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GRAIN DRYING AND STORAGE STUDIES IN SOUTHWEST GEORGIA
SIMONS, J.W. HARE, W.W. 1 OF 1

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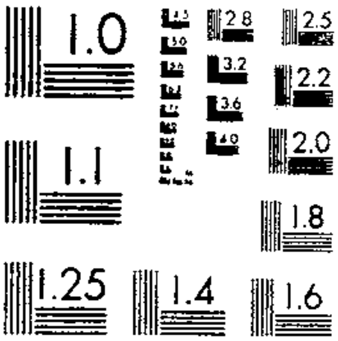

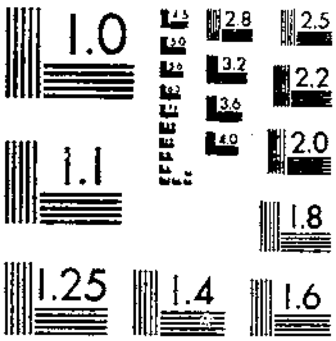

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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GRAIN DRYING and STORAGE STUDIES

In Southwest Georgia

Technical Bulletin No. 12[illegible]2

Agricultural Research Service
U.S. DEPARTMENT OF AGRICULTURE

In Cooperation With
Georgia Agricultural Experiment Stations

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Grain Drying and Storage Studies in Southwest Georgia

By J. W. SIMONS, *research agricultural engineer, Agricultural Engineering Research Division, Agricultural Research Service,* and *research associate, Agricultural Engineering Department, University of Georgia,* and W. W. HARE,[1] *agricultural engineer, Agricultural Research Service*

Research studies on drying and storing grain have been conducted for several years at the College Experiment Station, Athens, Ga.—in the Piedmont area of the State. In this work emphasis was placed on drying with unheated natural air because of lower equipment and operation costs and simplicity of operation. The results indicated that drying with unheated air is practical and economical in northern Georgia. They also indicated that, because of climatic differences, recommendations differed somewhat from those for the Midwest and other areas where similar research has been conducted.

The research at Athens was limited primarily to drying with unheated air in parallel flow. It was not known whether the recommendations from this research[2] would be satisfactory for drying with air in nonparallel flow under climatic conditions in southwestern Georgia. Thus it was deemed advisable to establish a project in this section to answer this question, to develop practical ways of maintaining grain quality economically for farm application, and to study certain basic relationships essential to the safe handling, drying, and storage of grain crops.

The project was initiated in January 1956 at the Southwest Georgia Branch Station, Plains, Ga., and was discontinued June 30, 1960.

Considerable grain is produced in southwestern Georgia and other parts of the Coastal Plain section of Georgia and production is increasing more rapidly there than in other sections of the State. By far the heaviest corn-producing counties are in that section. The climate in southwestern Georgia is fairly similar to that in an area extending eastward into South Carolina and westward through Alabama. Thus any recommendations on drying and storing developed for southwestern Georgia would apply to a fairly large section in at least three Southeastern States.

During the drying seasons this section of Georgia has slightly higher wet-bulb temperatures and wet-bulb depressions[3] than those at Athens, as indicated by the temperature map for August 1956–59 (fig. 1). There was less difference in the wet-bulb depression in late fall. Thus, whereas drying may proceed at slightly higher rates in the Coastal Plain section because of the higher drying capacity of the air during certain seasons, the higher temperatures tend to cause more rapid mold development and, consequently, greater danger of spoilage of high-moisture grain.

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[1] Stationed at Tifton, Ga. Formerly assistant agricultural engineer, Georgia Agricultural Experiment Stations.

[2] SIMONS, J. W. HOW TO DRY AND STORE GRAIN AND SEED ON GEORGIA FARMS. Ga. Agr. Expt. Sta. Bul. 33, 80 pp. 1958. (Revised.)

[3] The wet-bulb depression is a measure of the potential capacity of natural air to assimilate moisture.

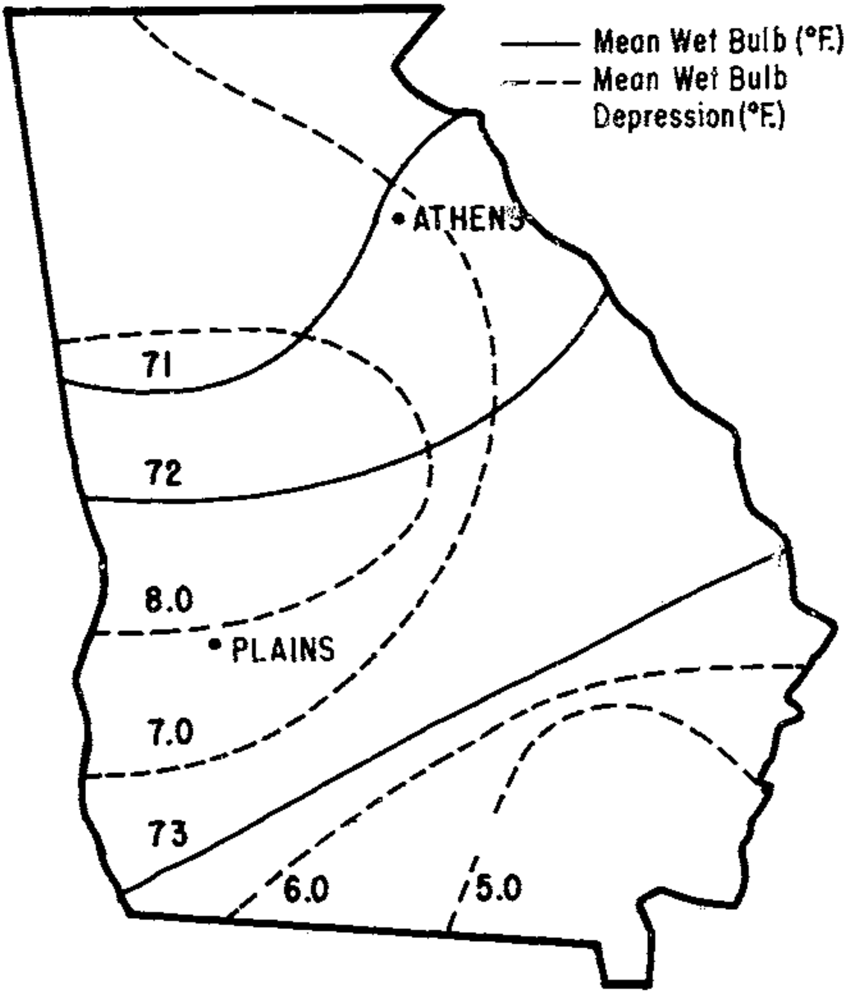

FIGURE 1.—Mean wet-bulb temperature and wet-bulb depression isotherms for August 1956–59 in Georgia.

FACILITIES AND GENERAL PROCEDURES USED

Description of Facilities

Drying and Storage Building

A Quonset "20" building, 36 feet in length and oriented with the long axis in a north-south direction, in which to conduct the studies, was erected in May 1956 (figs. 2 and 3). Several modifications of the standard Quonset "20" were made in this building. The crown was made of 12-foot curved sheets in place of the standard 8-foot ones. The building was divided into three 12-foot sections, with a grain bin in

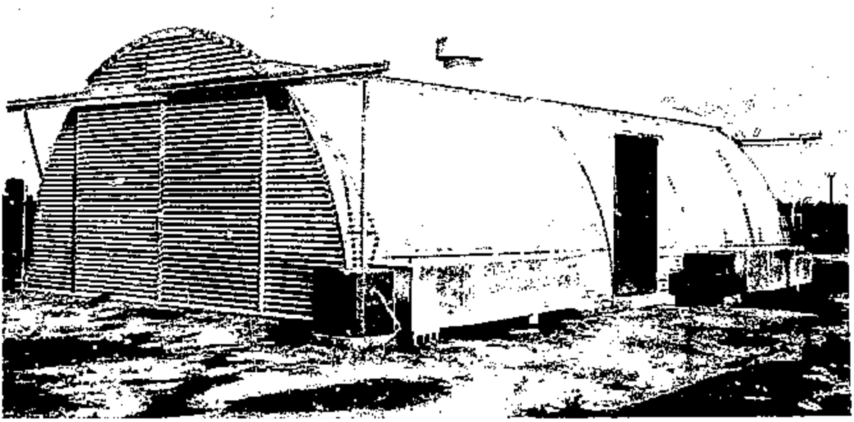

FIGURE 2.—Quonset "20" building erected for grain drying and storage studies.

each end and a workroom in the center. In keeping with the orientation of the building the grain bins are referred to as the north bin and the south bin. Each end of the building was provided with a pair of 6-foot by 8-foot sliding doors. A loading hatch was provided in the roof above the center of each bin. Small adjustable louvers were installed near the crown of the roof in end and partition walls

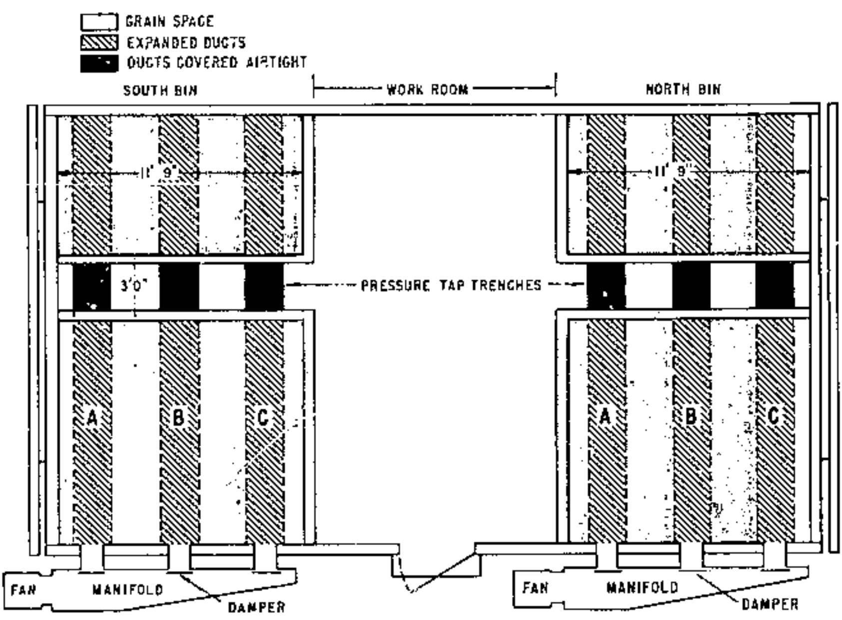

FIGURE 3.—Floor plan of Quonset "20" building.

to permit airflow from or to the bins. Access to the workroom was provided by a door in the east side. A ventilator at the center of the roof provided an air outlet from the workroom.

Fans and Air-Distribution System

Initially an Aerovent 18-inch, 7-blade propeller fan, direct-driven by a 3-horsepower, 3,450 r.p.m. motor and attached to each manifold, supplied air to each bin. In 1958 a 5-horsepower, 24-inch, 7-blade fan with larger manifold was installed on the south bin.

Each bin was equipped with three expanded metal ducts, 4 feet on centers, running across the 20-foot width of the building. The ducts were standard Stran-Steel design approximately 22 inches wide at the base and 15 inches high, with a cross-sectional area of 1.5 square feet, and were covered with 16-mesh screen for drying small grain and shelled corn. The ducts in each bin were connected by sleeves through the wall to a manifold outside the building. An adjustable damper was installed in the connection to each duct to permit regulation of airflow.

Shielded pressure taps were placed in each lateral duct near the manifold openings, midway across the building, and 16 feet from the manifold openings. These taps facilitated regulation of equal airflow in the three ducts through the use of the adjustable dampers. Pressure readings were taken by means of an inclined manometer graduated in 0.01-inch divisions.

Devices for Measuring Air Pressure and Airflow

A plywood trench, 3 feet wide and 6 feet high, was constructed across the 12-foot width of each bin near the center of the building; this was to facilitate taking air-pressure readings in the grain (fig. 3). The plywood sides were cut to fit over the ducts. Those parts of the ducts within the trench were covered with an airtight material, and the joints were caulked to prevent air leakage. Access to the trenches was gained through openings in the end and partition walls. These trenches provided vertical surfaces, at right angles to the axis of the ducts, from which air-pressure measurements in the grain mass could be taken to determine airflow patterns.

Ninety-three pressure taps were made between centerlines of two of the ducts in the east wall of each trench. Holes (1/8-inch diameter) were drilled into the plywood up to the outside ply on the grain side. These holes were filled with caulking compound, and a short section of aluminum tubing was inserted. The last ply was drilled—with a No. 60 drill—in alinement with the tubing bore.

Pressure points were placed on the curved liner sheets on both east and west walls in each bin; aluminum tubing was fastened to the inside of the liner sheets and run into the workroom. The end of the tubing was closed and four holes were drilled, with a No. 60 drill, 1/4 inch apart through the tubing. The locations of these and other pressure points mentioned are shown on airflow net charts in the section "Description and Results." Because of the possibility of air flowing laterally along the surfaces of the tubing, which might cause errors in readings, the pressure taps on the curved liner sheets were later replaced. Holes were drilled in the liner sheets with a No. 60 drill and copper elbows soldered over the holes on the outside surface of the sheets. Aluminum tubing connected to the elbows with plastic tubing was run in the wall cavity to the workroom. In later tests additional taps were extended into the grain; with these the airflow pattern around the extension of the sleeve between the liner sheet and the duct connector hood could be determined.

Devices for Measuring Temperatures and Moisture Contents in Grain

Thermocouple cables were placed horizontally in both bins primarily for checking temperatures to avoid possible spoilage. The location of these cables for the south bin is shown in figure 4. There

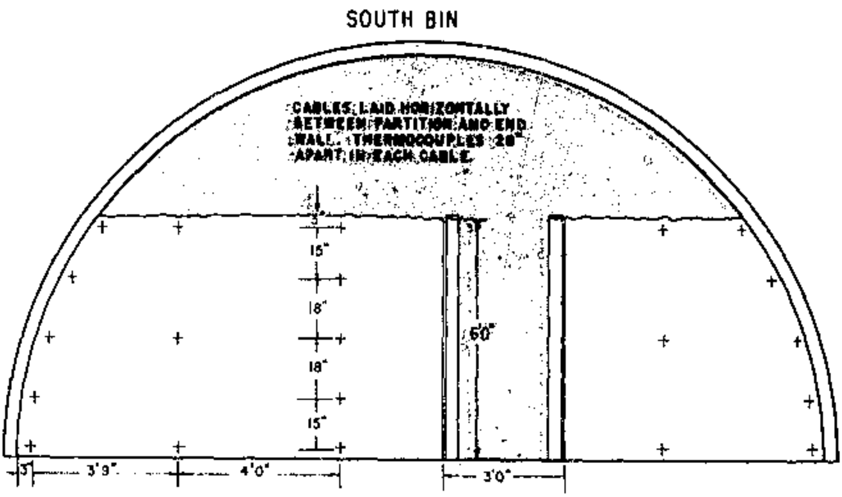

FIGURE 4.—Cross-section of south bin of Quonset "20" building, showing location of thermocouple cables.

were 126 thermocouples in the south bin; these were placed 26 inches apart on each cable with one thermocouple 5 inches from each end wall. A similar thermocouple arrangement was used in the north bin with the exception of the vertical row of cables 8 feet from the east wall. This area was partially covered with moisture elements in which thermocouples were incorporated. These moisture elements were located between ducts A and B, 8 feet 8 inches from the east wall, measured at the floorline. The moisture elements were of the pipecleaner type developed by W. V. Hukill, of the Agricultural Research Service. Moistures in the grain mass were read by means of the humidity elements and an experimental indicator. At low moisture it was found necessary to calibrate and make readings with the Tag-Heppenstall moisture indicator.

General Procedure for Tests

Small grain was brought directly from the combine to the storage building. Corn was generally harvested by a picker and was hauled to a commercial sheller before it was placed in storage. Both small grain and corn were harvested with as high a moisture content as existing conditions would permit, which in most cases was lower than desired.

Sampling and Grading Grain Prior to Tests

Each load of grain was sampled on the truck; a standard 5-foot, 11-cell probe was used. The sample taken was large enough to be representative of the lot and to permit obtaining moisture and grading determinations. A standard grain divider facilitated obtaining representative small samples for individual moisture and grading determinations. Samples for grading purposes were dried to or below the moisture content necessary for No. 1 grain before delivery to the grader. Grading was done by a licensed grain grader located at the College of Agriculture at Athens.

The grain was loaded into the bins through the roof hatch by means of an elevator. A movable chute attached beneath the loading hatch facilitated a fairly even distribution of grain into all parts of the bin and prevented the accumulation of trash immediately below the hatch. The fan was generally operated during the filling process with the air forced up through the grain to aid in the removal of trash. When high-moisture grain was loaded in the bin, the fan was operated continuously at night to prevent buildup of heat in the grain mass.

Thermocouple cables and moisture elements, when used, were placed in the grain as the bin was being filled.

Measuring Moisture Content

All moisture contents were measured and are given on a wet basis. In 1956 and the spring of 1957 moisture determinations were made by means of a Tag-Heppenstall moisture meter. Large fluctuations of the meter needle caused by green foreign matter and by live field insects in the grain made it impossible to obtain accurate moisture determinations. A Brown-Duval moisture tester was installed during the summer of 1957 and was used for the rest of the tests.

Sampling Grain in the Bins

Sampling of the grain during and at the completion of drying was done with the standard probe. No probe samples were taken in the bins until the top layer of grain was 16 percent or lower in moisture content in order to reduce possible channeling of air in the grain with high moisture content. Five probe samples, equally spaced, were taken between each set of ducts. Grain from the bottom three cells of the probe was used for the bottom sample; that from cells five, six, and seven was used for the middle sample; and that from the top three cells was used for the top sample. A special box was constructed to catch and keep separate the grain from each of the three levels.

Consumption of Electricity, Fan Operation Time, and Humidistatic Fan Control

The electricity consumed by each fan was metered with a standard watt-hour meter. Fan operation time was recorded from a time meter in each circuit. A switch permitted either manual or automatic operation of each fan. The automatic circuit included a humidistat to limit fan operation at humidities below maximum desired levels for drying and above minimum desired levels for rewetting tests. These humidistats were mounted in a small weather shelter adjacent to the quonset building.

Calibrating Fan Delivery

Fan delivery was calibrated by two methods.

In the spring of 1956 calibration was accomplished by the Pitot tube method with the bin filled and the fan unit attached to the manifold. The length of the duct in pipe diameters, the position of the Pitot tube, and the construction and location of the eggcrate straightener were in accordance with the National Association of Fan Manufacturers Standard Test Code for Centrifugal and Axial Fans. Test data were taken in accordance with the Code. Manifold dampers were adjusted until uniform pressure readings were obtained in all three ducts and until a center reading of the Pitot tube indicated approximately the correct air delivery desired (based on estimated center reading factor). A complete survey across the duct was then taken and further adjustments were made, if necessary. This procedure was followed for three different duct pressures to establish a curve for each fan. Only the 3-horsepower fans were calibrated by this method.

In the fall of 1956 the 3-horsepower fan for the south bin was calibrated by the use of three plenum chambers built by Stran-Steel according to the standards of the American Society of Mechanical Engineers Fan Test Code. Calibration [4] provided curves relating plenum pressures and fan delivery to manifold pressures. Barometric pressures were read from an aneroid barometer. Dry- and wet-bulb temperatures were measured with a sling psychrometer. Fan speeds were measured with a stroboscopic tachometer. Data were corrected to standard air conditions and rated fan speed.

The 3-horsepower fan assembly for the north bin and the two 5-horsepower fans with manifolds were calibrated later in a similar manner.

Measuring Temperatures and Relative Humidities

Temperatures in the grain mass were measured by means of thermocouples, previously described, with a portable potentiometer. A solenoid-operated 8-bank, 20-point stepping switch arrangement in each bin permitted rapid reading of the numerous thermocouples.

[4] Under the direction of Henry L. Ringle, research engineer, Stran-Steel Corp.

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Air temperatures and relative humidities were recorded by means of a hygrothermograph. This was housed in a standard Weather Bureau instrument shelter located 0.2 of a mile from the quonset site. Sling psychrometer checks made occasionally at the quonset site indicated close agreement with the hygrothermograph data.

Determining Insect Count and Damage

Samples for insect count and damage were not taken until the grain had 14 percent moisture content or lower. Sampling was done at irregular intervals; the time the grain had been in storage and the number of insects in the previous sample determined the sampling interval. Both surface and probe samples were taken from the four quarters of each bin. The probe sample from each quarter was examined as a composite sample until 1959. Then top, middle, and bottom samples for each quarter were examined separately. The insect count and the damage was determined by the Agricultural Marketing Service, U.S. Department of Agriculture, at Tifton, Ga.[5]

Determining Fat Acidity and Germination

Determination of fat acidity and germination were made in early tests. Since grade and moisture content appeared to be adequate criteria for drying and since the value of tests for fat acidity and germination were questionable for some grains the latter tests were discontinued.

DESCRIPTION AND RESULTS

Spring Grains (Oats and Wheat)

Description of Tests

In the 4 years, 1956 through 1959, the tests were conducted, high-moisture grain could not be obtained because of disease and adverse weather. Rust in oats caused almost complete crop failure. High winds blew down grain and dried it rapidly before harvest could begin. Rains over a period of 2 or 3 weeks prevented combining but did not prevent natural drying. Only in the spring of 1956 was it possible to obtain oats and wheat for drying tests, and the initial moisture content of these grains was lower than desired.

The wheat available at the Georgia station filled the north bin to a depth of 5 feet 8 inches. Sufficient oats were available to fill the south bin to its full depth of 6 feet. At this depth and with the plywood pressure trench in place, there were 808 bushels in the bin on the basis of 1.25 cubic feet per bushel. Thermocouple cables and the humidity elements (in the north bin) were placed in the grain as filling of the bin progressed. The fan was operated part time during the night while the bin was being filled, to cool the grain. Because of the low initial moisture content of the grain, the fan was controlled, after filling of the bin was completed, by the humidistat so that it operated

[5] D. W. LaHue, entomologist in charge.

only when the relative humidity was below 70 percent. Complete data on temperatures, pressures, and grain moisture were taken twice a week during drying. Temperatures were sometimes checked oftener.

Results

Results of drying wheat and oats are summarized in table 1. The results indicated safe drying at an economical cost of about 1½ cents per bushel for wheat reduced from 15.8 to 9.2 percent moisture content and 1 cent per bushel for oats reduced from 15.2 to 9.2 percent moisture content, with electrical power at 2 cents per kilowatt-hour. The airflow rate was higher than that recommended as minimum (2 c.f.m. per bushel for wheat and 1½ c.f.m. per bushel for oats and 15 percent initial moisture content) for northern Georgia with parallel airflow; the grain was dried to almost 9 percent, which is lower than normal. A lower total cost would have been achieved by drying to only 11 percent—the recommended level for southern Georgia. A slight infestation of insects was noted in the wheat in mid-July. No fumigant was applied, and the damage was not excessive when the bin was unloaded in mid-September. No insect activity was found in the oats.

Fall Grain (Grain Sorghum)

Description of Tests

The north bin was filled with grain sorghum to the full 6-foot depth once each season during the 4 years the project was in operation. The grain sorghum was used as it came from the combine, without cleaning. During the first 2 years the humidity elements were used in an effort to delineate the drying fronts.

During the 1956 and 1957 seasons unheated atmospheric air was used for the drying process. In 1956 the humidistat was set so that the fan operated only when the relative humidity was below 85 percent. This setting was later reduced to 70 and finally to 50 percent. In 1957 drying was started with the humidistat set at 75 percent; the humidistat was later set at 50 percent.

For the 1958 and 1959 seasons a Stran-I supplemental heat unit with butane gas burner was installed at the intake to the fan. Automatic control was achieved by a humidistat, located in one of the manifold sleeves, that permitted the burner to operate only when the relative humidity of the air discharged into the lateral duct was above 60 percent.

Results and Discussion

Results of drying the four bins of grain sorghum are summarized in table 2. In the first year, drying was started late in November with an airflow rate lower than that recommended for parallel airflow in northern Georgia. Low temperatures further reduced the rate of drying; this resulted in a high per-bushel consumption of electricity. At this airflow rate, however, spoilage might have occurred because of higher temperatures if drying had been attempted earlier in the season. The moisture content on January 2, 1957, was 12.5 percent—higher than would be desired for longtime storage. Further drying

TABLE 1.—*Summarized results of drying wheat and oats, Plains, Ga., summer 1956*

Crop	Moisture content		Grade		Airflow rate	Drying time		Electricity used per bushel	
	Initial	Final	Initial	Final		Fan operation	Total in bin	Total	Per 1 percent moisture removed
	Percent	*Percent*			*C.f.m. per bu.*	*Hours*	*Days*	*Kw.-hr.*	*Kw.-hr.*
Wheat	15.8	9.2	2	2	3.5	182	13	0.79	0.12
Oats	15.2	9.2	1	1	3.7	135	12¾	.53	.09

TABLE 2.—*Summarized results of drying grain sorghum, Plains, Ga.*

Date drying started	Moisture content		Grade		Airflow rate	Drying time		Electricity used per bushel		LPG used per bushel	
	Initial	Final	Initial	Final		Fan operation	Total in bin	Total [1]	Per 1 percent moisture removed [1]	Total	Per 1 percent moisture removed
	Percent	*Percent*			*C.f.m. per bushel*	*Hours*	*Days*	*Kw.-hr.*	*Kw.-hr.*	*Gallon*	*Gallon*
Nov. 23, 1956	21. 7	12. 5	2	2	3. 6	330	40. 3	1. 50	0. 163	0	0
Oct. 16, 1957	19. 6	11. 2	4	4	3. 8	250	25. 5	. 94	. 112	0	0
Nov. 11, 1958	18. 6	11. 2	1–2	1–2	3. 1	206	9. 5	[2]. 86	[2]. 116	[2]. 125	[2]. 017
Oct. 8, 1959	20. 3	9. 7	1–2	1–2	3. 5	221	17. 4	[2]. 82	[2]. 078	[2]. 197	[2]. 019

[1] Number of bushels based on minimum test weight of 55 pounds per bushel at 14 percent moisture content and corrected for initial moisture content.

[2] Weight estimated to calculate per bushel consumption.

reduced the moisture content to 10.3 percent by February 18, 1957, at an additional electricity consumption of 0.75 kilowatt-hour per bushel.

Data for 1957 and 1958 showed little difference in the electricity used per bushel per 1 percent of moisture removed although supplemental heat was used in 1958. Drying began almost a month earlier in 1957 than in 1958; thus, the drying was faster because of the higher atmospheric temperatures. In the first 2 years the cost of electricity, at 2 cents per kilowatt-hour, per bushel per 1 percent of moisture removed was less than $3/10$ of a cent. The last 2 years with the same electrical rate and LPG at 18 cents per gallon the comparative cost was $1/2$ cent. Thus the cost of a 10-percent reduction in moisture content under average conditions did not exceed about 3 cents per bushel with unheated air and 5 cents per bushel with LPG for supplemental heat.

Safe drying was accomplished with unheated air, as indicated by the fact that there was no reduction in grade. The time of drying can be held to a minimum by early harvesting and drying, but more power and a higher airflow rate is needed with the higher moisture content to assure safe drying. In many instances the supplemental heat provides excellent insurance against spoilage or downgrading, which might otherwise occur in high-moisture grain during extended periods of rainfall. This was the case in 1959 when the atmospheric relative humidity was 60 percent or below only 29 hours during the entire drying period. The average wet-bulb depression was only 2.5 degrees during this period; whereas, the normal is probably about 6.0 degrees.

Fall Grain (Corn)

Description of Tests

One batch of shelled corn was dried in the south bin each year during the 4 years the project was in operation. The bin was filled to a depth of 6 feet each season. In 1956 the fan was operated continuously until the grain moisture content of the wettest layer was lowered to 17 or 18 percent. The fan was then controlled by the humidistat to operate at a relative humidity of 70 percent or below until the moisture content reached 14 or 15 percent. Further economical drying was obtained by lowering the humidistat setting to 60 percent and finally to 50 percent. Some slight variance from this procedure was followed in succeeding years, such as omitting the 60-percent step or operating during the initial drying with a thermostat setting of 90 percent rather than continuously during long periods of foggy or rainy weather. Temperature, pressure, and grain-moisture data were taken the same way they were in tests on drying oats and wheat. They were taken less frequently during the later stages of drying because of the longer drying periods.

The first 2 years the pressure trench and the 3-horsepower fan were used. The 5-horsepower fan, with larger manifold, was installed and the pressure trench removed in 1958.

Results and Discussion

Results of drying the four bins of shelled corn are summarized in table 3. The difference in the fan operation time for a somewhat comparable moisture reduction is indicated in the comparison of 1956 and 1959 data. The rate of 2.8 c.f.m. per bushel took over twice the time a rate of 5.5 c.f.m. per bushel did for only about 1 percent greater reduction in moisture content. The time required was influenced some by the weather and by the schedule of setting the humidistat—neither of these was identical for the 2 years. The electricity consumed per bushel per 1 percent of moisture removed was about 45 percent higher in 1956 than in 1959. This was apparently the result primarily of a less efficient scheduling of the humidistat control. Even with these differences the average consumption of electricity for a 10-percent moisture reduction could be estimated to be about 1⅓ kilowatt-hours per bushel, or 2⅔ cents per bushel with electricity at 2 cents per kilowatt-hour. These costs could be expected, except under very unfavorable weather conditions, with the drying operation beginning generally not later than early October. Actually the wet-bulb depression for these years was 1° to 3° less than the normal 3- to 6-year averages for the two Weather Bureau stations closest to Sumter County, Ga., where the project was located. The Weather Bureau records for these stations have not been kept long enough to establish norms, but the data indicate that the normal atmospheric temperatures might be considerably better than those during the tests. Thus the time and cost figures resulting from the tests could be considered reasonably conservative.

Safe drying was achieved in 1956 and 1957 with an airflow rate slightly lower than that recommended as minimum for parallel airflow in northern Georgia.

The 1958 season was the only one in which downgrading was known to have definitely occurred during the drying process. This downgrading occurred mainly in the top third of the bin between ducts. Initially, the bottom third graded No. 2, the middle third graded between No. 3 and 4, and the top third graded No. 4. The bottom two-thirds had 22.2 percent moisture content and the top third 26.7 percent. Based on studies at Athens the airflow rate of 5.5 c.f.m. per bushel was adequate for drying the bottom two-thirds safely but not the top third. The airflow was reversed 11 days after drying began to provide drying from the top down because of molding occurring between ducts. The minimum safe airflow rates determined at Athens applied to No. 1 and No. 2 corn. It would be expected that a higher-than-minimum airflow rate would be needed to maintain the grade of corn initially low in quality because of kernels damaged in harvesting.

TABLE 3.—*Summarized results of drying shelled corn, Plains, Ga.*

Date drying started	Moisture content		Grade		Airflow rate	Drying time		Electricity used per bushel	
	Initial	Final	Initial	Final		Fan operation	Total in bin	Total [1]	Per 1 percent moisture removed [1]
	Percent	*Percent*			*C.f.m. per bu.*	*Hours*	*Days*	*Kw.-hr.*	*Kw.-hr.*
Sept. 14, 1956	19. 1	11. 0	1	1	2. 80	307. 4	25. 0	1. 16	0. 159
Oct. 15, 1957	15. 2	11. 2	[2] 1	([3])	2. 75	141. 2	27. 0	. 49	. 128
Sept. 14, 1958	23. 8	10. 4	[4] 2–4	[4] 1–5	5. 46	82. 9	26. 0	[5] 1. 57	[5] . 117
Sept. 25, 1959	18. 3	11. 3	[6] 1	([3])	5. 50	143. 0	12. 0	. 77	. 110

[1] Number of bushels based on minimum test weight of 54 pounds per bushel at 14 percent moisture content and corrected for initial moisture content.

[2] Grade not representative owing to improper method of sampling. Later samples much lower in grade because of cracked kernels and foreign material.

[3] Sample not taken.

[4] Individual loads graded. Initial low grades due to damaged kernels. Final low grade also due to molding of damaged kernels.

[5] Weight estimated to calculate per-bushel consumption.

[6] One-half No. 1 weevily.

Drying Corn to Lower-Than-Normal Moisture Content To Control Insects

Description of Tests

Corn stored into the summer normally must be fumigated at least twice and sometimes more in order to prevent excessive insect damage. The cost of fumigant for each fumigation is about 2 cents per bushel. Some fumigants are lethal, and all fumigants must be handled carefully to avoid undesirable effects on the worker. Grain insects cannot breed in grain with a moisture content below 9 percent, and their activity is greatly restricted in grain below 11 percent. It was thus decided to dry the grain to lower-than-normal moisture contents in an effort to control insects without the use of fumigants.

This drying was accomplished by continuing fan operation at a relative humidity of 50 percent and lower after the corn reached the normal moisture content for safe storage.

Results and Discussion

Results of drying shelled corn to lower-than-normal moisture content are summarized in table 4. The moisture reduction was fairly comparable for the 4 years the experiment was conducted; however, in the fall of 1958 the fan operated only about 30 percent of the time required in 1956 and used about 50 percent as much electricity as it did in 1956. This resulted from the higher temperatures in the fall of 1958. In 1957–58 the long drying time and the high consumption of electricity were caused primarily by the lower-than-normal wet-bulb depressions since the airflow rate was not too much greater than in 1956–57. The extra cost of electricity for drying required to reduce the moisture content to a lower-than-normal level ranged from 0.4 to 1.2 cents per 1-percent reduction, with electricity costing 2 cents per kilowatt-hour. For a 2½-percent reduction in moisture content the extra electricity cost might be expected to vary from 1 to 3 cents per bushel; hence, the average would be comparable with the cost of fumigant for one fumigation. If the short time Weather Bureau records at stations closest to Sumter County could be considered as norms, then the average electricity cost for normal temperatures would be less than 1½ cents per bushel.

In 1956–57 insect samples were not taken until the drying had been completed. In 1957–58 about 4 percent of the kernels were infested with live insects or were damaged at the beginning of this drying period, and 3 percent at the end of the period. This reduction in infestation may have resulted partly from unloading and reloading the bin, to facilitate air-distribution studies. As the grain was moved mechanically, insects and foreign materials were sifted and blown out, which improved the grain quality. Also in 1958–59 insect samples were not taken until after drying was completed. Very few live insects were found in the sample taken on November 21, 1958, and virtually no insects were found in that taken on March 2, 1959.

In the fall of 1959 almost one-half of the grain in the bin graded No. 1 weevily. Samples taken October 14, 1959, indicated considerable

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TABLE 4.—*Summarized results of drying shelled corn to lower-than-normal moisture content, Plains, Ga.*

Date drying started	Moisture content		Grade		Airflow rate	Drying time		Electricity used per bushel	
	Initial	Final	Initial	Final		Fan operation	Total in bin	Total	Per 1 percent moisture removed
	Percent	*Percent*			*C.f.m. per bu.*	*Hours*	*Days*	*Kw.-hr.*	*Kw.-hr.*
Oct. 9, 1956	11. 0	8. 5	1	1	2. 8	284. 9	97	1. 10	0. 438
Nov. 12, 1957	11. 2	9. 0	(1)	[2] 2–4	3. 5	342. 4	139	1. 38	. 626
Sept. 30, 1958	10. 4	8. 0	[3] 1–5	[3] 1–5	5. 7	83. 3	17	. 52	. 216
Oct. 7, 1959	11. 3	9. 5	(1)	[4] 2–3	5. 5	139. 3	61	. 78	. 433

[1] Sample not taken.
[2] Bottom, No. 2; middle, No. 3; top, No. 4. Low grades at all 3 levels were due to cracked kernels and foreign material.
[3] Low grades due to kernel damage in harvest.
[4] Low grades due to insect damage.

insect damage and a resulting need for fumigation. Drying to lower-than-normal moisture content had been started October 7, and it was decided to continue the process in an attempt to restrict insect activity without fumigation. Because of interference with other work, however, fan operation from October 7 to 28 was limited to 16 hours. The grain sample taken on December 2, when the moisture content was down to about 9.5 percent, also indicated a need for fumigation; a fumigant was applied January 15, 1960. The sample taken on April 8 showed an almost complete insect kill.

Reconditioning Corn Dried to Lower-Than-Normal Moisture Content

Description of Tests

Drying grain to a lower-than-normal moisture content for protection against insects results in a monetary loss to the farmer who sells his grain, because buying standards give no credit for the lower moisture content and the extra weight loss. Rewetting the grain successfully to an acceptable moisture level would be the final step to avoid such a monetary loss in this alternate method of protecting grain against insect damage.

Tests were run on shelled corn during the four seasons to determine the feasibility and cost of such reconditioning. The humidistat was set to operate the fan when the atmospheric relative humidity was 70 percent or higher in late winter or early spring of 1957, 1959, and 1960. In the spring of 1958 the setting used permitted fan operation at 80 percent or above, in an effort to reduce fan-operation time. The airflow rates were the same as those used in drying. During the first year pressure operation, as in drying, was used initially until the corn in approximately the bottom half of the bin reached 14 to 15 percent moisture content. The fan was then reversed to pull air downward through the corn to complete the rewetting process. In April 1958 (1957 crop) the air was pulled downward through the corn the first 82 hours and then reversed; this kept the wettest layer of corn on top where it could be easily inspected. The same procedure was followed in February 1959. In April 1960 the air was pulled down through the corn until the top reached 16 percent moisture content. The humidistat was then set to operate the fan at 70 percent and below in order to reduce the high moisture content at the top.

Results and Discussion

The first two seasons, with fairly comparable rates of airflow, about 4.4 percent moisture, on the average, was replaced in the corn; this increased the average level to 13.1 percent (table 5). This was accomplished in 17 days with less than 0.7 kilowatt-hour per bushel. During the last two seasons the moisture replacement amounted to about 3.3 percent. This took 5 to 17 days and used 0.4 to 1.3 kilowatt-hour per bushel. At 2 cents per kilowatt-hour the average cost was less than 1½ cents. Thus the average cost of drying to lower-than-normal

TABLE 5.—*Summarized results of rewetting low-moisture-content corn to an acceptable level, Plains, Ga.*

Date rewetting started	Moisture content		Grade		Airflow rate	Rewetting time		Electricity used per bushel	
	Initial	Final	Initial	Final		Fan operation	Total in bin	Total	Per 1 percent moisture added
	Percent	*Percent*			*C.f.m. per bu.*	*Hours*	*Days*	*Kw.-hr.*	*Kw.-hr.*
Jan. 17, 1957	8.5	13.2	1	[1] 1	2.8	188.5	18	0.723	0.154
Apr. 14, 1958	9.0	13.0	2–4	[2]	3.5	178	16	.645	.161
Feb. 9, 1959	9.0	12.5	[3] 1–5	3-sample grade.	5.7	176	17	1.260	.360
Apr. 1, 1960	9.6	12.8	[4] 3–4	[4] 2–3	5.5	72.5	5	.400	.125

[1] Top and middle graded No. 1; bottom, No. 1 weevily.
[2] Sample not taken.
[3] Low grades due to kernel damage in harvest.
[4] Low grades due to kernel damage in harvest. Improvement in final grade believed to be caused by difference in sampling conditions.

moisture content and rewetting to 13 percent moisture was about 3½ cents per bushel, or slightly less than the cost of fumigant for two fumigations. Therefore the grain could be sold at a higher moisture content than the safe storage moisture content.

The rewetting process should be used only if the corn will be used within a short time. This is evidenced by the increased insect activity in corn stored for about 2 months after rewetting. In 1957, the insect infestation in the lower layers, which were the wettest, increased to about 9 percent. In 1958, 1959, and 1960, the infestation shortly after rewetting was extremely low.

Measuring Grain Pressures When Low-Moisture Corn Is Rewetted

Description of Tests

Three methods were tried in an attempt to measure the increase in pressure when low-moisture corn is rewetted.

In the first method, cube-shaped cells made of sheet brass, with SR-4 strain gages attached to the inner surface on three sides of the cube representing the X-Y-Z axes, were used (fig. 5). The cubes were placed in the corn at middepth approximately halfway between the pressure tunnel and the east wall, near the center of the bin longitudinally. This was done in the fall of 1957.

In the second method, strain gages were placed on liner sheets and two studs of the partition wall facing the workroom, in the fall of 1957.

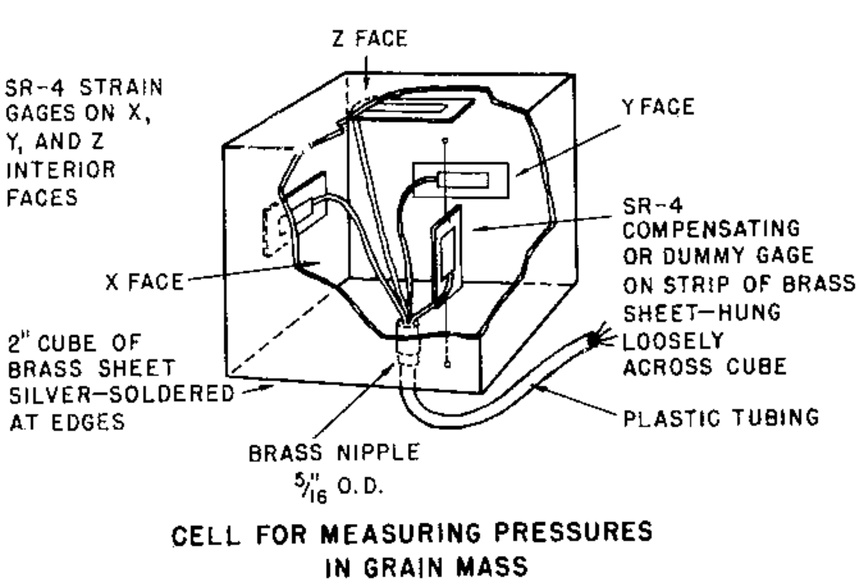

FIGURE 5.—Cell for measuring pressures in the grain mass.

In the third method, pressure panels made and previously used at Ames, Iowa,[6] were recalibrated and installed in the partition wall in the fall of 1959. Figure 6 shows the construction of a pressure panel, and figure 7 illustrates the installed panels as viewed from the workroom.

A piece of corrugated galvanized sheet was fastened to the face of each panel, so that the panels would present a surface almost identical to that of the partition liner sheet. The pieces were closely fitted but not in contact with adjoining pieces, and the joints were covered with tape to prevent kernels from wedging in the joints. Some slack was

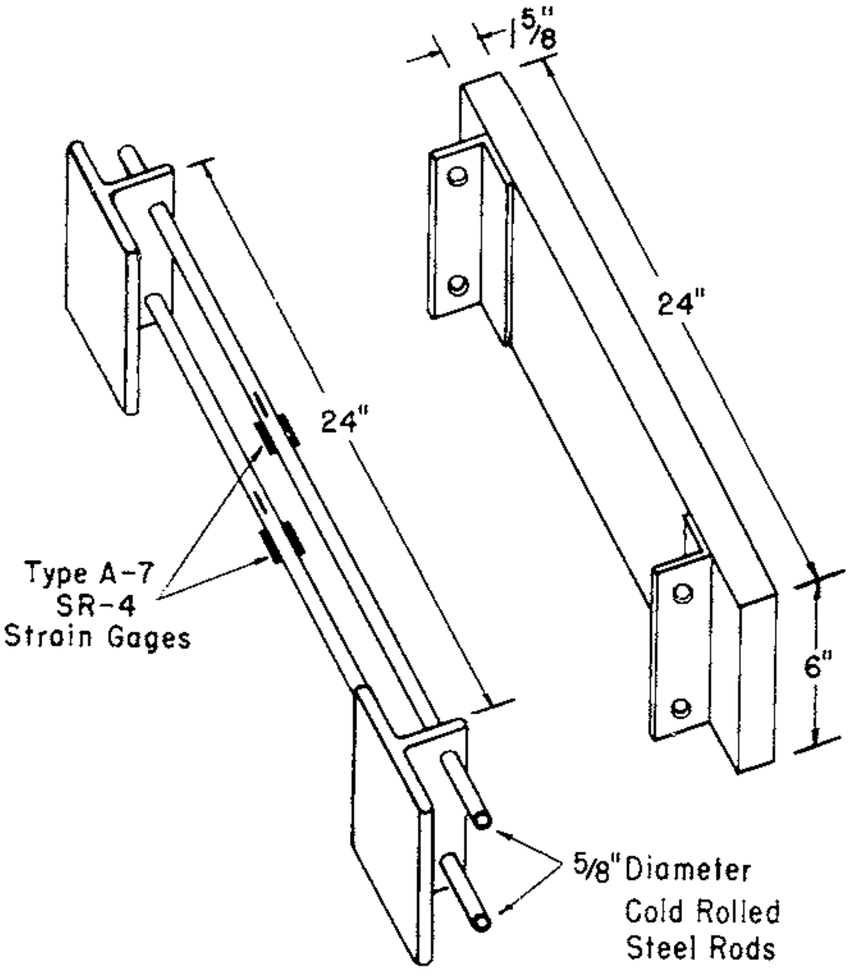

FIGURE 6.—Construction details of pressure panel.

[6] SAUL, R. A. MEASUREMENT OF GRAIN PRESSURES ON BIN WALLS AND FLOORS. Agr. Engin. 34 (4) : 231–234. 1953.

FIGURE 7.—Pressure panels installed in partition between south bin and workroom.

allowed in the tape at the joints to reduce the possibility of pressure being transmitted from one panel to another.

The studs supporting the panels were the same as the other partition studs but were installed specifically for this purpose. The studs were not fastened with pin connectors, but they were otherwise free to flex under load. Thus the resulting pressures measured would not represent the entire force developed in rewetting the corn. Readings of the strain gages on the panel-supporting bars were taken before rewetting started and at least once a day during rewetting. Moisture samples were taken by probe just before making the strain-gage readings.

Results and Discussion

Figure 8 shows the daily deviations in strain-gage readings from dry-grain measurements for one face each of two cells—one facing the end wall and the other the partition wall. The trend of the curves is upward of considerable magnitude, except for the January 29 readings. The readings on that day are believed to be in error because of malfunctioning of the strain-gage indicator.

Figure 9 shows the deviations for sides of the same cells facing the curved east wall. Here the general trend is downward, following the initial pressure increase after only 1 day of rewetting (January 17–18). This downward trend has at least two possible explanations. The first one is that displacement of the plywood pressure tunnel and flexing of the curved ribs of the building, in addition to relieving increases in pressure, might also permit the expanding kernels to slip and rise vertically; this reduced the pressure below that of dry corn. However, higher pressures on two of the faces of the cube (facing end and partition walls) may have resulted in outward deflection of the other faces and, thus, negative deviations in strain-gage readings for these other faces. The second is that calibration of the cubes in water, as was done in this case, resulted in conversion data with almost equal pressure on all faces. Thus the calibration might not be valid under the corn pressures encountered. The first explanation seems plausible because of the reversals in trend on January 22–23 and on January 24.

Figure 10 shows the deviations for strain-gages on one stud and the corrugated liner sheet. A definite upward trend resulted as the moisture content of the corn increased. Results in terms of actual pressure increases are indeterminate, since the stud connections were not hinged. The problem was further complicated by girts fastened between adjacent studs. These shortcomings were recognized in the beginning, but it was felt that even limited knowledge of deviation trends would be of value.

Figure 11 shows the relationship between lateral pressures, measured by the pressure panels in the partition wall, and moisture contents for three depths below the top surface of the grain. Because of the vertical arrangement of cells in the grain probe, grain from one cell only does not give a fair representation of the grain covering any single pressure panel. Thus at the depth of 1 foot 4 inches the grain moisture sample represents an area covered by three panels, and pressures for these three panels were averaged. At the 3-foot depth the grain moisture sample represents the area covered by two panels, although the strain gages on one did not function. At the depth of 4 feet 8 inches the sample represents an area covered by two panels, and these pressures were averaged.

While it was possible to obtain pressures on the bottom panel, the moisture contents at that level could not be obtained because the bottom

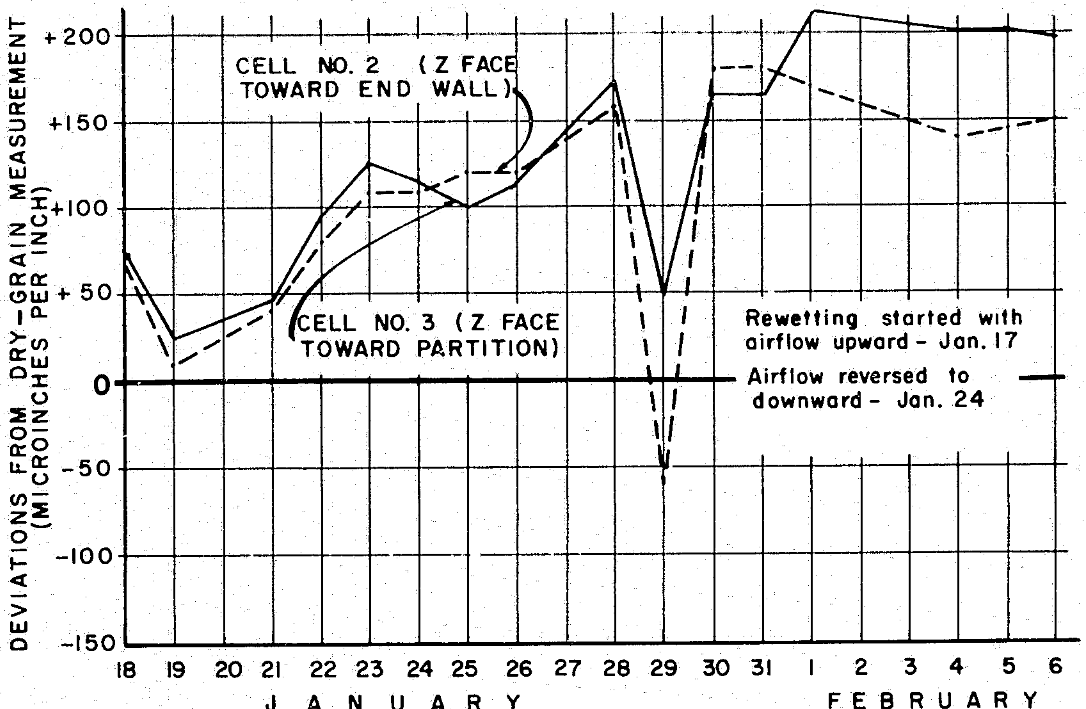

FIGURE 8.—Daily deviations in strain-gage readings of pressure cells facing end and partition walls in south bin.

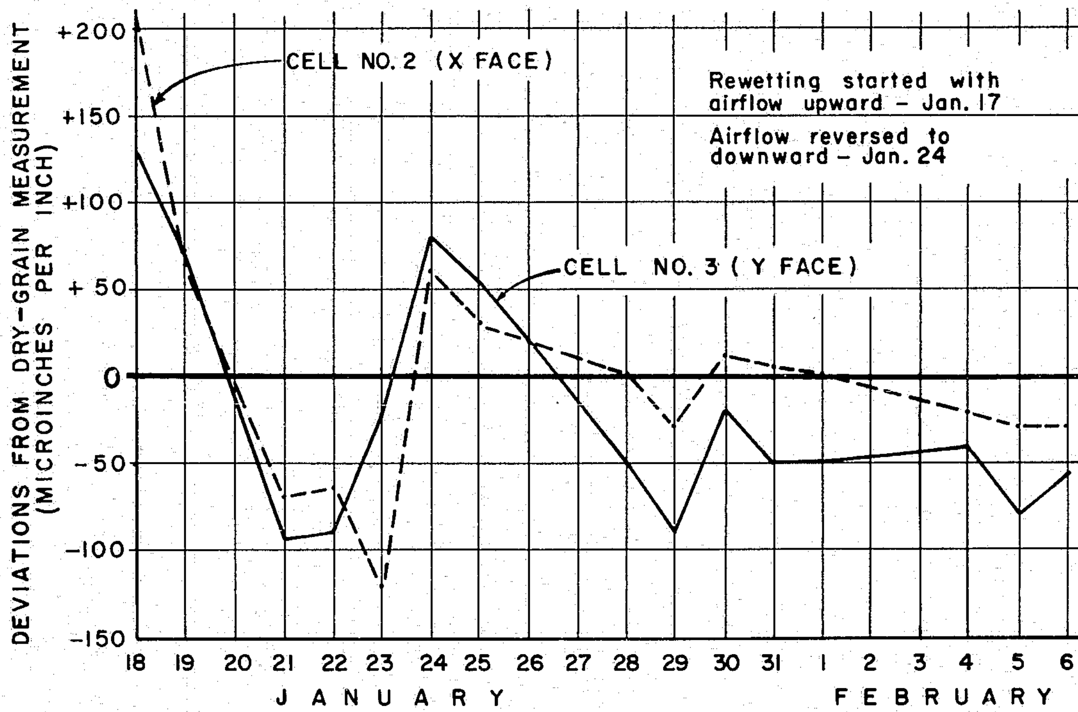

FIGURE 9.—Daily deviations in strain-gage readings of pressure cells facing curved wall of south bin.

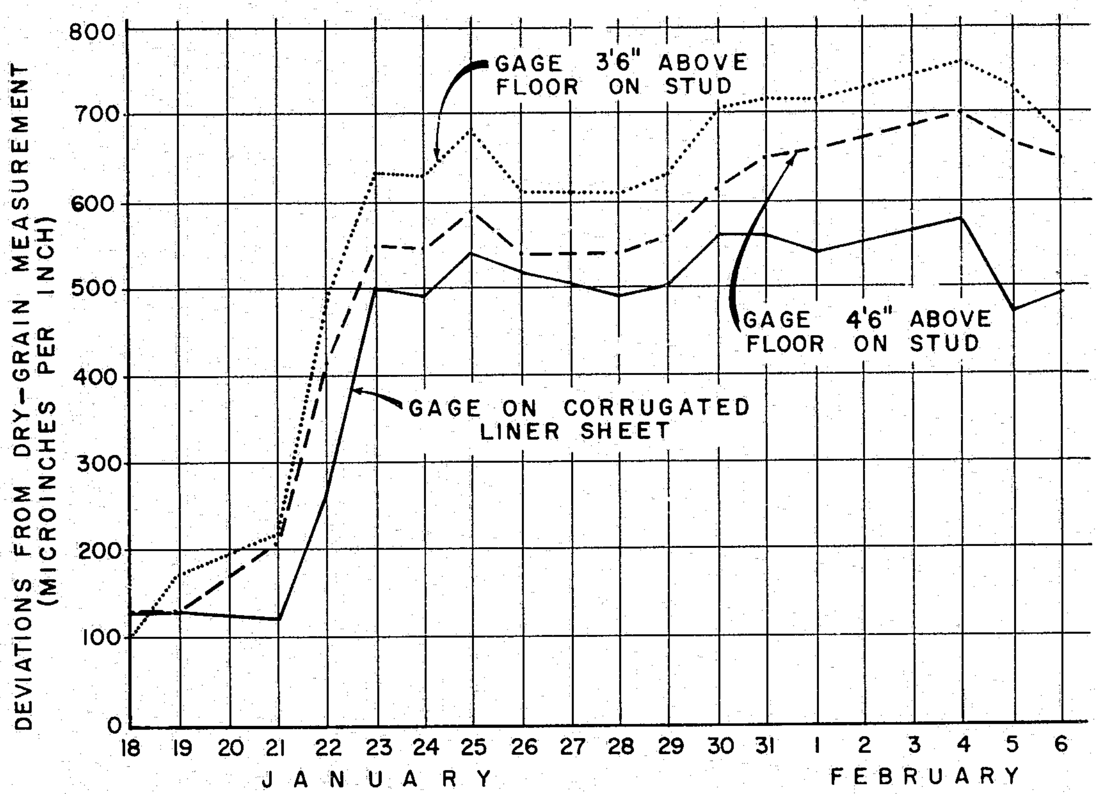

FIGURE 10.—Daily deviations in readings of strain-gages mounted on stud and corrugated liner sheet of south bin.

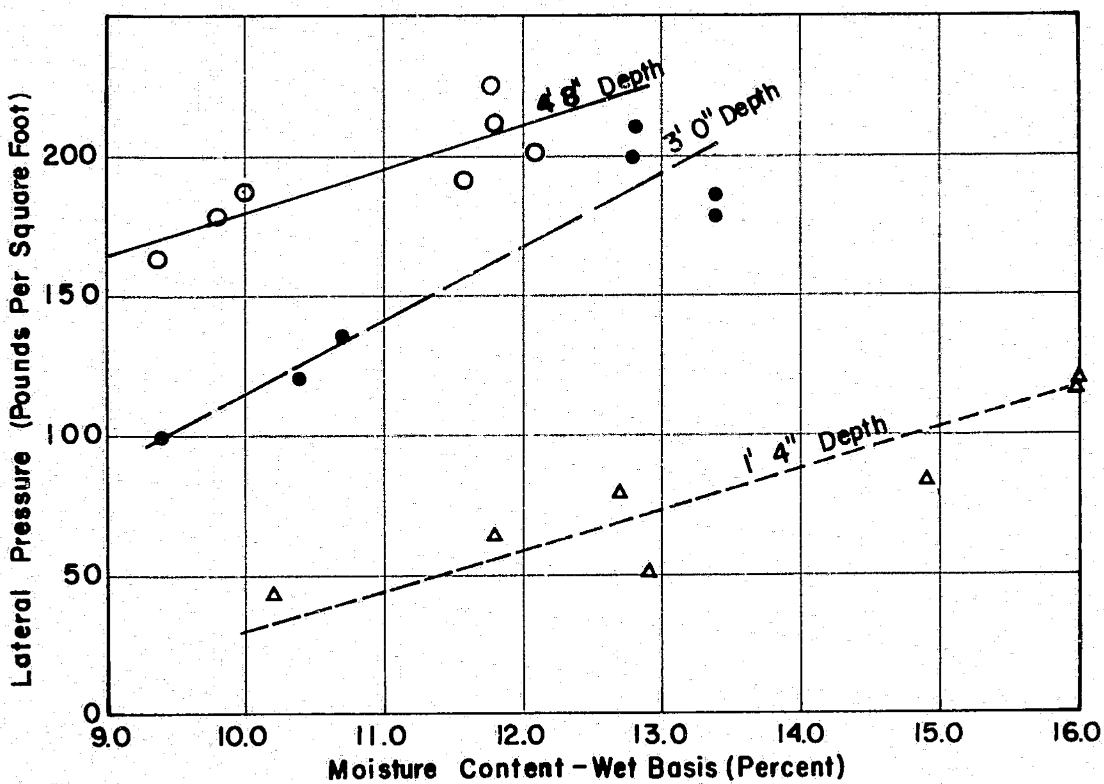

FIGURE 11.—Relationship between lateral pressures, measured by means of pressure panels, and moisture content.

cell is several inches above the lower end of the probe. Thus the maximum pressures in the bin were not plotted.

In figure 11 the line for the 3-foot depth should undoubtedly be parallel to the lines for the depths of 4 feet 8 inches and 1 foot 4 inches. The line for the depth of 4 feet 8 inches shows that the pressure increased from 165 pounds per square foot to 210 pounds per square foot, an increase of about 25 percent, when the moisture content rose from 9 to 12 percent. This may not be a measure of the full increase in pressure because flexure occurred in framing members and liner sheets.

A slight increase in vertical pressures at the depths of 1 foot 4 inches and 3 feet occurred as the moisture content increased (fig. 12). It would be expected that the line for the 3-foot depth should lie between and be parallel to the lines for depths of 1 foot 4 inches and 4 feet 8 inches. However, the points for the line for depth of 4 feet 8 inches are widely dispersed and additional data would be desirable in establishing this line. Apparently some unknown factor or factors have resulted in the crossing of the lines for the depths of 3 feet and 1 foot 4 inches.

General results of rewetting in terms of increased pressures indicated that an increase in corn moisture content from approximately 8½ to 16 percent at various levels in the corn did no apparent damage to the building.

Determining Drying Fronts Through Grain

Description of Tests

Humidity elements, previously described, were placed at the selected depths in three bins of grain during one spring and two fall seasons. The elements had been calibrated previously in grain at three moisture levels of roughly 12, 17, and 20 percent for each of three temperatures—45°, 80°, and 100° F.

Results and Discussion

Three charts (figs. 13, 14, and 15) show the drying fronts in one bin of grain sorghum. The moisture content of the grain sorghum was 21 percent initially; however, because of difficulty with the equipment, valid readings were not obtained until 4 days after drying started. The chart for November 27 (fig. 13) shows a 17-percent moisture line between the ducts almost in line with the top of the ducts. This may be because of slower drying in the area, but it is probably because of reabsorption of moisture caused by fan operation at high humidities. The drying fronts are not well defined. The moisture elements indicate a general level of moisture content rather than accurate values so that definitive drying fronts could not be expected. The chart for November 30 (fig. 14) shows an increase in moisture between ducts in this area; this indicates definitely the reabsorption of moisture from high-humidity air. Some reabsorption on top apparently occurred during the 3-day period, also. Considerable drying occurred in the 3 days between November 30 and December

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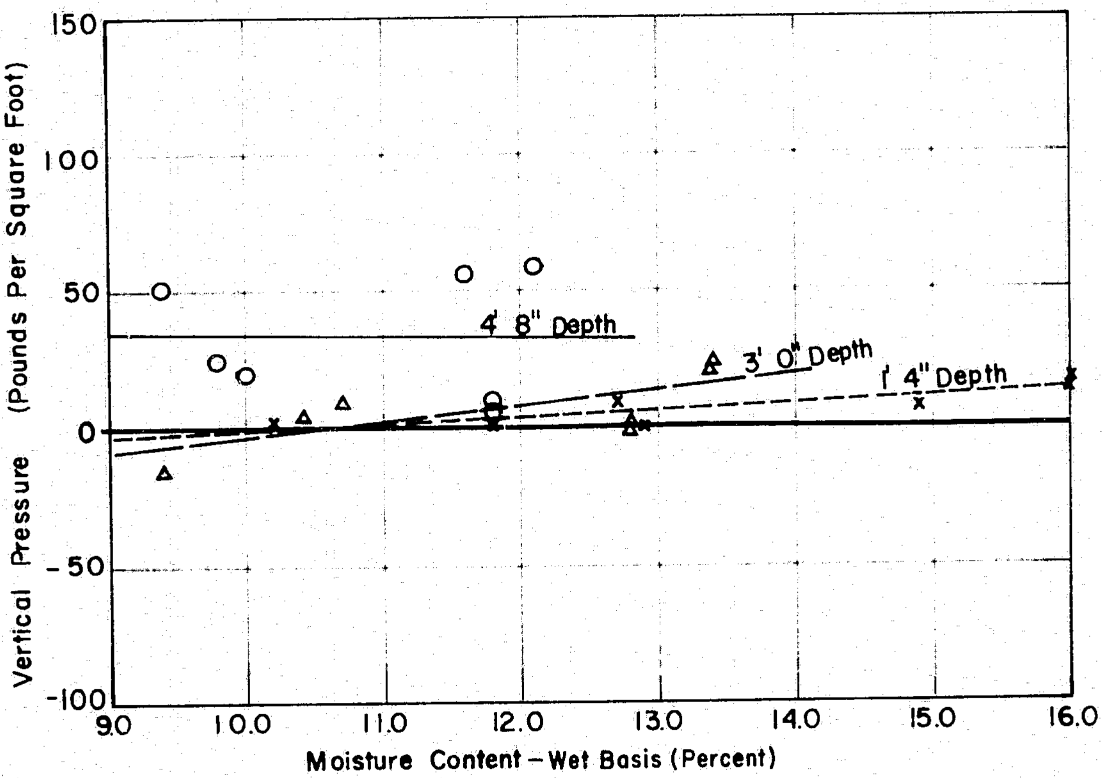


FIGURE 12.—Relationship between vertical pressures, measured by means of pressure panels, and moisture content.

3 (fig. 15). Some improvement was noted in the bottom third of the bin, although the humidistat setting permitted the fan to operate at relative humidities of 85 percent and below.

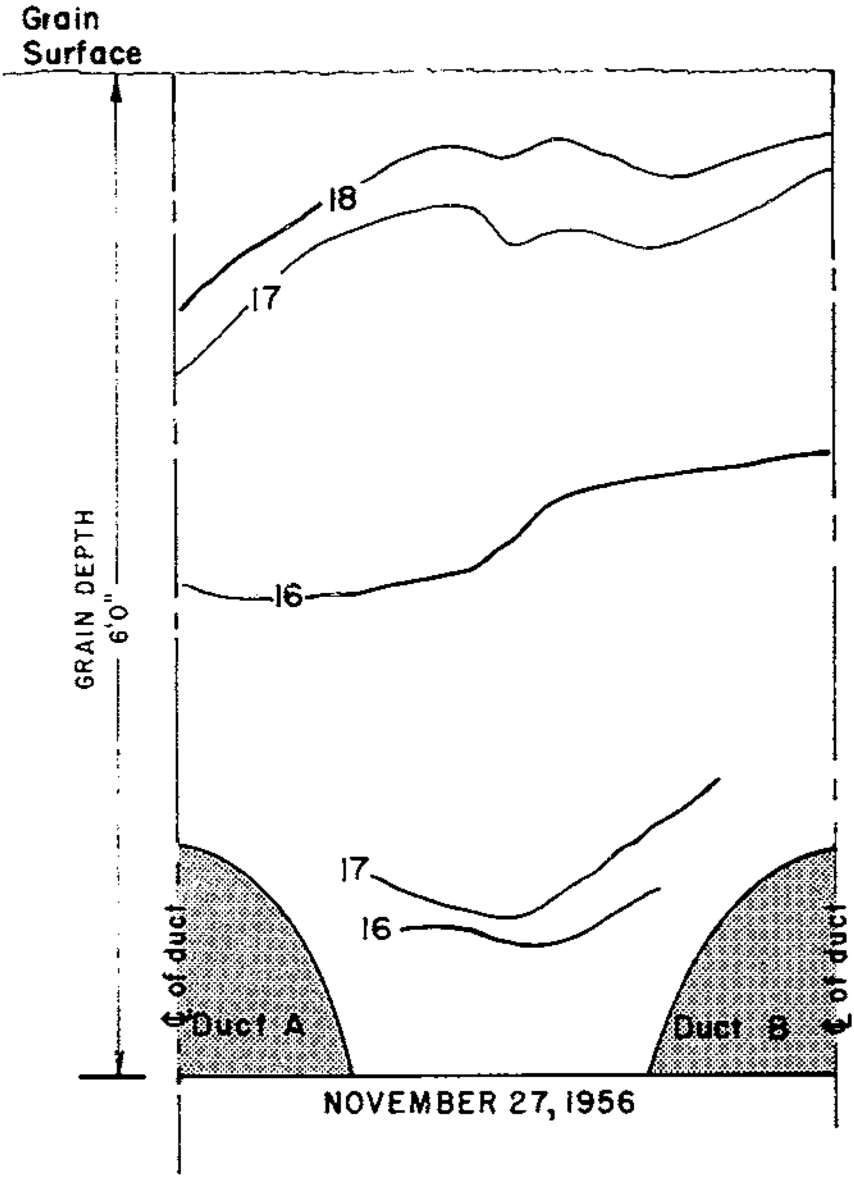


FIGURE 13.—Lines of equal moisture content show drying fronts in bin of grain sorghum.

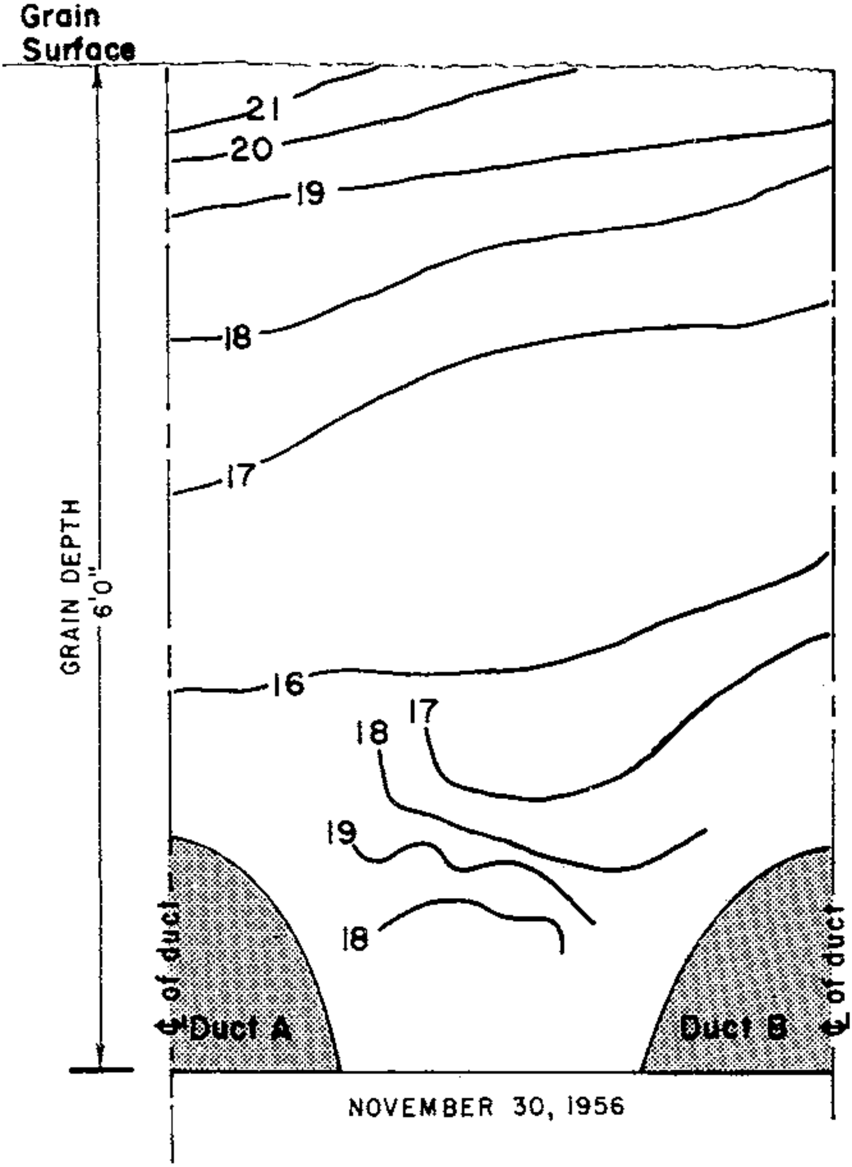


FIGURE 14.—Lines of equal moisture content show increased moisture content fronts, as compared with November 27 chart, due to fan operation at high humidities.

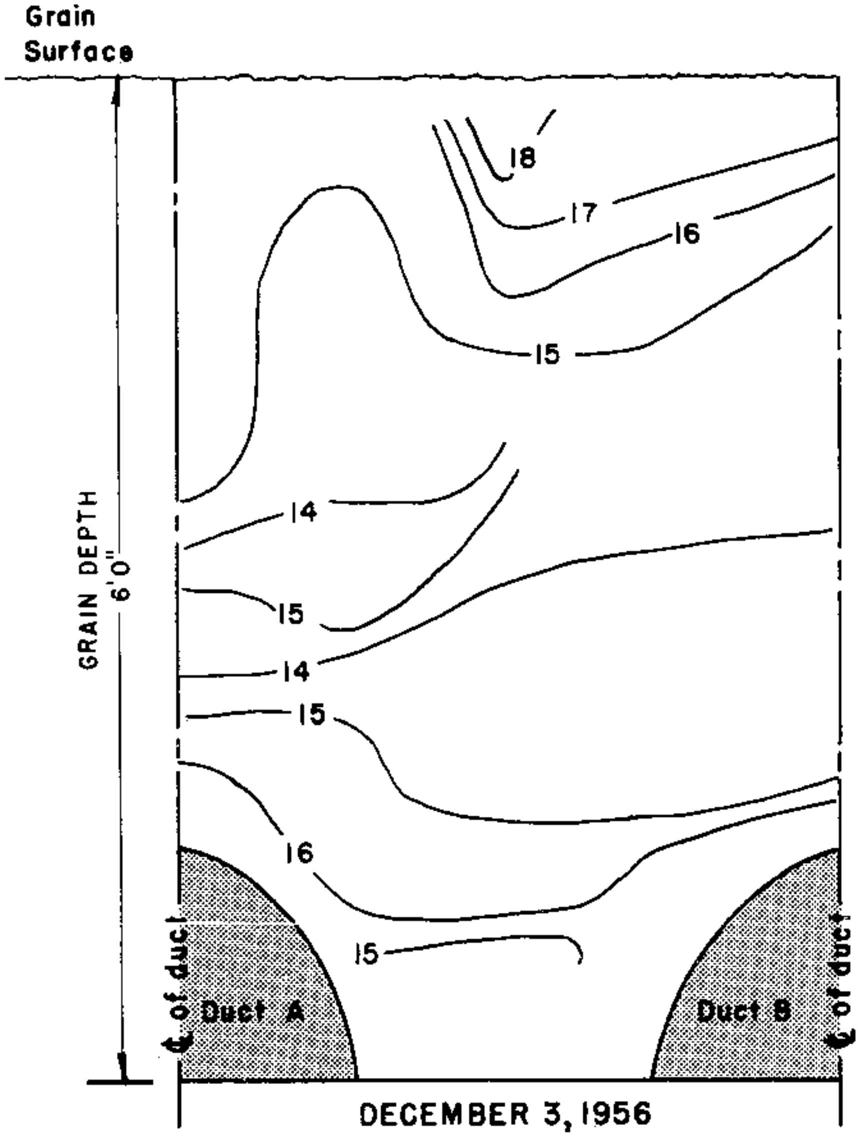


FIGURE 15.—Lines of equal moisture content show reduced moisture content fronts, as compared with November 30 chart; but they also show some rewetting of grain in lower layers caused by inability to control fan properly.

Determining Airflow Patterns Through Grain

Description of Tests

Lateral ducts were covered with 16-mesh screen wire. Pressure readings were taken at intervals during and after drying by means of pressure taps in the face of the plywood tunnel and the curved east and west walls of the building. These readings were used to establish airflow patterns through the grain in accordance with a method previously developed.[7] These airflow patterns provide a means of delineating apparent areas of unsatisfactory ventilation and of comparing the ventilation time at various points over and between the lateral ducts.

A performance ratio [7] is another measure of the effectiveness of the air-distribution system; this is the ratio of the slowest to fastest traverse time for the arbitrarily selected flow lines. It expresses the ratio of the approximate length of drying times required and indicates how much longer the fan has to operate because of the nonuniformity of air distribution.

Results and Discussion

Airflow patterns, with arbitrarily selected flow lines, for typical tests are shown in figures 16 through 20. Lines of equal traverse time, which have been assumed to denote lines of equal ventilation, are also shown. The test results shown were selected primarily to illustrate differences of airflow rates and flow patterns at the various walls. The airflow rates for oats were 1.5 and 3.7 c.f.m. per bushel. The airflow rate for grain sorghum was 3.1 c.f.m. per bushel, and that for wheat 3.3 c.f.m. per bushel.

Dampers in the three lateral ducts were adjusted to provide almost uniform pressures in the three ducts. The air distribution at the pressure trench and at the west wall was relatively uniform but it was not at the east wall. The chart for wheat (fig. 20) shows a skewed distribution at the east wall for duct A compared with duct B. This could be partially due to accumulation of trash over duct A in this particular test so that the airflow rate from duct A through the wheat mass would be actually less than from the adjacent duct B; this would result in a skewed equal-time-line pattern. A longer traverse time can be noted on east and west walls than on the plywood wall of the pressure trench, because of the greater distance of travel up the curved walls.

Usually, airflow paths are not shown for an area midway between ducts, extending a short distance above the floor. What happened in this area is not known exactly; the lines of flow in all probability do not show the true paths of airflow through this area. Part of the drying in this area may have resulted from temperature and vapor pressure differences that caused moisture transfer to the cooler, dryer grain. In all the tests where rates of airflow obtained were equal to

[7] HUKILL, W. V., and SHEDD, C. K. NON-LINEAR AIR FLOW IN GRAIN DRYING. Agr. Engin. 36 (7): 462–466. 1955.

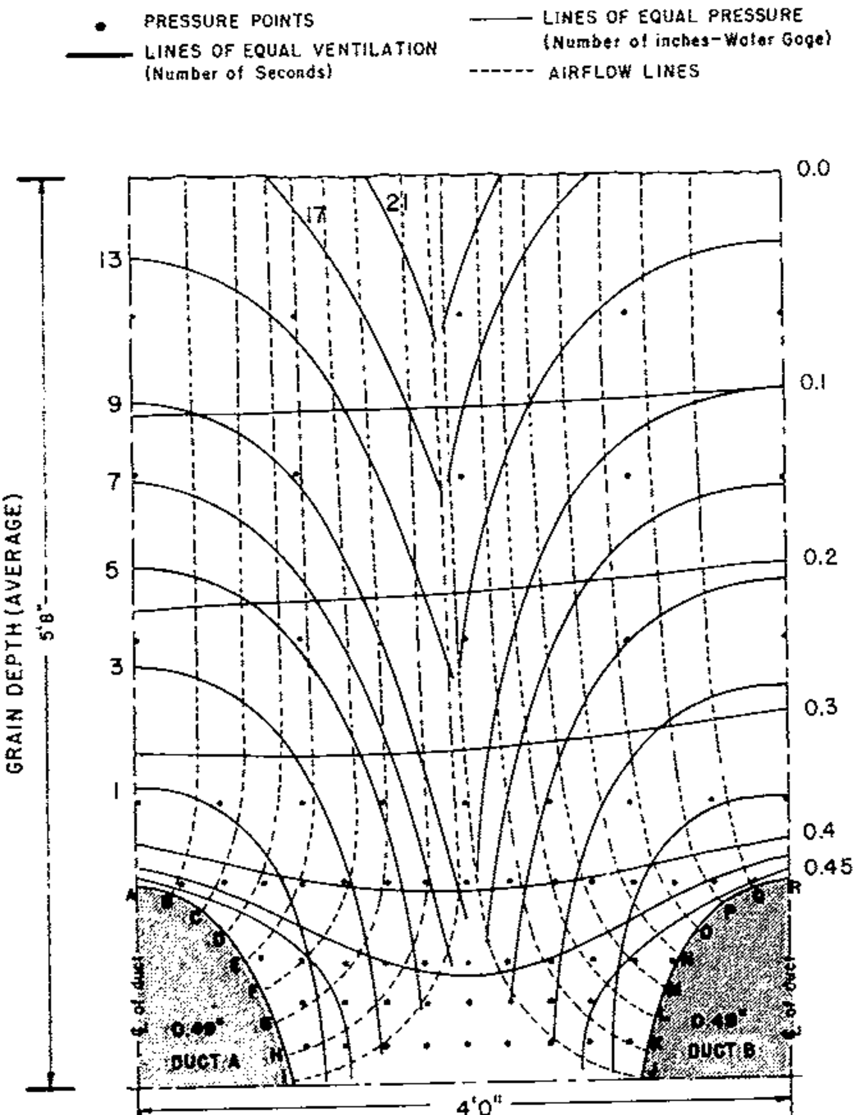


FIGURE 16.—Airflow net and equal ventilation lines for oats at wall of pressure tap trench. Average grain depth, 5 feet, 8 inches; airflow, 1.5 c.f.m. per bushel. Summer 1956.

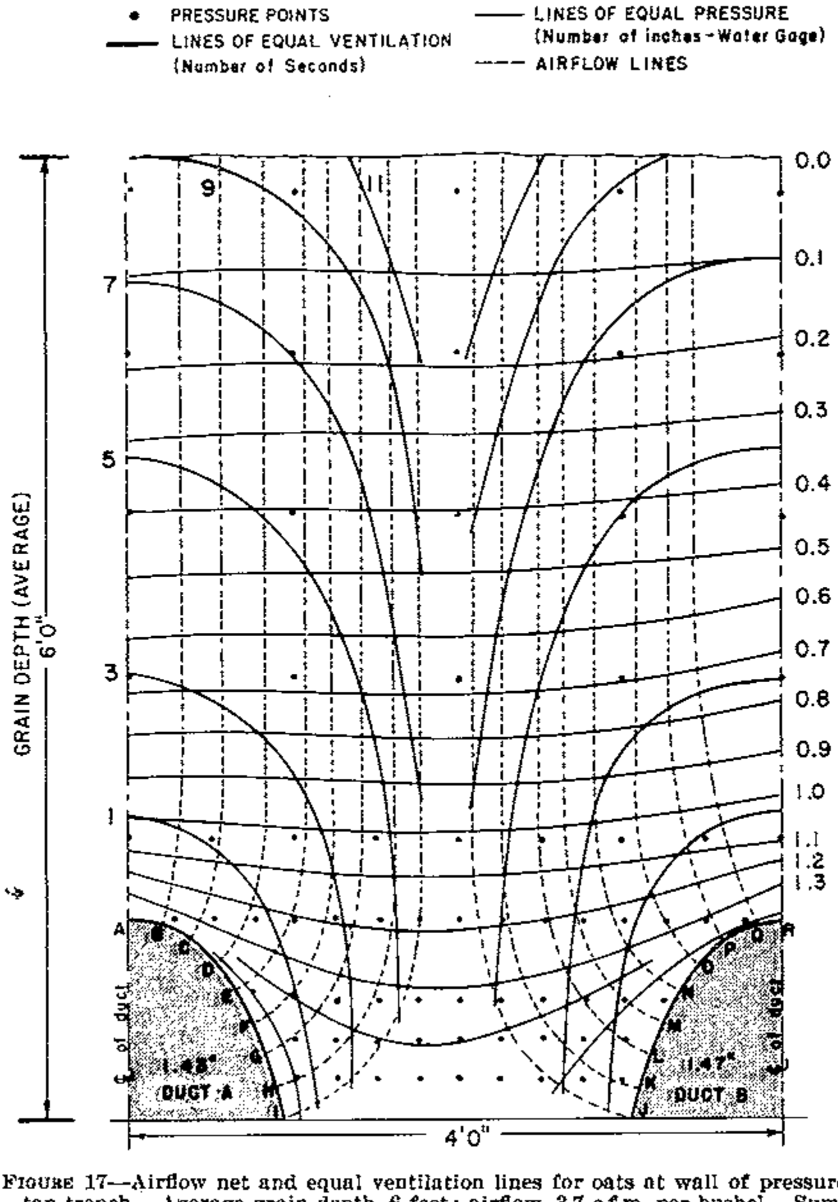


FIGURE 17—Airflow net and equal ventilation lines for oats at wall of pressure tap trench. Average grain depth, 6 feet; airflow, 3.7 c.f.m. per bushel. Summer 1956.

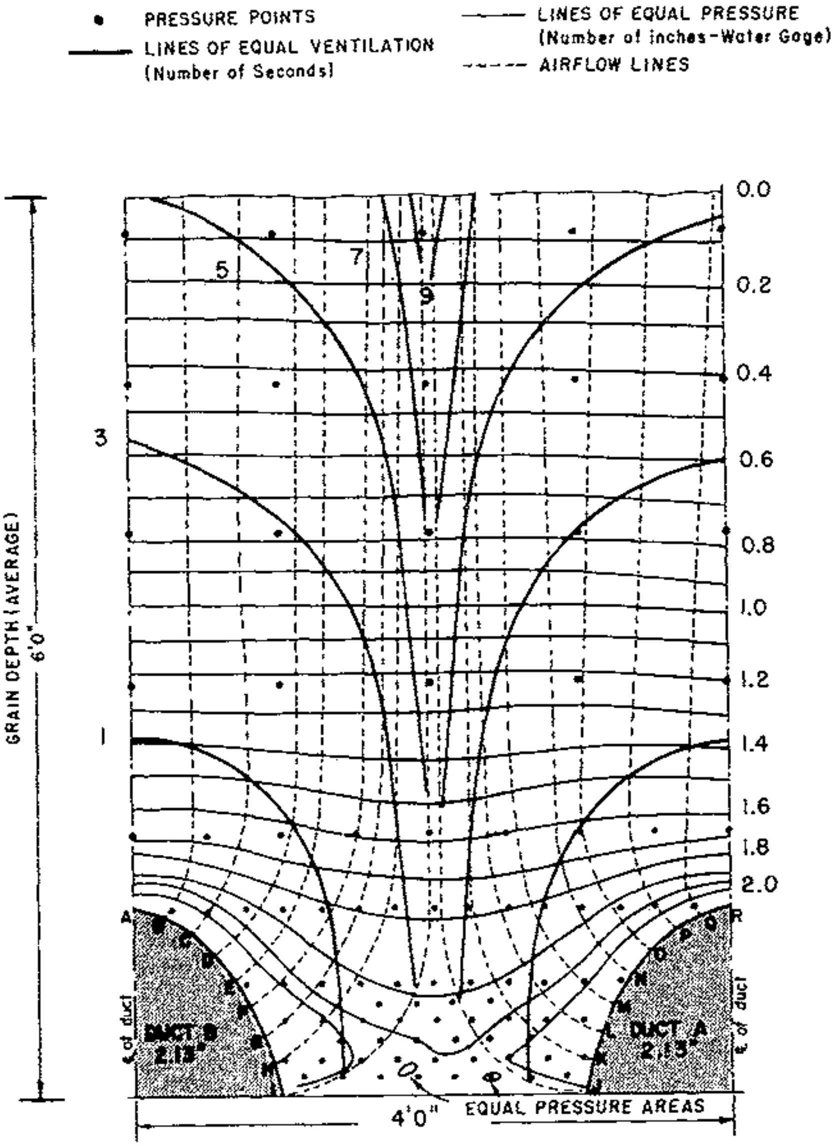


FIGURE 18.—Airflow net and equal ventilation lines for grain sorghum at wall of pressure tap trench. Average grain depth, 6 feet; airflow, 3.1 c.f.m. per bushel. Fall 1956.

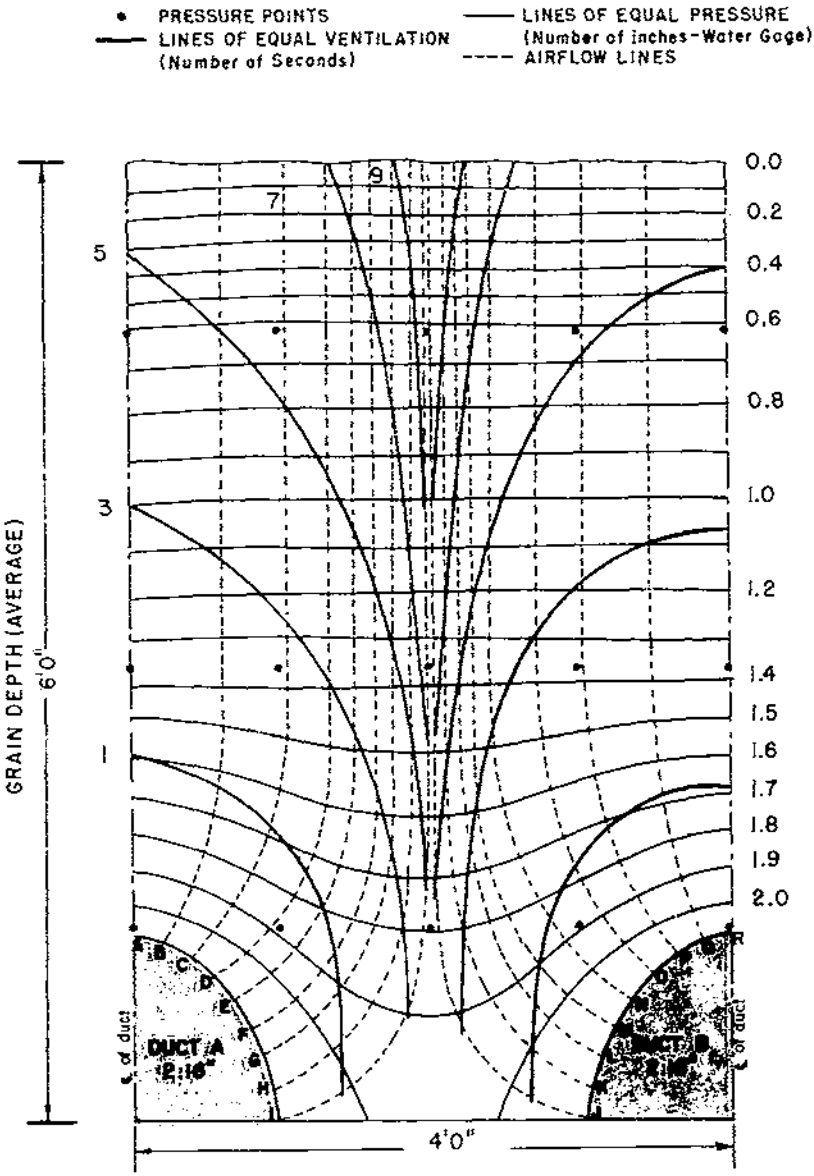


FIGURE 19.—Airflow net and equal ventilation lines for grain sorghum at west wall. Average grain depth, 6 feet; airflow, 3.1 c.f.m. per bushel. Fall 1956.

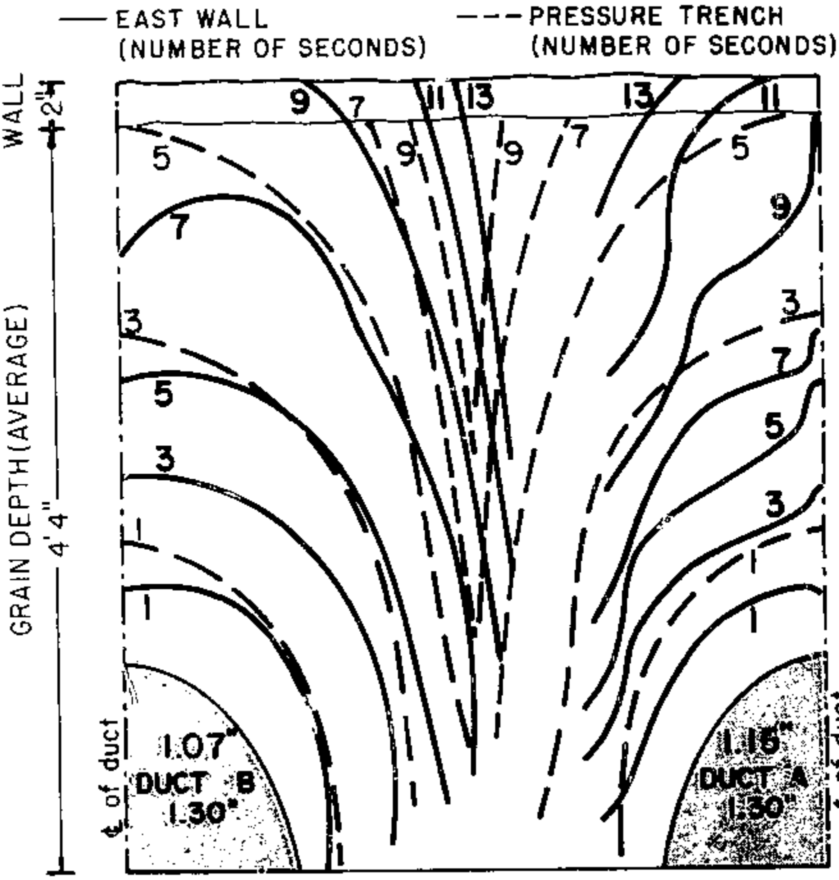


FIGURE 20.—Equal ventilation lines for wheat at east wall and pressure tap trench. Average grain depth, 4 feet, 4 inches; distance along curved wall, 4 feet, 6 inches; airflow, 3.3 c.f.m. per bushel. Spring 1957.

those found safe for drying with parallel airflow in northern Georgia, no visible deterioration of grain occurred in the questionable area.

The performance ratios (table 6) are approximately the same for any particular grain regardless of rate of airflow in this air distribution system. The ratio for oats is lower than those for corn, grain sorghum, and wheat; this indicates greater uniformity in airflow and better performance in drying oats than in drying the other grains.

TABLE 6.—*Slowest and fastest traverse times of air passing through grain and ratios of traverse times*

Crop, location, and flow rate	Traverse time					
	Lines A to I			Lines J to R		
	Fastest	Slowest	Ratio	Fastest	Slowest	Ratio
	Seconds	*Seconds*		*Seconds*	*Seconds*	
Wheat at pressure tunnel:						
3.5 c.f.m. per bushel	6. 25	11. 28	1. 8	6. 05	11. 63	1. 9
2.0 c.f.m. per bushel	10. 28	19. 27	1. 9	10. 49	19. 84	1. 9
Oats at pressure tunnel:						
3.7 c.f.m. per bushel	7. 59	12. 31	1. 6	7. 07	12. 32	1. 7
1.5 c.f.m. per bushel	15. 32	25. 06	1 6	14. 90	24. 80	1. 7
Corn at 2.0 c.f.m. per bushel:						
At pressure tunnel	5. 62	10. 86	1. 9	5. 66	10. 87	1. 9
At west wall	5. 39	10. 70	2. 0	5. 38	10. 76	2. 0
Grain sorghum at 3.1 c.f.m. per bushel:						
At pressure tunnel	4. 96	9. 50	1. 9	5. 04	9. 38	1. 9
At west wall	5. 50	11. 28	2. 0	5. 62	11. 32	2. 0

Improving Air Distribution in Shelled Corn

Lateral Ducts Covered on Top With Paper

Description of Tests

Previous tests had shown that the air leaving the top of the lateral duct took only 50 to 60 percent as long to reach the top surface as air leaving the bottom of the duct. Therefore, tests were initiated in an attempt to improve this air distribution, particularly in the area near the floor between ducts. A simple method—that of putting paper over the tops of the ducts—was studied. Three widths of paper were used—14, 10, and 6 inches—and the tests were run in that order. The dry corn was removed and heavy multilayered paper was placed longitudinally over the top of the ducts and equal distance on each side of the centerline.

Results and Discussion

As the width of paper decreased the duct pressure and traverse time decreased and the rate of airflow increased (figs. 21 and 22). Values for the 10-inch width were intermediate between values for 6- and 14-inch widths. Unfortunately the same fan was not used during the season these tests were in progress as was used previously. Changes had been made in the dampers and pressures were not obtained under these conditions with no covers over the ducts. Thus no direct comparison can be made between ducts covered and not covered. However, a comparison with data from previous seasons indicated little or no improvement with duct covers. The 14-inch

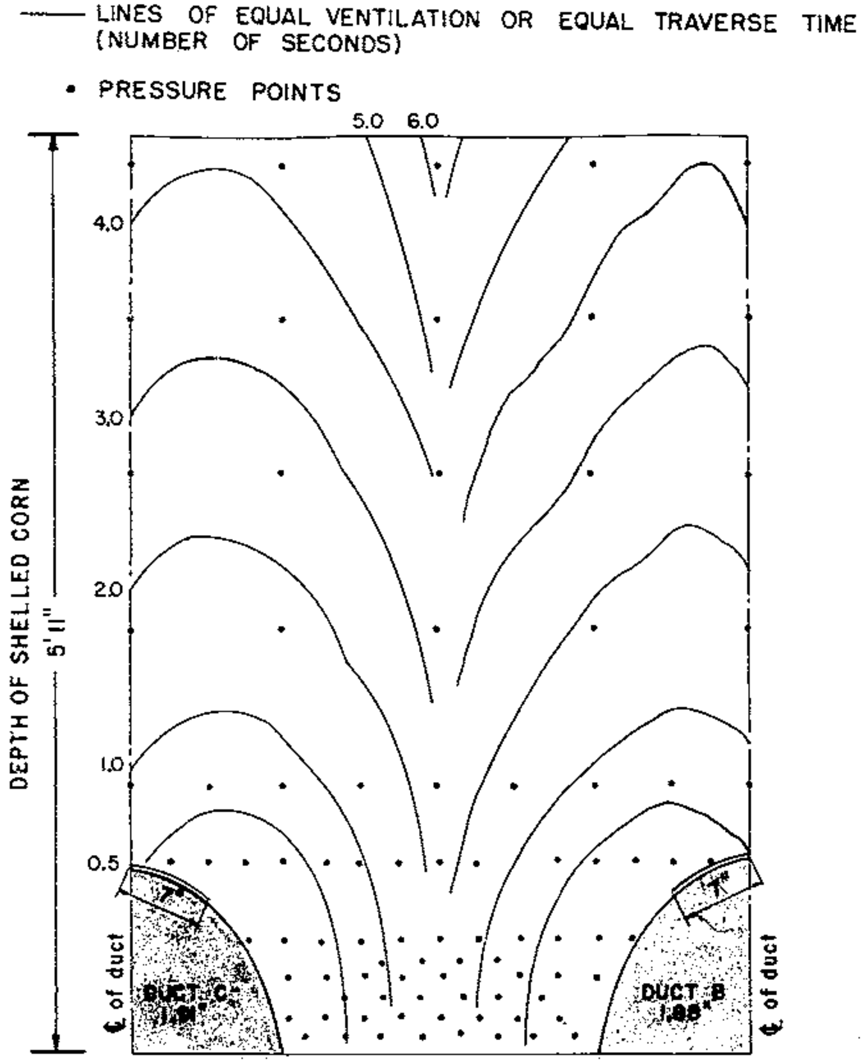


FIGURE 21.—Equal ventilation lines at wall of pressure tap trench with 14-inch width of paper over top of lateral ducts. Average depth of shelled corn, 5 feet, 11 inches; airflow, 3.3 c.f.m. per bushel. Winter 1958.

width of paper reduced airflow considerably below that recommended as the safe minimum rate for corn of 22 percent moisture content. Even the 10-inch cover resulted in a rate on the borderline of this minimum. The increase in airflow rate as the cover width decreased was undoubtedly influenced by the loss of trash and foreign matter each time the corn was removed to change covers. However, it is believed that this would have little effect on the air distribution near the floor between ducts.

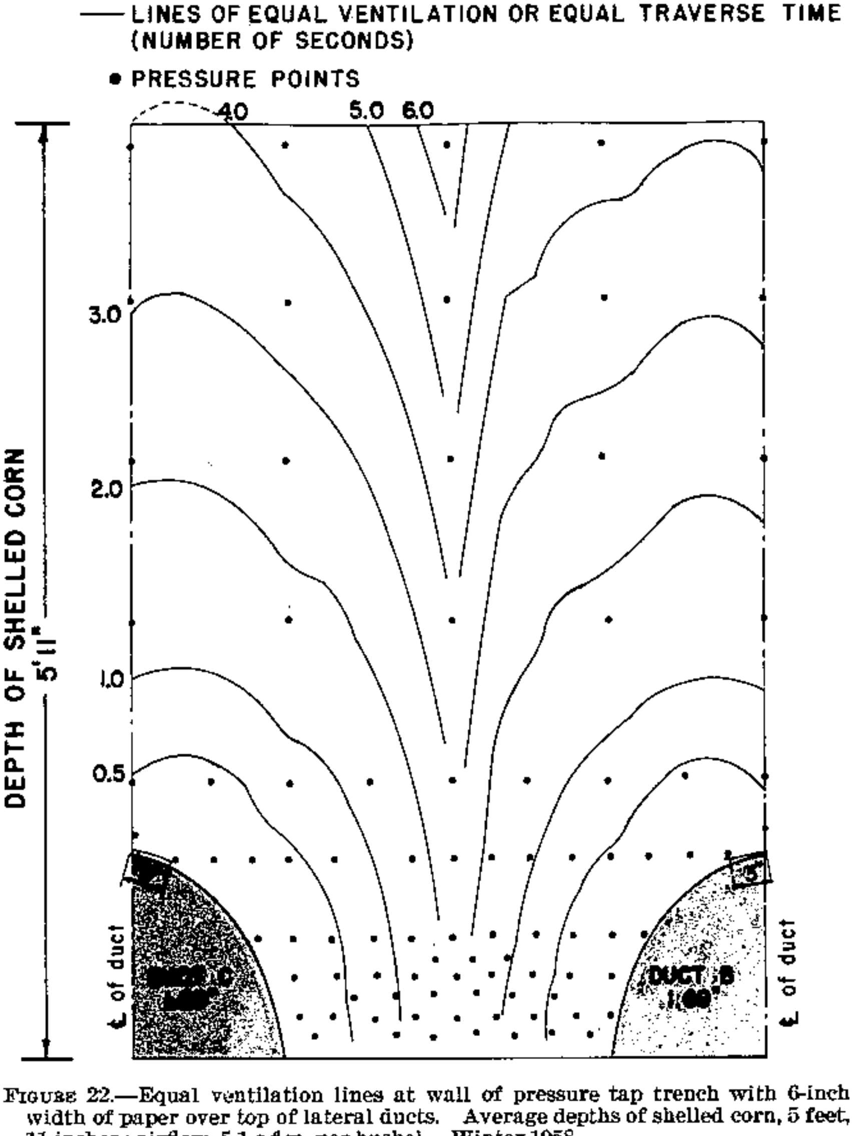


FIGURE 22.—Equal ventilation lines at wall of pressure tap trench with 6-inch width of paper over top of lateral ducts. Average depths of shelled corn, 5 feet, 11 inches; airflow, 5.1 c.f.m. per bushel. Winter 1958.

Changes in Duct Adapters

Description of Tests

On duct A, the lower two-thirds of the adapter shield was perforated with sufficient ¼-inch-diameter holes to provide 10 percent free opening. On duct B, the sleeve was cut off and the adapter fastened directly to the wall. Duct C was left unaltered with the adapter shield extending into the building 8½ inches. Special care was taken in loading each bin to assure even distribution of shelled corn over the entire area and to prevent trash from accumulating in spots.

Results

Considerable improvement is shown in the ventilation pattern for duct B in comparison with unaltered duct C (fig. 23). A comparison

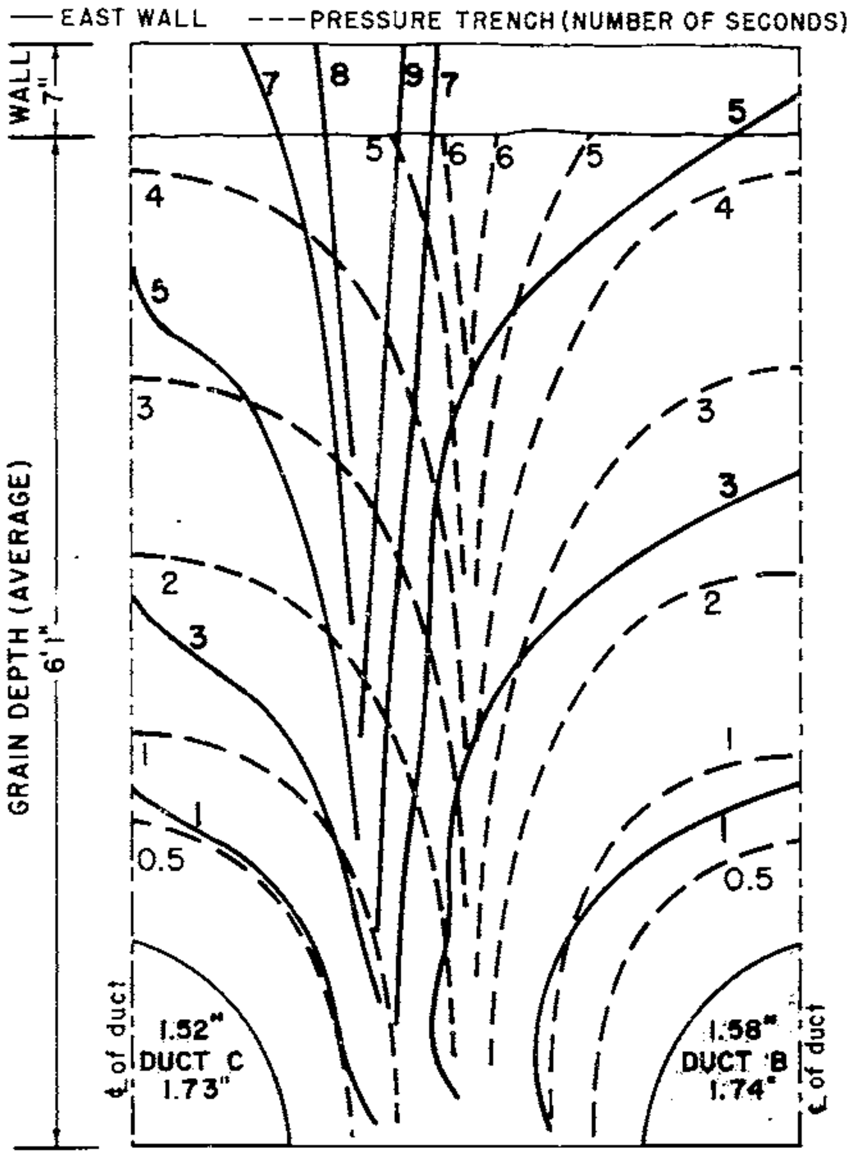


FIGURE 23.—Equal ventilation lines at east wall and pressure tap trench. Duct B has adapter attached directly to wall; duct C has unaltered adapter. Average grain depth, 6 feet, 1 inch; distance along curved wall, 6 feet, 8 inches; airflow, 4.1 c.f.m. per bushel.

of the summations of time, reciprocal-area products for areas subtended by equal ventilation lines indicates 50 percent improvement in performance for duct B at the east wall. Ventilation at the pressure trench was only about 10 percent better than at the east wall for duct B. Insufficient data were taken at duct A to plot a similar chart.

Storage of Fall Grain (Grain Sorghum)

During the last 3 years the grain sorghum was stored for about 5 months each season without loss in grade. In 2 of these years the grade was improved approximately one grade (No. 4 to No. 3 in 1957–58 and No. 1 and 2 to No. 1 in 1958–59) because of the increased test weight. The initial storage moisture content was 11.2 percent. The grain apparently dried in storage and reached a final moisture content of 10.4 percent. The third year both the initial and final moisture contents were 9.7 percent and there was no change in grade. There was no indication of insects in any of the initial samples. But in February 1959, after 5 months of storage, insect activity indicated a need for fumigation, and 5 gallons of fumigant were applied to the grain in the bin. Thus high quality was maintained for storage periods of approximately 5 months with a grain moisture content approaching 10 to 10½ percent when insects were not active. The moisture content was apparently not low enough in all 4 years to provide adequate insect control for long storage periods.

PHYSICAL AND RHEOLOGICAL PROPERTIES OF GRAIN

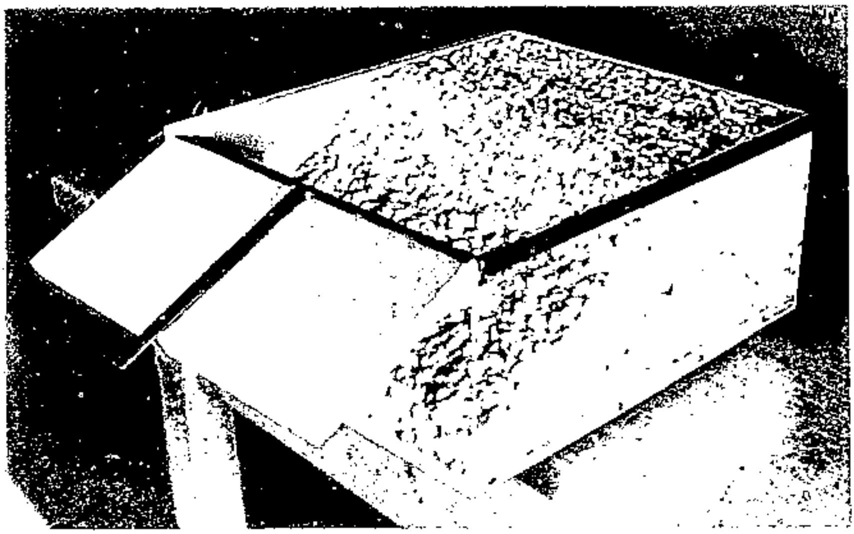
Some physical properties of grain have been determined by other investigators. However, the scope of such information is inadequate for present-day needs in designing grain-storage buildings and handling equipment. The problem was brought to a focus by the need for determining increases in lateral pressures developed when grain is rewetted. Determining pressure by means of cells or panels had been tried, but it was felt that another approach might be fruitful.

Two of the basic physical properties on which there was a lack of data pertained to the angle of repose of grain on grain (separation of shear plane) and the coefficient of friction of grain on the materials of the bin wall. These properties have been determined by other investigators, but only at one moisture content, in most cases, and often no information is available of the specific moisture content, size of kernels, or variety of grain used. Thus if grain is to be dried to 8 percent moisture content, for better insect control, and then rewetted to 14 percent or higher, the changes occurring in the angles of repose and coefficient of friction need to be known. Information on the resilience of the material to be stored was lacking, also. The resilience of any body is the stress energy that may be recovered from a deformed body when the load causing the stress is removed. Within the proportional limits the resilience is equal to the external work required to deform the body, usually measured in inch-pounds. The modulus of resilience is the elastic energy stored up in a unit volume of a material at the proportional limit. A knowledge of the modulus [illegible] of material to be stored would aid greatly in the design [illegible]. With this knowledge full advantage could be taken [illegible] of the structural members, with the possibility that [illegible] the design requirements could be reduced.

Angle of Repose—Grain on Grain

Description of Equipment and Tests

[illegible] of determining the angle of repose of grain on grain [illegible]. The one finally decided upon as giving repeatable re[illegible] a box with one hinged end (fig. 24). The box was filled



[illegible] 24. [illegible] for determining the angles of repose of grain on grain [illegible] moisture contents.

[illegible] moisture content and kernel size, the spring [illegible] the grain was allowed to spill into the container [illegible] were made for each type of grain at each [illegible]

[illegible] of Plex glass with slope lines scribed [illegible] reading the angle of repose. The grain was [illegible] necessary to obtain the desired moisture content. [illegible] used were graded to determine the per[illegible] sizes, so that this size composition could [illegible] tests.

[illegible] percent moisture content. The weight was [illegible] Screens with [illegible] oblong slots were used. [illegible] passed through a [illegible] inch screen [illegible] inch screen [illegible] inch screen [illegible] retained on a [illegible] inch screen

Grain sorghum weighed 47.3 pounds per cubic foot and had a moisture content of 10.8 percent when sized. Screens with round holes were used. The percentages by kernel sizes were as follows:

Of the kernels that passed through a 12/64-inch diameter screen—
- 1.7 percent was retained on a 11/64-inch screen
- 25.1 percent was retained on a 10/64-inch screen

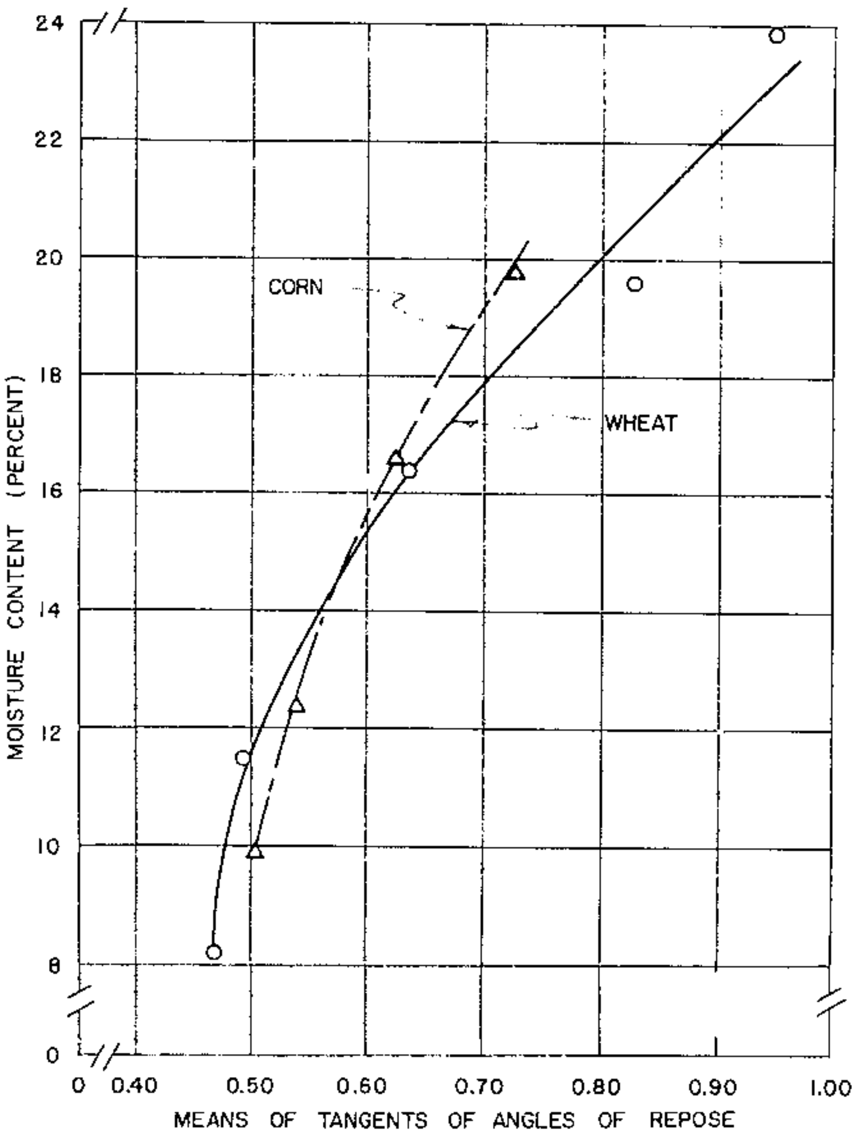


FIGURE 25.—Relationship between the means of the tangents of angles of repose and moisture content for corn and wheat.

49.8 percent was retained on a $\frac{9}{64}$-inch screen
20.1 percent was retained on a $\frac{8}{64}$-inch screen
3.3 percent was retained on a $\frac{7}{64}$-inch screen

Corn was sized at a moisture content of 14.0 percent and a weight of 47.5 pounds per cubic foot. The proportion of flats and rounds obtained by running through a seed-corn grader was as follows:

Large round—retained on $\frac{14}{64}$-inch slotted screen—16.6 percent.
Large flat—passed through $\frac{14}{64}$-inch slotted screen—36.3 percent.
Medium round—retained on $\frac{13}{64}$-inch slotted screen—4.3 percent.
Medium flat—passed through $\frac{13}{64}$-inch slotted screen—3.1 percent.
Small round—retained on $\frac{12}{64}$-inch slotted screen—2.6 percent.
Small flat—passed through $\frac{12}{64}$-inch slotted screen—29.2 percent.
Undersize rounds and flats—7.8 percent.

Results

Statistical analyses were made of the data. Curves showing the relationship between the means of the tangents of the angles of repose and the moisture contents ranging from about 8 to 24 percent are shown for corn and wheat in figure 25. A similar curve could not be plotted for grain sorghum, because of apparent errors in two sets of the readings.

For all three grains the mean angles of repose at different levels of moisture showed difference at the less-than-1-percent-probability level by statistical tests of significance (table 7).

TABLE 7.—*Analysis of variance of angle of repose measurements at several moisture levels for corn, wheat, and grain sorghum*

Variable	Degrees of freedom	Mean square
	CORN	
Moisture	3	**0.14109133
Error	56	.00020481
	WHEAT	
Moisture	4	**0.64798975
Error	70	.00025234
	GRAIN SORGHUM	
Moisture	6	**0.00483266
Error	98	.00010654

**Highly significant at 1-percent level.

Coefficients of Friction—Grain on Bin Wall Materials

Description of Equipment and Tests

Figure 26 shows the pivoted table constructed for the determination of the coefficient of friction of grain on bin wall materials. Leveling feet were provided on the bottoms of the legs, and level bubbles were attached to the table to obtain correct leveling. The material under test was mounted on plywood and supported in the pivoted table. A cylindrical band was placed on the material, partly filled with grain at a known moisture content, and a weighted cover was inserted in the band. The band was lifted slightly to avoid contact with the wall material. The table was elevated by the crank until movement of the grain on the bin wall material was noted. The angle of friction was read from the scale in one-half degree increments, and the coefficient of friction was determined from the angle of friction.

Angles of friction were determined for corn and wheat on four materials—Douglas-fir plywood, cold rolled steel sheet, galvanized steel sheet, and corrugated galvanized steel sheet. The corrugated sheet had corrugations 2⅔ inches on centers, and the movement of grain was across the corrugations. Tests on plywood were run with the

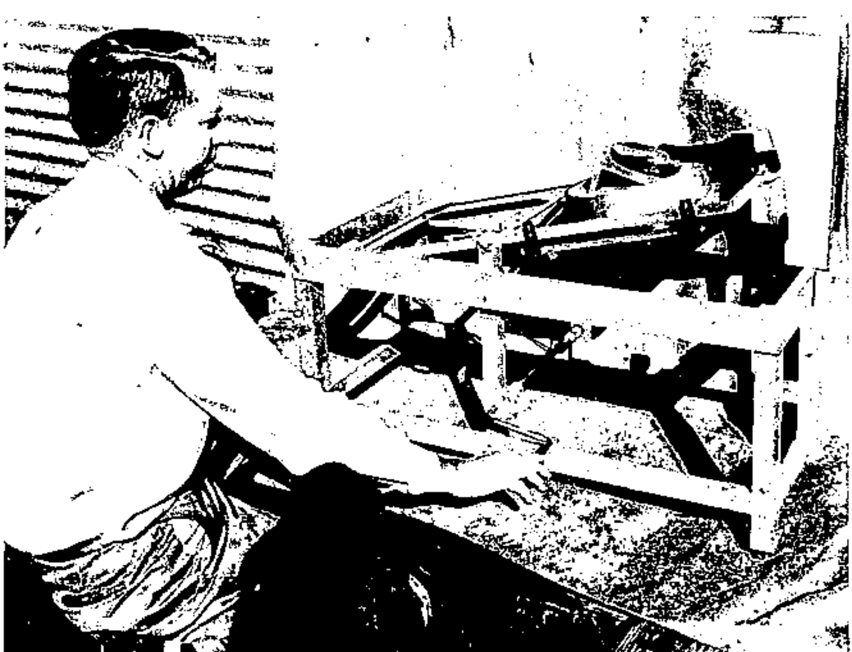


FIGURE 26.—Apparatus for determination of the angles of friction of grain on bin wall materials at various moisture contents.

grain movement both parallel to and across the grain. Grain sorghum tests were run similarly, except that data were not obtained for galvanized steel sheet.

Grain for these tests were taken from the same lots used in the tests on angle of repose. Three trials were made with each sample and 10 samples were used, or a total of 30 trials, for each moisture level.

Results

Data from the tests on the angle of friction were analyzed statistically. Curves showing the relationship between the means of the tangents of the angles of friction and the moisture contents are shown for corn and wheat on four different bin wall materials in figures 27 and 28.

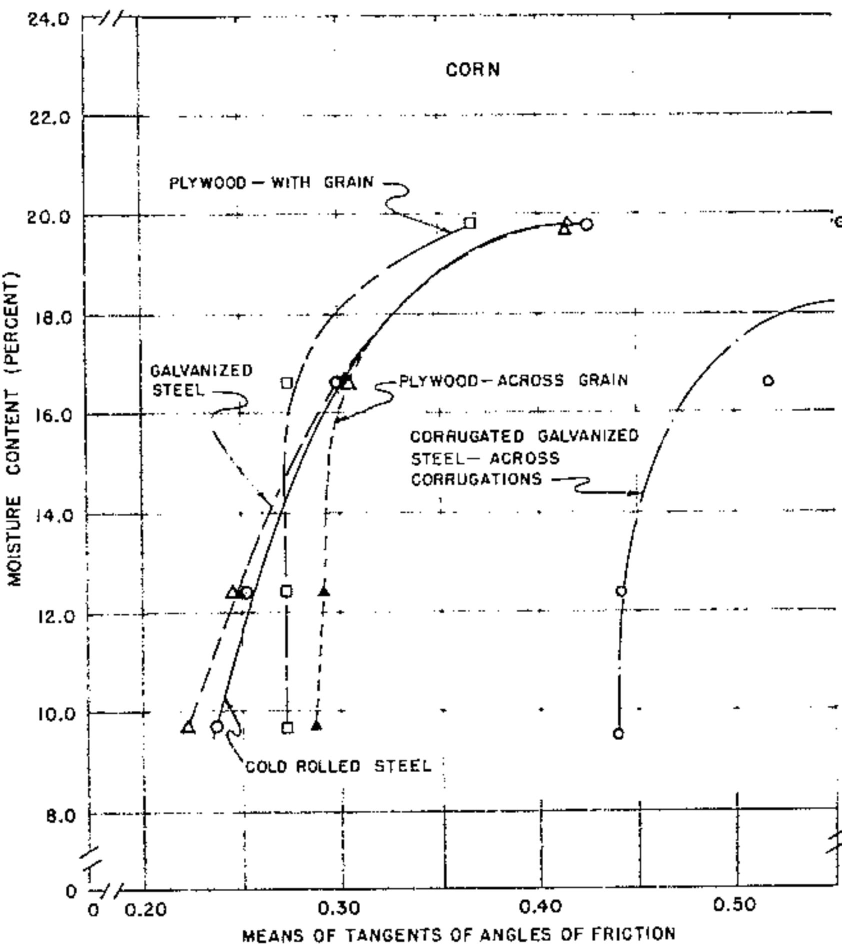


FIGURE 27.—Relationships between the means of the tangents of the angles of friction and moisture contents for corn on several bin wall materials.

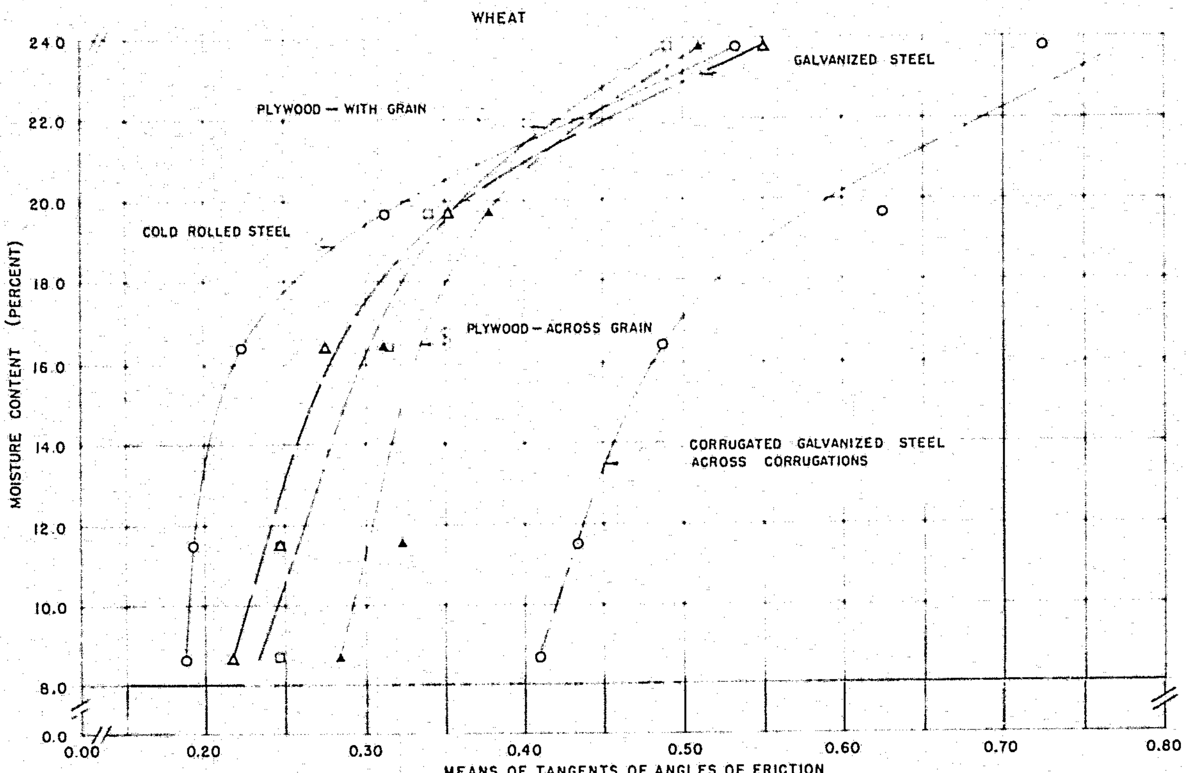


FIGURE 28.—Relationships between the means of the tangents of the angles of friction and moisture contents for wheat on several bin wall materials.

For all three grains, the mean angles of friction at different moisture levels showed highly significant differences (table 8). The same was true for mean angles of friction on various bin wall materials. Highly significant differences for corn and wheat at different moisture levels were shown for the various bin wall materials. This was not true for grain sorghum because of apparent errors in readings at two moisture levels.

TABLE 8.—*Analysis of variance of angle of friction measurements on different bin wall materials for corn, wheat, and grain sorghum at several moisture levels*

Variable	Degrees of freedom	Mean square
	CORN	
Moisture	3	**0.6598
Material	4	**.8122
Moisture × material	12	**.0176
Error	580	.00043
	WHEAT	
Moisture	4	**2.1246
Material	4	**1.4133
Moisture × material	16	**.0309
Error	725	.00026
	GRAIN SORGHUM	
Moisture	6	**0.2712
Material × moisture	20	**.3273
Samples × material and moisture	243	.0002
Error	540	.00009

** Highly significant at 1-percent level.

Modulus of Elasticity and Resilience

Description of Equipment and Tests

Figure 29 illustrates the equipment used in the initial phase of this study. Essentially, it consisted of a cylinder 8 inches in diameter and 54 inches long, made of 18-gage cold rolled steel butt-welded, an angle iron frame, and a hydraulic jack. SR-4 gages were attached, 90° apart radially, to the outside surface of the cylinder at levels of 3, 24, and 36 inches above the bottom to measure the strain at these points resulting from pressure on the grain within the cylinder. The gage on the hydraulic jack was calibrated before it was used in the study.

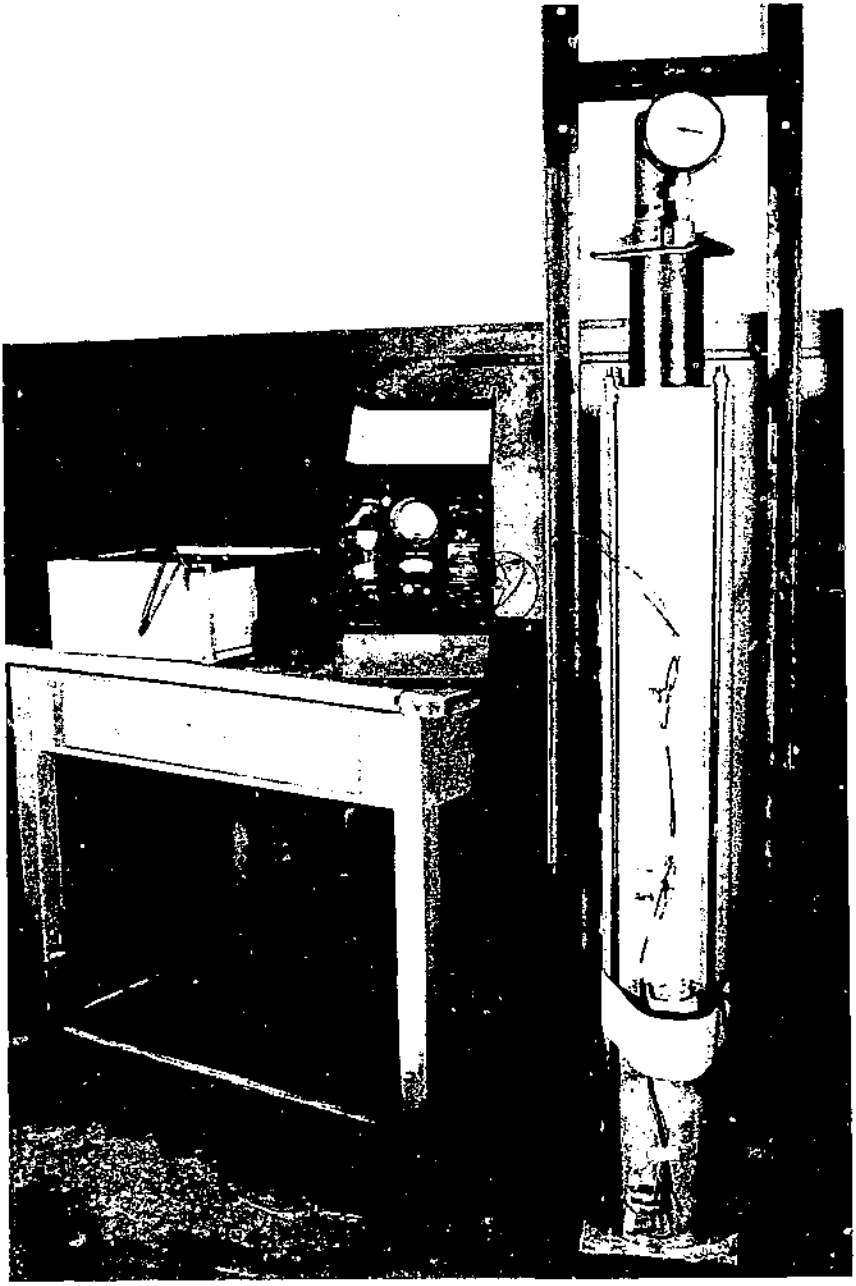


FIGURE 29.—Apparatus with tall column of grain used initially in study of modulus of elasticity.

An electric vibrator attached to the cylinder aided in obtaining a more uniform density of the grain mass. Later, a heavier vibrator was used in an effort to make the grain, considered as a semiliquid, act more like a solid and thus relieve the friction on the cylinder walls.

After initial tests a pressure dynamometer was constructed, and readings were taken to determine the magnitude of the load transmitted through the column from top to bottom. This dynamometer consisted of three aluminum pins ¾-inch in diameter attached to a plate and placed as a support under the floating bottom. Two strain gages were mounted, 180° apart diametrically, on each pin; and the six gages were connected in series to increase the magnitude and accuracy of the readings.

To help reduce friction on the cylinder walls, the cylinder was coated inside with Teflon. This is a fluorocarbon resin for which the manufacturer claims a very low dynamic and static coefficient of friction.

Since efforts to reduce friction and overcome "dome" action within the cylinder did not meet with success, a change was made to a column approximately 1 inch high. The equipment devised for this series of tests is shown in figure 30. The grain sample was held between two compression plates that were machined and polished to provide smooth surfaces. The thickness of these plates is sufficient to provide negligible "cupping" under the pressures involved. A stainless steel butt-welded band fitted closely around these plates and retained the grain sample. The band was unsupported and was thus free to move vertically. The grain provided just enough frictional resistance to keep the band from falling off. Four strain gages, spaced 90° apart radially, were attached to the band at midheight to measure lateral pressures developed under load.

The general procedure used for the short column was somewhat similar to that used for the tall column. The sample of grain was placed inside the band on the base plate and the top compression plate was inserted. Vibration was applied for 90 seconds, which was the period determined by tests to be the minimum necessary to "settle" the corn, in order to obtain readings reproducible to a satisfactory degree; otherwise, excessive variation in deformations occurred with the same load.

Loads were applied by means of a mechanical jack in 100-pound increments which represented a pressure of 1.99 pounds per square inch. Measurement of the load was determined by a hydraulic pressure cell with calibrated gage. After the sample was vibrated, the total height of the column, including top and base compression plate, was measured with a micrometer at three points, 120° apart radially, near the circumference of the plates. The plates did not always remain absolutely parallel in the vibration and compression process. Hence, pins, with rounded tops, were inserted in the top plate at these points to aid in obtaining more accurate measurements.

Micrometer readings were taken with the load applied; the load was then released, and the column was allowed to stand for 3 minutes to permit the kernels to recover from the compression effects before final micrometer readings were taken. The three micrometer readings were averaged to give a single reading. The top compression plate was

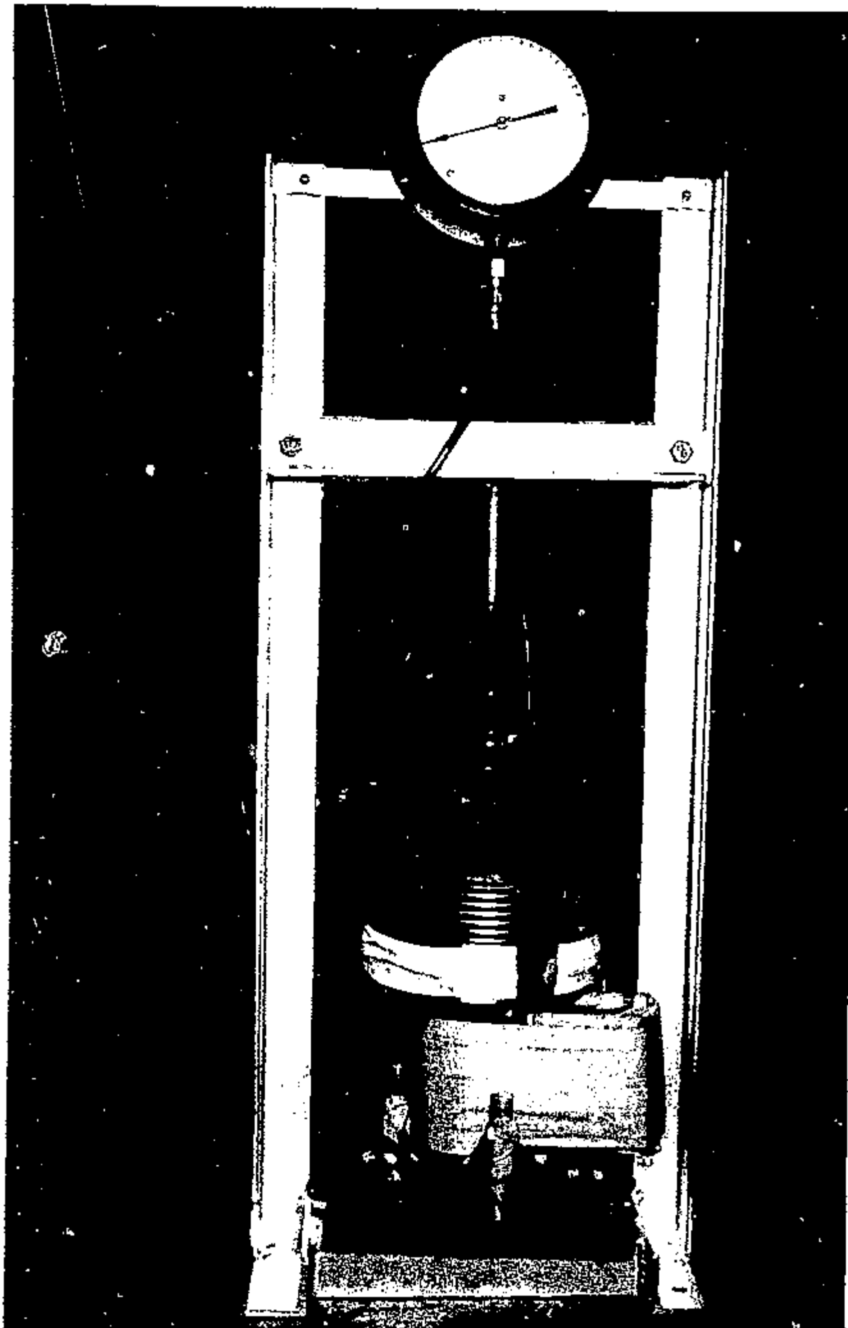


FIGURE 30.—Apparatus with grain column 1 inch high devised later for series of tests on modulus of elasticity and resilience of grain.

then removed, and the corn was stirred to change kernel location and position. This entire procedure was repeated for each 100-pound increment until a maximum of 1,600 pounds (31.86 lbs. per sq. in.) was reached. This maximum load represents over 10 times the maximum unit lateral pressures occurring when wheat is stored in a 20-foot-diameter bin 20 feet deep.

Results and Discussion

Preliminary results with the tall column of grain indicated a much greater increase in lateral pressure at the top than at the bottom, which was to be expected because of "dome" action. Even with heavy vibration a maximum load at the top of 239 pounds per square inch resulted in a vertical pressure of only 67 pounds per square inch at the bottom, or only 28 percent of the load applied. With the Teflon lining and the same load, 45.6 percent of the load was transmitted to the bottom.

With the short column the total deformation measured was the decrease in column height when the load was applied. The elastic deformation was considered as the difference in column height under load and with the load removed after compression. Plastic deformation represented the difference between the original column height before compression and the height after the load was removed. In no case did the column recover to the original height after it was compressed; therefore, plastic deformation was considered as occurring at all loads. Some of the assumed plastic deformation may actually have been the result of slippage and realinement of kernels.

Figures 31 and 32 show results of tests on corn at four moisture contents with elastic deformation plotted against the stress that caused deformation. It was assumed that equal amounts of work were required to produce equal amounts of elastic and plastic deformation. Thus the part of the load causing elastic deformation would be equal to the product of the ratio of elastic to total deformation and the total load.

Values of E, the modulus of elasticity, taken from the straight-line parts of the curves (figs. 31 and 32) to which Young's modulus applies, are given in table 9. For moisture contents of approximately 12, 14, and 16 percent little difference is indicated in the modulus of elasticity, but that for 8 percent is somewhat higher. Values of stress and strain

TABLE 9.—*Stress-strain values at the proportional limit and moduli of elasticity and resilience for shelled corn at four moisture contents, Plains, Ga.*

Moisture content, percent (wet basis)	Stress	Strain	Modulus of elasticity	Modulus of resilience
	Pounds per square inch	*Inch per inch*	*Pounds per square inch*	*Pounds per cubic inch*
8.2	0.80	0.00175	457	0.00070
12.3	.68	.00200	340	.00068
14.1	.69	.00200	345	.00069
16.3	1.50	.00410	365	.00308

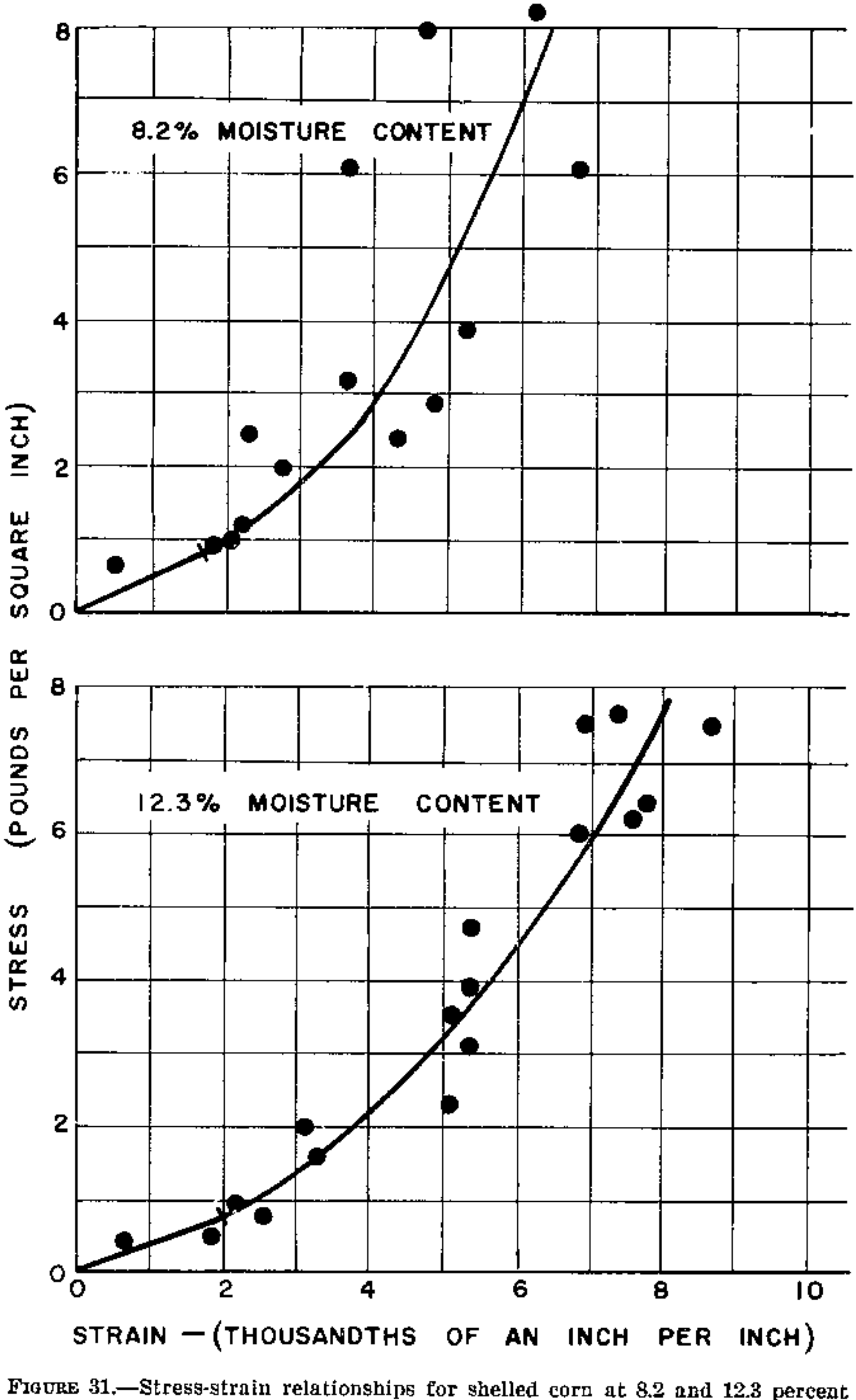


FIGURE 31.—Stress-strain relationships for shelled corn at 8.2 and 12.3 percent moisture contents.

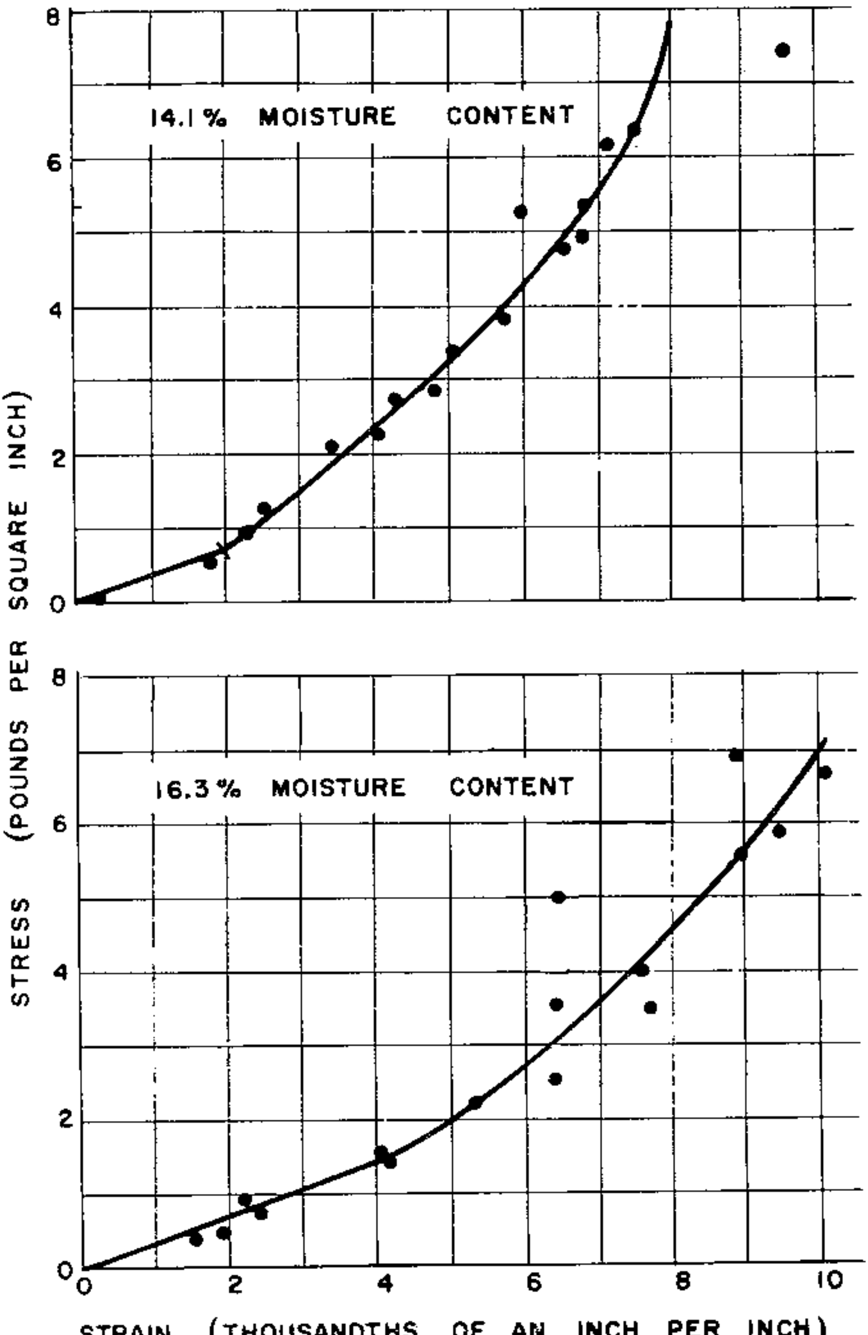


FIGURE 32.—Stress-strain relationships for shelled corn at 14.1 and 16.3 percent moisture contents.

taken at the proportional limits from these curves (figs. 31 and 32) were used in calculating the resilience moduli (table 9). The modulus of resilience is about the same for corn of 8, 12, and 14 percent moisture content, but that for corn of 16 percent is about three times higher. As would be expected, all the values are extremely low as compared with those for materials such as steel and wood, with which the engineer is accustomed to working.

In the analysis of data just discussed, it was assumed that a straight-line relationship, in accordance with Hook's law, exists in the initial part of the curve. Insufficient data were obtained to actually justify establishment of the straight-line parts. It is possible that these properties of corn in compression are similar to those of materials such as cast iron, concrete, and sometimes wood, which demonstrate a curvilinear relationship in all parts of the stress-strain diagram. It is evident that more data are needed, especially in the low-stress values.

SUMMARY AND CONCLUSIONS

The use of airflow rates determined as minimum for safe drying of grain with unheated air in parallel flow in northern Georgia resulted in safe drying in southwestern Georgia with air in nonparallel flow where good-quality grain was received from the field.

At 2 cents per kilowatt-hour, the electricity cost for drying with unheated air to a moisture content of 11 percent—the level for safe normal storage—would amount to almost 1 cent per bushel for oats and 1¼ cents per bushel for wheat for a 5-percent reduction in moisture content. For a 10-percent reduction the cost for shelled corn would average about 2½ cents per bushel and for grain sorghum about 2¾ cents. The electricity costs for corn and grain sorghum would generally apply where drying begins in early October unless weather conditions were very unfavorable.

The drying schedule ordinarily used permitted continuous fan operation until the wettest layer of grain reached 17 or 18 percent moisture content; humidistatic control then permitted operation at 70 percent relative humidity or below, until 14 or 15 percent moisture was reached, after which the humidistat setting was lowered to 60 percent and finally to 50 percent.

Under comparable weather conditions and within the range of unheated airflow rates used, the drying time approached a straight-line relationship with airflow rate.

With unheated air a 5-percent reduction of moisture content in oats and wheat took about 9 days. A 10-percent reduction in shelled corn and grain sorghum in early fall took 17 to 31 days; the time required would depend on the weather and drying procedures.

Drying grain sorghum with supplemental heat took 10 to 17 days during two seasons, with the heater controlled to operate when the relative humidity was 60 percent or higher. With electricity at 2 cents per kilowatt-hour and LPG at 18 cents per gallon, the cost of these items for a 10-percent reduction in moisture content averaged 5 cents per bushel, or about 2¼ cents per bushel higher than the cost of electricity for drying with unheated air. The supplemental heat, however, provided good insurance against possible spoilage by increasing the rate of drying.

Shelled corn was dried from 11 percent to a lower-than-normal moisture content of 8.5 percent to reduce insect activity and possibly avoid the necessity of fumigating. The fan was operated with unheated air when the relative humidity was 50 percent or below. The electricity cost varied from 1 to 3 cents per bushel; hence, the average cost would about equal the cost of fumigant for one fumigation. This drying required from 17 to 61 days in early fall with an airflow rate of 5.6 c.f.m. per bushel; 139 days were required in late fall and winter at an airflow rate of 3.5 c.f.m. per bushel. The corn could not be kept long enough to determine the effectiveness of controlling insects by this method.

The shelled corn, which was dried to lower-than-normal moisture content, was rewetted to an acceptable level for marketing by operating the fan at relative humidities of 70 percent or higher. The moisture content was increased about 3.3 percent in 5 to 17 days at an electricity cost of from less than 1 cent to 2½ cents per bushel. Thus the total cost of the electricity for the extra drying and rewetting averaged about 3½ cents per bushel, or less than the cost of fumigants for two applications. The procedure appears to be practical, but care must be taken in rewetting to avoid possible spoilage in warm weather.

Pressure increases on the structure due to rewetting shelled corn were measured by three methods. The method in which pressure panels were mounted in the partition wall provided the only usable results at various grain depths. The lateral pressure increased appreciably when the moisture content increased several percent. There was almost no increase in vertical pressure.

Definitive drying fronts cannot be indicated by means of the pipe cleaner elements used, although the readings provide a general indication of moisture levels in the cross-section of the grain mass. The results indicate that there is considerable reabsorption of moisture by the grain where drying occurs at a wide range of atmospheric relative humidities, since manual setting of the humidistat does not always permit full advantage to be taken of drying accomplished at the lower humidities.

Air distribution as indicated by airflow patterns in the cross section of the grain mass was relatively uniform at the wall of the pressure trench across the center of the bin and at the west wall. Skewed distribution was sometimes noted at the east wall where the air enters the lateral ducts; this may have been primarily caused by trash accumulation. Air paths between ducts near the floor cannot be described adequately with the data available. The lack of such description makes it appear that the area was inadequately ventilated, but no spoilage occurred under proper operating procedures. When arbitrarily selected flow lines were used, results indicated greater uniformity in airflow and better performance in drying the oats than in drying the other grains.

Tests with different widths of paper over the tops of the perforated lateral ducts indicated no improvement in air distribution due to this treatment.

Cutting off the 8½ inch length of sleeve to the lateral duct and fastening the duct adapter shield directly to the wall resulted in 50 percent better ventilation performance at the curved wall—almost equal to that across the middle of the bin.

Grain sorghum was stored without loss in grade for 5 months at moisture contents of 10 to 11 percent. If insects are present at the beginning of the storage period, these moisture contents are not low enough to inhibit insect activity and fumigation may be necessary, especially when periods of warm weather occur in late winter or early spring.

Angles of repose were determined for corn, grain sorghum, and wheat. For an increase in moisture content from 10 to 20 percent, the means of the tangents of the angles increased from 0.51 to 0.73 for corn and from 0.48 to 0.80 for wheat. For all three grains the mean angles of repose at different moisture levels showed highly significant differences. A significant difference shown between trials for grain sorghum was apparently caused by errors in readings at two moisture levels.

Coefficients of friction of grain on bin wall materials were determined for corn, grain sorghum, and wheat on cold rolled steel sheet, corrugated galvanized sheet, and Douglas-fir plywood (movement both parallel to and across wood grain) at moisture contents ranging from about 8 to 24 percent. Coefficients for corn and wheat only were determined on galvanized steel sheet. For all three grains the mean angles of friction at different moisture levels showed highly significant differences. The same was true for mean angles of friction on the various bin wall materials. For corn and wheat at different moisture levels highly significant differences were shown for the various bin wall materials. However, this was not true for grain sorghum because of apparent errors in readings at two moisture levels. As expected, the means of the tangents of angles of friction for all three grains were considerably higher for corrugated galvanized steel, with the grain movement across the corrugations, than for the other materials.

Stress-strain tests were run on corn at four moisture contents, and the relationships between elastic deformation and stress were determined. It was assumed that equal amounts of work were required to produce equal amounts of plastic and elastic deformation. Thus, the part of the load causing elastic deformation would be equal to the product of the ratio of elastic to total deformation and the total load. Values of E, the modulus of elasticity, taken from the straight-line part of the stress-strain curves to which Young's modulus applies, show that for moisture contents of approximately 12, 14, and 16 percent little difference results but that for 8 percent is somewhat higher.

The resilience moduli were calculated from stress-strain values taken at the proportional limits of the curves. The resilience modulus is about the same for corn of 8, 12, and 14 percent moisture content, but that for corn of 16 percent moisture is much higher. All values are extremely low as compared with those for materials such as steel and wood. Insufficient data were obtained to actually justify establishment of the straight-line part of the curves. It is possible that these properties of corn in compression are similar to those of materials such as cast iron and concrete, which demonstrate a curvilinear relationship in all parts of the stress-strain diagram.

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