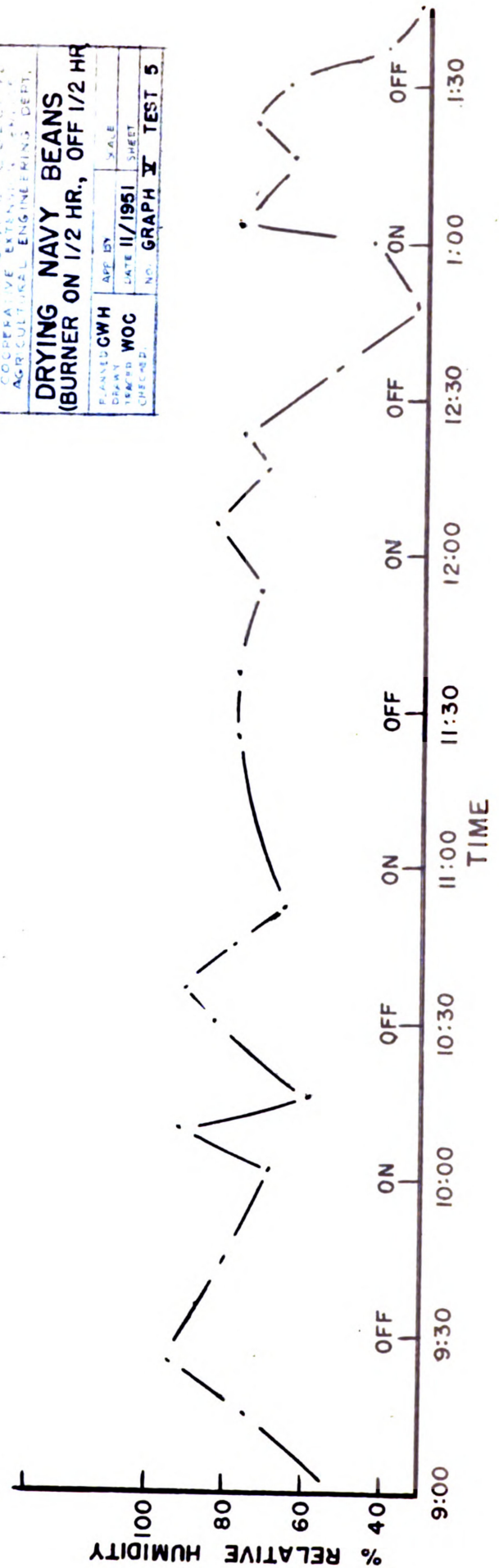




MICHIGAN STATE COLLEGE COOPERATIVE EXTENSION SERVICE Agricultural Engineering Dept.			
DRYING NAVY BEANS (25% RECIRCULATION)			
PLANNED GWH	DATE 11/1951	SCALE	NO. GRAPH IV TEST 4
DRAWN WOC	DATE 11/1951	RENT	
CHECKED			



MICHIGAN STATE COLLEGE			
COOPERATIVE EXTENSION SERVICE			
AGRICULTURAL ENGINEERING DEPT.			
DRYING NAVY BEANS			
(BURNER ON 1/2 HR., OFF 1/2 HR)			
PLANNED BY	CWH	APP BY	Y.A.E.
DRAWN	WOC	DATE	11/1951
TEMPERATURE		CHECKED	
		NO.	GRAPH IV TEST 5

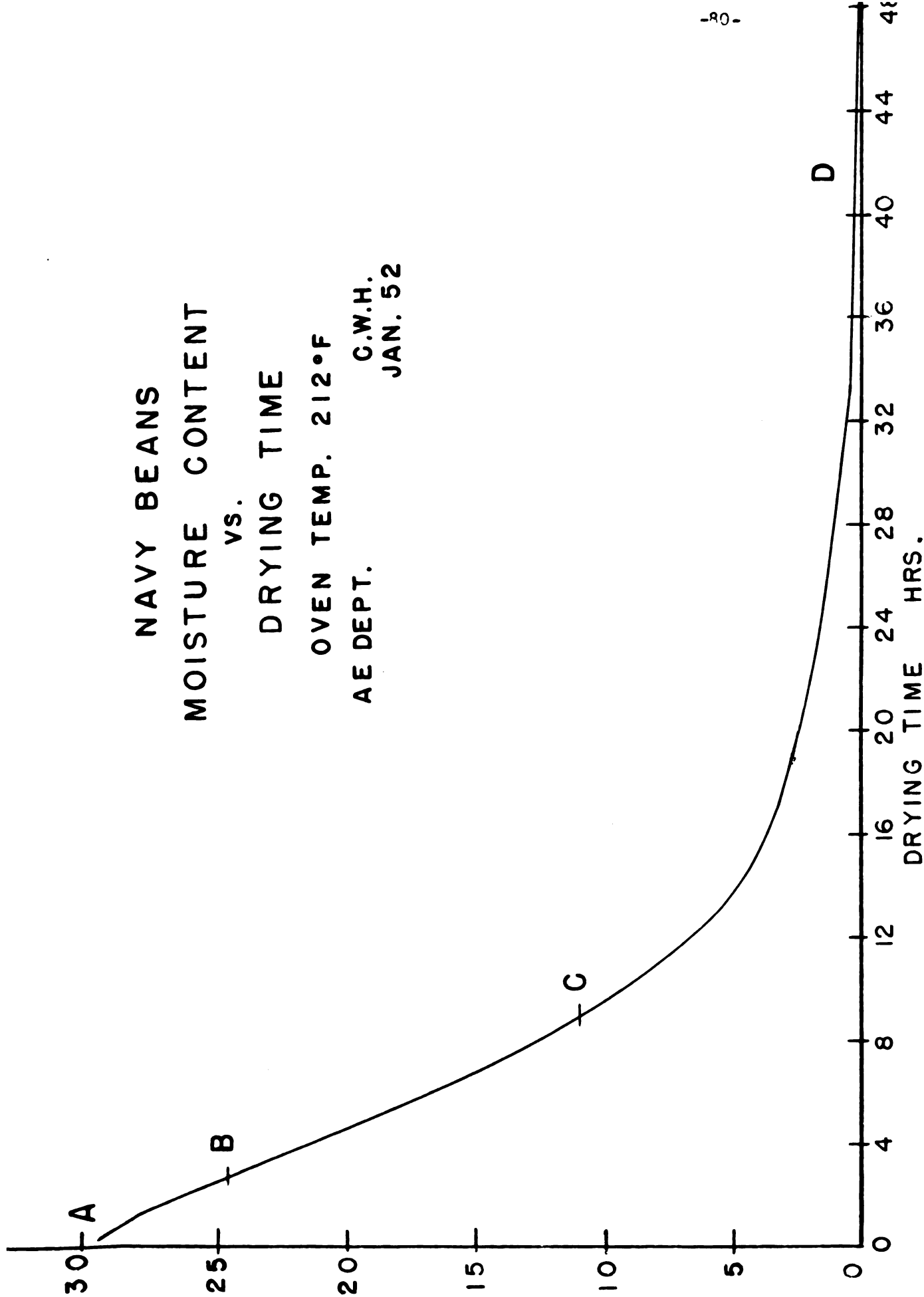


APPENDIX II

Drying Rate Curves for Oven Samples

The data used for drawing these curves was obtained by C. W. Hall by drying pea bean samples in the laboratory oven. These curves are included in this thesis for purposes of comparison with curves obtained by drying samples in the laboratory drying units.

PER CENT MOISTURE CONTENT (DRY BASIS)



NAVY BEANS
MOISTURE CONTENT
VS.

DRYING TIME

OVEN TEMP. 212°F

AE DEPT.

C.W.H.

JAN. 52

NAVY BEANS DRYING RATE

vs.

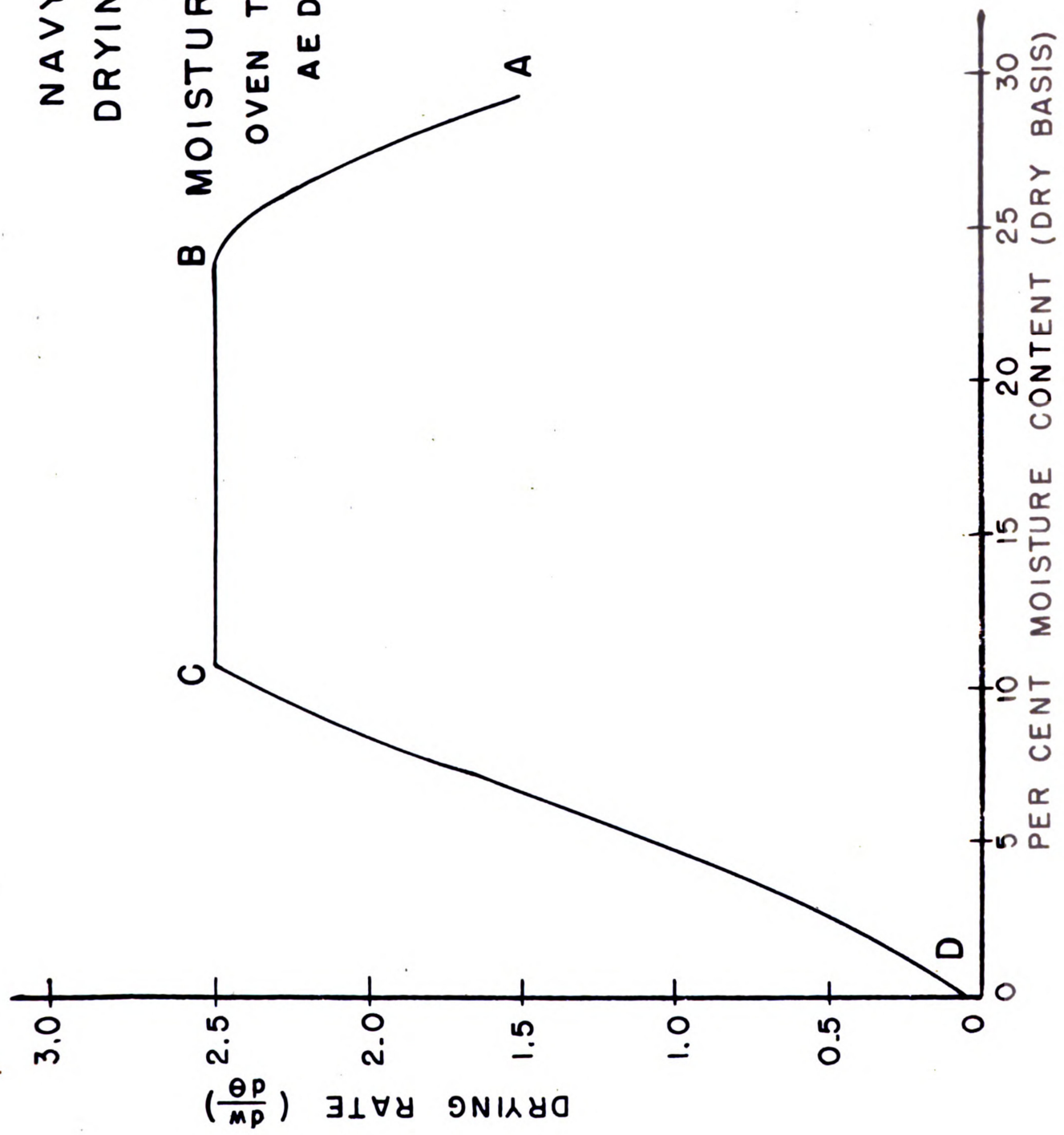
MOISTURE CONTENT

OVEN TEMP. 212° F

AE DEPT.

C.W.H.

JAN. 52



APPENDIX III

Test Data for Laboratory Drying Units

Tests 6 through 17 were run using low moisture beans rewet and the laboratory unit for controlled recirculation.

Tests 18 through 26 were run using high moisture beans and the laboratory unit for controlled recirculation.

Tests 27 through 31 were run using high moisture beans and the laboratory unit for controlled humidity.

TEST NO. 6

Aug. 12, 1952

Beans Rewet

Air Flow
Drying Temperature
Recirculation

5 c.f.m./ft.³
90°F.
0%

Room Temperature 88°F.
Relative Humidity 43%

Time	% Moisture		% Cracks
	Bottom	Top	
3:15	17.3	17.3	
4:00	17.0	18.4	
4:45		18.0	
5:00	16.1	17.1	
5:15	10.8		

TEST NO. 7

Sept. 12, 1952

Beans Rewet

Air Flow
Drying Temperature
Recirculation

5 c.f.m./ft.³
105°F.
0%

Room Temperature 88°F.
Relative Humidity 27%

Time	% Moisture		% Cracks
	Bottom	Top	
9:05	18.6	18.6	
9:45	18.4	18.5	
10:05	18.3	22.9	
10:40	16.9	19.0	
10:40	Crack sample 2" from bottom		3.55

TEST NO. 8

Sept. 16, 1952

Beans Rewet

Air Flow 5 c.f.m./ft³
Drying Temperature 130°F.
Recirculation 0%

Room Temperature
Relative Humidity

Time	% Moisture		% Cracks
	Bottom	Top	
2:50	19.1	19.1	
3:20	18.8	18.4	
3:50	18.7	18.6	
4:45	17.4	17.9	

Crack sample 2" from bottom - 14.1 4.33

TEST NO. 9

Sept. 16, 1952

Beans Rewet

Air Flow 20 c.f.m./ft³
Drying Temperature 90°F.
Recirculation 0%

Room Temperature 64.5°F.
Relative Humidity 58%

Time	% Moisture		% Cracks
	Bottom	Top	
9:20	18.3	18.3	
9:50	16.8	18.2	
10:25	16.2	17.5	
10:50	17.7	17.7	

Crack sample 2" from bottom - 14.9 4

TEST NO. 10

Sept. 17, 1952

Beans Rewet

Air Flow 20 g.f.m./ft.³
Drying Temperature 105° F.
Recirculation 0%

Room Temperature 77.5° F.
Relative Humidity 41%

Time	% Moisture		% Cracks
	Bottom	Top	
3:55	19.9	19.9	.45
4:20	18.3	19.0	
5:00	19.0	19.5	
5:50	18.7	19.3	
7:20	17.0	18.4	

Crack sample 2" from bottom 3.1

TEST NO. 11

Sept. 18, 1952

Beans Rewet

Air Flow 20 g.f.m./ft.³
Drying Temperature 130° F.
Recirculation 0%

Room Temperature 69.5° F.
Relative Humidity 81%

Time	% Moisture		% Cracks
	Bottom	Top	
10:00	19.4	19.4	.47
10:30	18.8	19.6	
11:10	18.8	19.2	
12:10	16.4	17.5	

Crack sample 2" from bottom 5.3

TEST NO. 12

Sept. 18, 1952

Beans Rewet

Air Flow 35 c.f.m./ft.³
Drying Temperature 90°F.
Recirculation 0%

Room Temperature 71.5°F.
Relative Humidity 65%

Time	% Moisture		% Cracks
	Bottom	Top	
7:45	19.2	19.2	.5
8:15	18.9	19.2	
8:45	17.5	18.1	
9:15	16.2	17.8	
9:45	17.4	17.7	
Crack sample 2" from bottom			.7

TEST NO. 13

Sept. 19, 1952

Beans Rewet

Air Flow 35 g.f.m./ft.³
Drying Temperature 105°F.
Recirculation 0%

Room Temperature 63°F.
Relative Humidity 64%

Time	% Moisture		% Cracks
	Bottom	Top	
9:50	19.5	19.5	.47
10:20	20.2	19.0	
10:50	18.3	17.8	
11:20	17.7	17.9	
Crack sample 2" from bottom			2.8

TEST NO. 14

Sept. 19, 1952

Beans Rewet

Air Flow 35 c.f.m./ft.³
 Drying Temperature 130°F.
 Recirculation 0%

Room Temperature 63.5°F.
 Relative Humidity 60%

Time	% Moisture		% Cracks
	Bottom	Top	
4:10	19.65	19.65	.51
4:45	18.65	18.2	
5:15	17.5	18.0	
5:25	Crack sample	14.8	5.5

TEST NO. 15

Sept. 20, 1952

Beans Rewet

Air Flow 5 c.f.m./ft.³
 Drying Temperature 150°F.
 Recirculation 0%

Room Temperature 66°F.
 Relative Humidity 62%

Time	% Moisture		% Cracks
	Bottom	Top	
3:10	21.8	21.8	2.7
3:40	19.8	19.8	
4:10	19.6	19.4	
4:40	19.7	19.5	
5:10	19.2	19.1	
5:45	19.0	19.9	
7:00	18.0	19.6	
7:40	19.3	19.8	

Crack sample 2" from bottom

17.2

TEST NO. 16

Sept. 22, 1952

Beans Rewet

Air Flow 20 c.f.m./ft.³
 Drying Temperature 150°F.
 Recirculation 0%

Room Temperature 60°F.
 Relative Humidity 73%

Time	% Moisture		% Cracks
	Bottom	Top	
9:50			2.7
10:25	16.8	16.5	
10:40	•16.5	16.7	
Crack sample 2" from bottom			31.2

TEST NO. 17

Sept. 22, 1952

Beans Rewet

Air Flow 20 c.f.m./ft.³
 Drying Temperature 150°F.
 Recirculation 33%

Room Temperature
 Relative Humidity

Time	% Moisture		% Cracks
	Bottom	Top	
9:05	18.8	18.8	1.6
9:40	17.5	18.1	
10:15	16.55	17.95	
10:35	Crack sample 2" from bottom		26.3

TEST NO. 18

Nov. 25, 1952

Air Flow 35 c.f.m./ft.³
 Drying Temperature 150°F.
 Recirculation 50%

Room Temperature 67°F.
 Relative Humidity
 Bean Temperature 44°F.

Time	% Moisture		% Cracks
	Bottom	Top	
2:30	23.1	23.1	.7
3:00	16.4	23.2	3.4
3:30	14.6	22.5	7.3

TEST NO. 19

Nov. 26, 1952

Air Flow 35 c.f.m./ft.³
 Drying Temperature 120°F.
 Recirculation 50%

Room Temperature 64.5°F.
 Relative Humidity 22%

Time	% Moisture		% Cracks
	Bottom	Top	
9:35	23.8	23.8	.7
10:05	18.4	23.6	2.3
10:35	16.3	23.7	3.6
11:05	13.8	23.3	
11:35	13.5	21.3	

TEST NO. 20

Nov. 27, 1952

Air Flow
Drying Temperature
Recirculation

35 c.f.m./ft.³
150°F.
0%

Room Temperature
Relative Humidity

Time	% Moisture		% Cracks
	Bottom	Top	
4:05	22.8	22.8	.7
4:20	18.9	22.3	5.9
4:35	17.2	23.1	9.2
4:50	15.0	22.6	14.0
5:05	14.7	22.9	
5:20	14.3	21.6	

TEST NO. 21

Nov. 28, 1952

Air Flow
Drying Temperature
Recirculation

35 c.f.m./ft.³
170°F.
50%

Room Temperature 65°F.
Relative Humidity 37%

Time	% Moisture		% Cracks
	Bottom	Top	
10:55	22.7		.7
11:10	18.2		9.6
11:25	17.8		11.2
11:40	17.0		
11:50	14.4	24.1*	

* Only one sample taken at top.

TEST NO. 22

Nov. 28, 1952

Air Flow 35 c.f.m./ft.³
Drying Temperature 90°F.
Recirculation 50%

Room Temperature 70°F.
Relative Humidity 27%

Time	% Moisture		% Cracks
	Bottom	Top	
2:05	22.8		.7
2:20	20.5		1.8
2:35	19.4		
2:50	18.0		2.0
3:05	17.9		
3:20	17.3		2.6
3:35	16.9	21.5	

TEST NO. 23

Nov. 29, 1952

Air Flow 35 c.f.m./ft.³
Drying Temperature 150°F.
Recirculation 75%

Room Temperature 65°F.
Relative Humidity 21%

Time	% Moisture		% Cracks
	Bottom	Top	
3:00	22.4		.7
3:15	18.3		5.3
3:30	16.0		6.1
3:45	15.6	23.5	

TEST NO. 24

Nov. 30, 1952

Air Flow	35 c.f.m./ft. ³	Room Temperature	65°F.
Drying Temperature	150°F.	Relative Humidity	25%
Recirculation	25%		

Time	% Moisture		% Cracks
	Bottom	Top	
3:35	22.3		.4
3:50	19.2		4.7
4:05	16.0		11.6
4:20	15.0	22.8	

TEST NO. 25

Dec. 17, 1952

Air Flow	15 c.f.m./ft. ³	Room Temperature	68°F.
Drying Temperature	150°F.	Relative Humidity	26%
Recirculation	33%		

Time	% Moisture		% Cracks
	Bottom	Top	
2:50	22.8		.7
3:05	22.9		
3:20	22.6		
3:35	22.2		
3:50	21.8		
4:05	24.1		
4:20	23.7		
4:35	22.9		
4:50	18.7		.7*

*Skin damp - hard to get sample.

TEST NO. 26

Dec. 17, 1952

Air Flow	15 c.f.m./ft. ³	Room Temperature	67° F.
Drying Temperature	150° F.	Relative Humidity	
Recirculation	0%		

Time	% Moisture		% Cracks
	Bottom	Top	
9:35	23.0		.7
9:50	23.1		
10:05	22.5		
10:20	22.9		
10:50	22.7		
11:05*	21.7		1.7

*Bin emptied; sample taken 2" above floor. Quite a few cracked beans next to perforated floor.

TEST NO. 27

April 2, 1953

Air Flow		Room Temperature	65° F.
Drying Temperature*		R.H.	37%
D.B. 100°	W.B. 84°	Abo. H.	.005
Air Stream*	R.H. 50%		
	Abo. H. .023		

Time	% Moisture		% Cracks
	Bottom	Top	
9:00	21.2		.7
9:30	23.8		
10:30	21.7		
11:30	21.1		
12:30	21.1		.7

*D.B. - dry bulb; W.B. - wet bulb; R.H. - Relative Humidity; Abo.H. - Absolute Humidity.

TEST NO. 28

April 3, 1953

Air Flow 10 c.f.m./ft.²

Drying Temperature

D.B. 100°F., W.B. 74.2°F.

Air Stream R.H. 30%

Abo.H. .013

Room Temperature 65°F.

Relative Humidity 38%

Time	% Moisture		% Cracks
	Bottom	Top	
10:00	21.5		.7
11:00	21.3		
12:00	21.1		
1:00	20.2		
3:00	18.3		.7

TEST NO. 29

April 9, 1953

Air Flow 10 c.f.m./ft.²

Drying Temperature

D.B. 140°F., W.B. 112°F.

Air Stream R.H. 40%

Abo.H. .052

Room Temperature 73°F.

Relative Humidity 57%

Time	% Moisture		% Cracks
	Bottom	Top	
10:45	21.5		.7
11:45	23.9		.8
12:45	22.4		.8
1:45	20.5		.8

TEST NO. 30

April 10, 1953

Air Flow 10 c.f.m./ft.³
 Drying Temperature
 D.B. 140°F., W.B. 90°F.
 Air Stream R.H. 15%
 Abo.H. .019

Room Temperature 66°F.
 Relative Humidity 48%

Time	% Moisture		% Cracks
	Bottom	Top	
7:30	21.3		.7
8:30	19.8		1.0
9:30	16.3		3.0

TEST NO. 31

April 10, 1953

Air Flow 10 c.f.m./ft.³
 Drying Temperature
 D.B. 160°F., W.B. 126°F.
 Air Stream R.H. 40%
 Abo.H. .09

Room Temperature 70°F.
 Relative Humidity 50%

Time	% Moisture		% Cracks
	Bottom	Top	
12:30	21.3		.5
1:30	22.7		1.4
2:30	21.3		4.3
3:30	20.5		5.7

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