PRODUCTION OF STARCH FROM WAXY SORGHUM GRITS

by

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INTRODUCTION AND LITERATURE SURVEY

The existence of waxy cereal starches has been known for many years, but they have been commercially available only since World War II. Waxy starches possess the physical properties ordinarily associated with tuber starches as contrasted with cereal starches. They can be used in products for which tapioca was formerly considered indispensible. Of the several glutinous or waxy cereals, corn appears to offer the best possibilities as a commercial source of waxy starch because its other characters are not essentially different from those of ordinary hybrid corn, which is already milled on a large scale. However, some interest is being shown in waxy sorghums, where starch is similar to that from waxy corn.

The fracture of glutinous cereal grains appears dull and opaque, while that of most common varieties is horny or vitreous. The name "waxy" was applied to corn in 1909 by Collins (5) who failed to recognize the fact that he was dealing with a glutinous variety. The term "waxy" refers to the physical appearance of the endosperm rather than to a chemical characteristic of the starch. "Glutinous" defined as "sticky" or "gluey" is more suitable because it describes the most obvious characteristic of the cooked flour or starch paste from this type of cereal.

In general, the waxy cereals contain less starch than the non-waxy types. Only a few of the glutinous sorghum varieties contain as much starch as the non-glutinous. However, higher contents of oil and protein, valuable by-products in starch production, tend to compensate for the lower starch content of the glutinous varieties. To observe the annual variation in composition of grains (2) is interesting. The variation may be due entirely to environmental factors.

Glutinous starches differ fundamentally from non-glutinous by containing no amylose. Because of the dissimilarity in composition, it is expected that some difference in property will be found between these starches. The most striking characteristic of starch from the endosperm of glutinous cereals is the red or red-brown color (other than blue) which it gives with iodine (9). Glutinous starches are very susceptible to injury and split into wedge-shaped fragments comparatively easily if pressure is applied to the cover slip under which they are mounted for microscopic observation (12). The gelatinization temperatures of the glutinous starches are about the same as the non-glutinous types. The viscosity of glutinous starch pastes is much higher than that of the non-glutinous type, and is comparable to that of tapioca. As a result, both the tapioca and waxy sorghum starch have a sharp and high viscosity peak on the semi-log scale viscosity concentration curve (13). The glutinous and non-glutinous pastes have dissimilar rheological properties. While the non-glutinous paste is "short" with high rigidity and low viscosity, the glutinous paste is "long" and tacky with low rigidity and high viscosity. Glutinous starch pastes are translucent and flavorless. These properties are distinct advantages in the use of the starch in food products or adhesives for envelopes.

Much work has been done on the industrial utilization of sorghum during the past decade. Hightower (8) and Taylor (14) described processes for producing starch from sorghum grains. Hilbert (12) described the properties of both waxy and non-waxy starches from sorghum in 1944. Zipf, Anderson and Slotter (16) and Watson, Williams and Wakely (15) investigated the effect of steeping conditions on the quality and yield of starch in

1950 and 1951. A series of studies in these fields was also conducted at Kansas State University. Johnson (11) used a batch grinding process to get starch with high purity and quality in 1942. Banowetz (1) and Drobot (6) developed processes for the recovery of starch from sorghum grains by a semi-continuous process using a hydraulic mill in 1950. Fan (7) used a closed circuit continuous process to study the extraction of starch from sorghum in 1951. Chiang (4) studied various factors which affect the process. Chai (3) studied the effect of steeping agents and the milling equipment for the process. Hsieh (10) studied the effect of design variables in the hydraulic mill of the process.

Since most of the previous work has dealt with non-waxy sorghum grits, the present investigation was undertaken to study the effect of the main factors on the hydraulic grinding process using waxy sorghum grits. Because of the many variables in the process, the experiments were conducted in accordance with a factorial design, prepared with the assistance of the statistical laboratory. Thus, the various effects were evaluated by the analysis of variance and regression.

Besides this, several runs were made to evaluate the effect of high temperature steeping and the pH of the steeping water using non-waxy sorghum grits.

EQUIPMENT

The equipment for this work was essentially the same as that used by Hsieh (10). A flow sheet of the process is shown in Plate I and a photograph of the pilot plant in Plate II. There are four steps which can be listed as: 1. steeping; 2. grinding; 3. screening; 4. tabling. The equipment used will be discussed in this order.

Steeping Equipment

Four 15-gallon stainless steel tanks arranged as shown in Plate III served as the steeping facilities for sorghum grits. One of these tanks was used as the heating tanks, while the other three were used as steeping tanks. Heat was generated by passing low-pressure steam through a coil of 3/8 inch o.d. copper tubing inside the heating tank. The water temperature, which was recorded by a Bristol Temperature recorder, was controlled by a Taylor self-acting steam regulator. Hot water was pumped by a centrifugal pump, (Eastern Industries, Model D-6, 1/30 hp., 3450 rpm.) through a 1/4 inch galvanized iron pipe to the top of the steeping tanks. Water flowed downward through the grits in the tanks, and back into the heating tank for circulation. Part of the water in the steeping tanks overflowed into the heating tank for balancing the inlet and outlet water rates.

Grinding Equipment

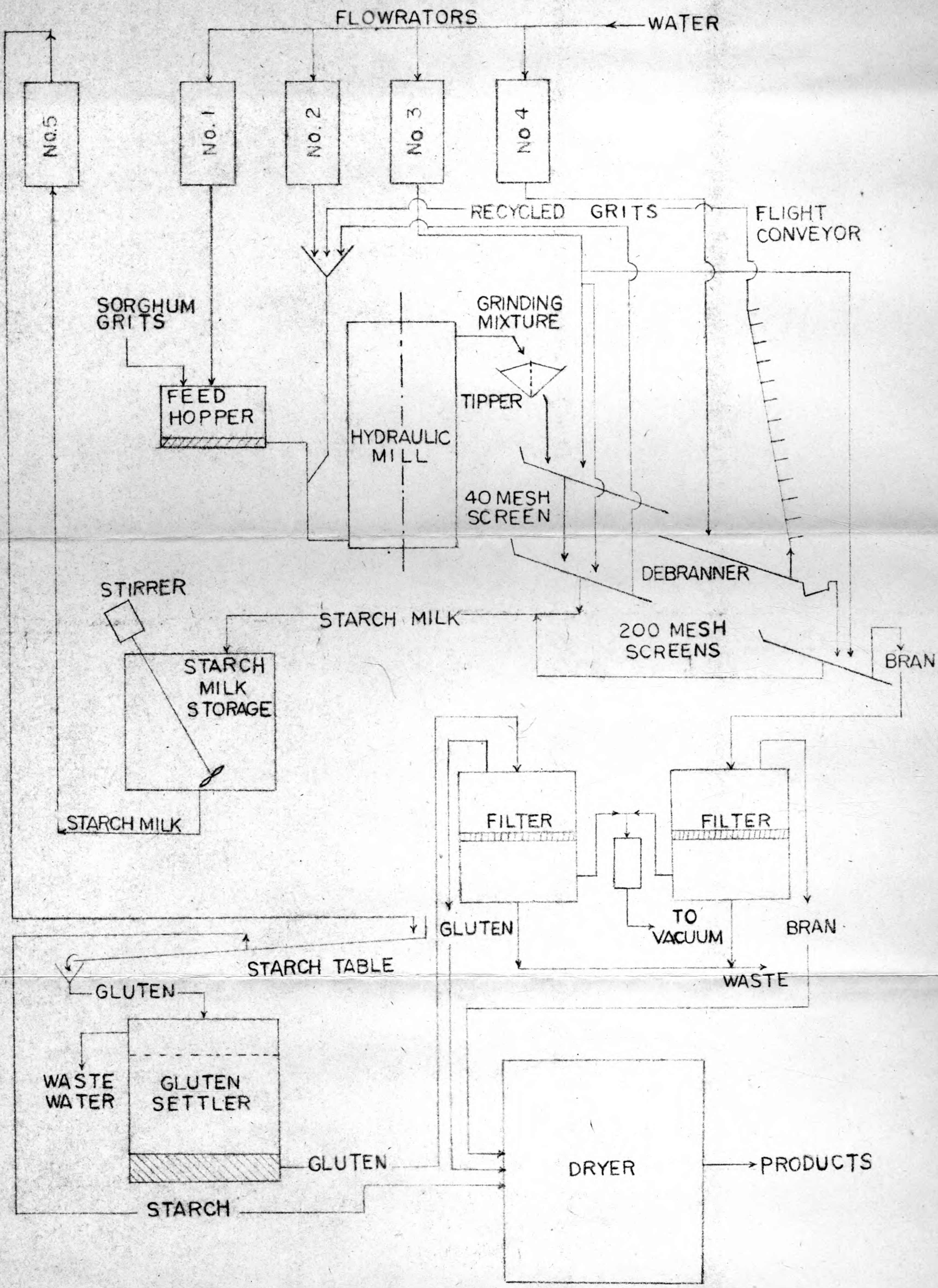
Feeding Device. A V-shaped feed hopper with a capacity of about 20 lbs. of grits was used for feeding. The steeped grits were fed to the mill by a 1 hp. Reeves Varimotor with speeds adjustable from 26 to 156 rpm. In order to control the feed rate, both the pulleys and the rpm setting were adjusted for different runs. A 1-1/2 inch standard iron pipe was connected at the outlet of the screw conveyer to the bottom of the hydraulic mill for grinding. The feed water was introduced through a 1/4 inch galvanized iron pipe to the hopper, and entered the mill with the grits.

Hydraulic Mill. An elevation and a detailed drawing of the hydraulic mill are shown in Plates IV and V. The casing was mounted on a base carrying a vertical stainless steel shaft which had nine pairs of horizontal

EXPLANATION OF PLATE I

Flow Diagram of the Continuous Hydraulic Milling Process for the Production of Starch from Sorghum Grits

PLATE I

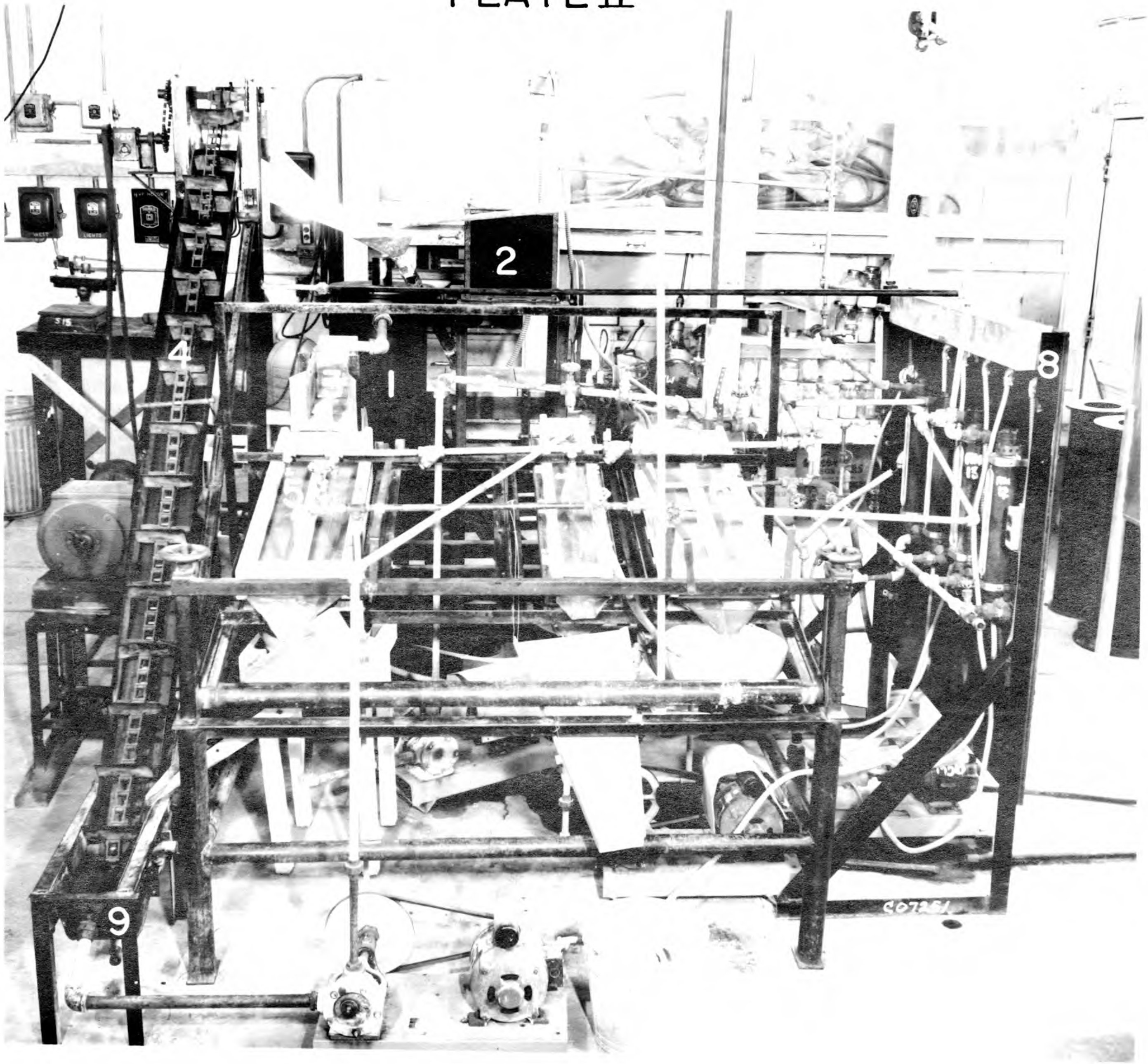

FLOWRATORS
WATER
No.5
No.1
No.2
No.3
No.4
RECYCLED GRITS
FLIGHT CONVEYOR
SORGHUM GRITS
GRINDING MIXTURE
FEED HOPPER
TIPPER
HYDRAULIC MILL
40 MESH SCREEN
DEBRANNER
STIRRER
STARCH MILK
200 MESH SCREENS
BRAN
STARCH MILK STORAGE
FILTER
FILTER
STARCH MILK
GLUTEN
TO VACUUM
BRAN
STARCH TABLE
WASTE
GLUTEN
WASTE WATER
GLUTEN SETTLER
GLUTEN
DRYER
PRODUCTS
STARCH

EXPLANATION OF PLATE II

View of Pilot Plant

1. Hydraulic Mill
2. Feed Hopper
3. Tipper
4. Flight Conveyer
5. Coarse Screen (40-mesh)
6. Fine Screen (200-mesh)
7. Bran Washing Screen (200-mesh)
8. Control Panel
9. Debranner
10. Bran Pump
11. Bran Receiver

PLATE II

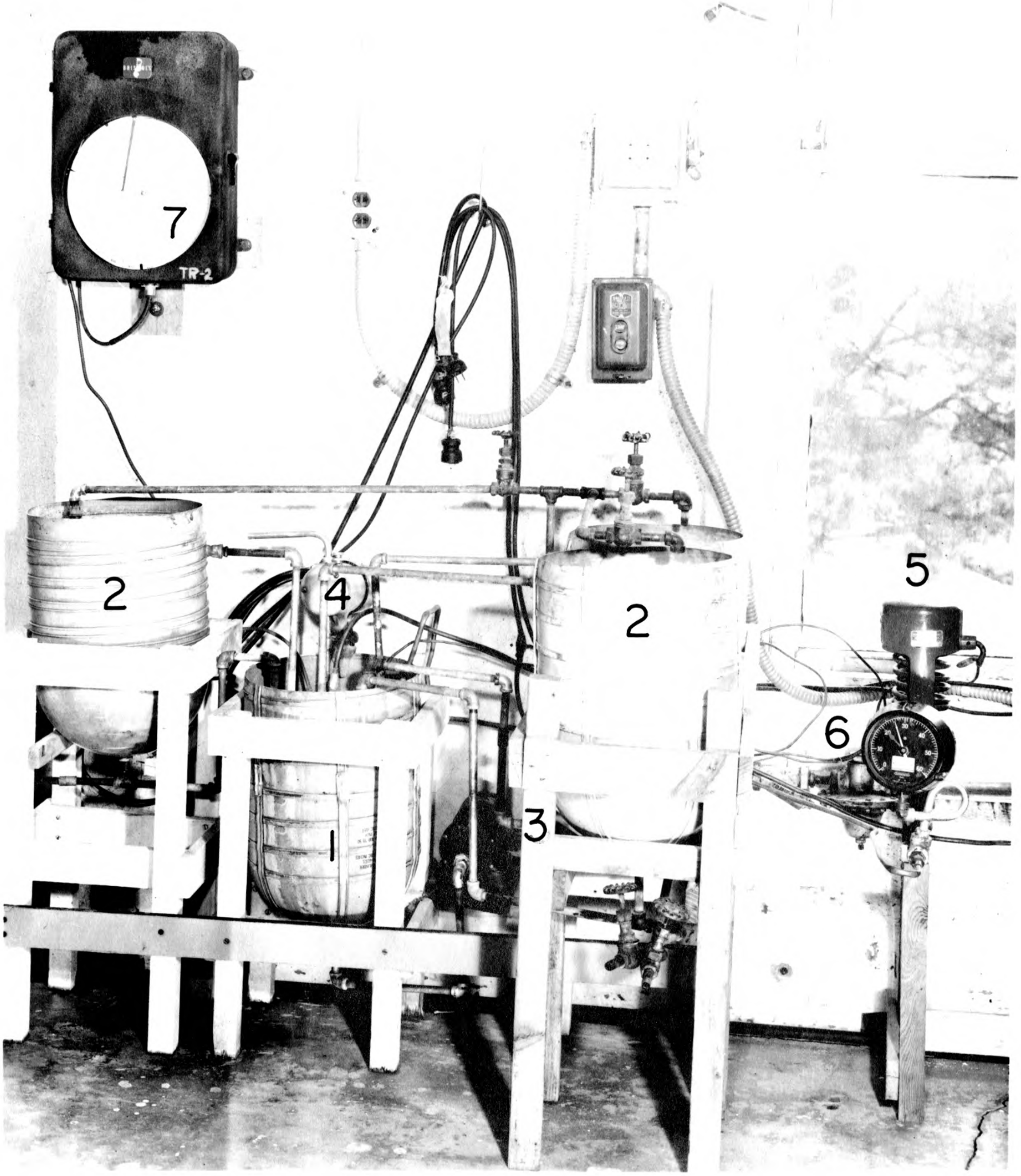


EXPLANATION OF PLATE III

Steeping Equipment

1. Heating Tank
2. Steeping Tanks
3. Steep Water Circulating Pump
4. Lightning Mixer
5. Taylor Self-acting Steam Regulator
6. Steam Pressure Gauge
7. Bristol Temperature Recorder

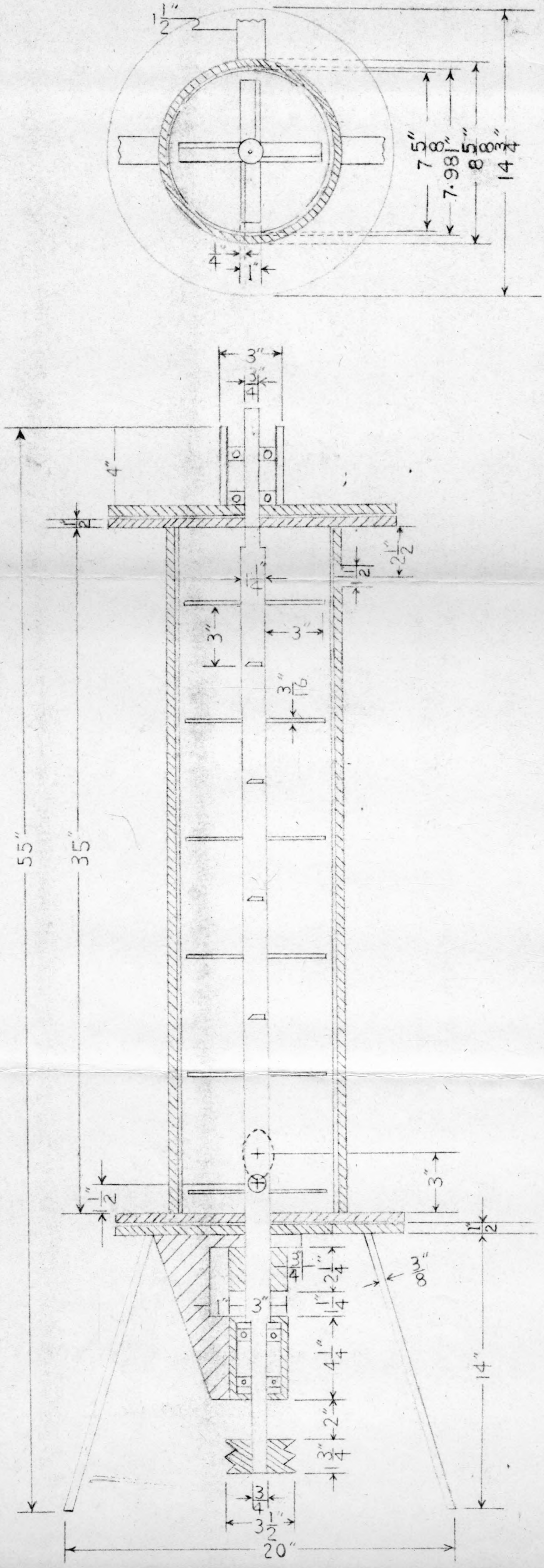
PLATE III



EXPLANATION OF PLATE IV

Detailed Drawing of Hydraulic Mill

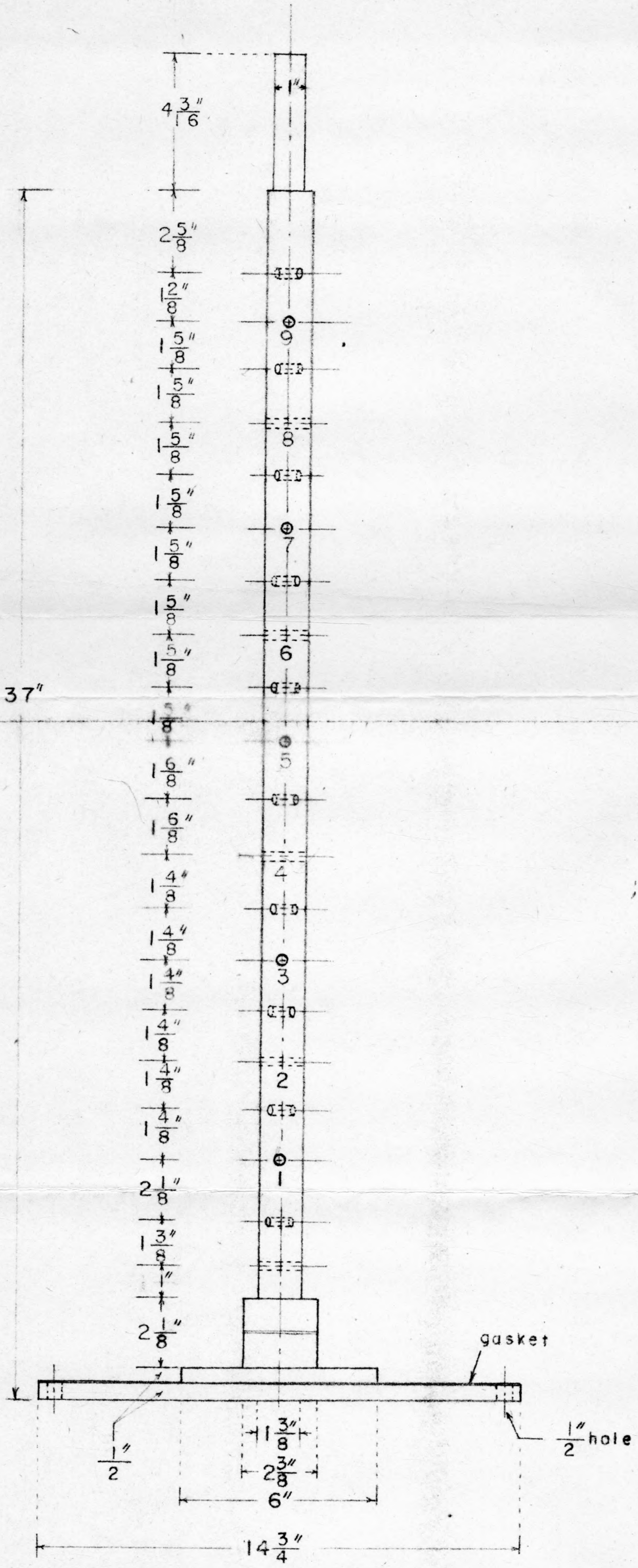
PLATE IV


1/2"
7 5/8"
7.98"
8 5/8"
14 3/4"
1/4"
1"
3"
4"
1/2"
2 1/2"
55"
35"
3/16"
3"
2 1/4"
1 1/4"
4 1/4"
2"
1 3/4"
3/8"
14"
3 1/2"
20"

EXPLANATION OF PLATE V

Detailed Drawing of Mill Shaft

PLATE V



flat blades. This is the casing and blade arrangement found to form the highest grinding efficiency and the least power consumption by Hsieh (10).

The shaft was driven by a ten hp. 1170 rpm, Fairbanks-Morse induction motor through two V-belts. The speed of shaft was adjusted by using various pulley ratios. A T-2 Frahm tachometer and a Stewart-Warner tachometer were used to measure the shaft speed of the mill. The power consumption was indicated by a General Electric type V-3-A polyphase watt hour meter.

Screening Equipment

Screens. Two 40-mesh and three 200-mesh screens each 31-1/2 inches by 4 inches were used in this experiment. The ground grits with water overflowed from the mill through a one inch standard pipe into a tipper and then onto the two 40-mesh screens in parallel. The tipper was used to measure the overflow rate from the mill. The overflow from the 40-mesh screens was washed into the debranner, from which the bran portion was pumped by a gear pump to one of the 200-mesh screens. The underflow was pumped by another gear pump to two 200-mesh screens, then the underflows from the three 200-mesh screens were pumped to the storage tank as starch milk. The overflow of the 200-mesh screen was the bran portion, and the overflow of the two 200-mesh screens was pumped back to the mill by a gear pump for further grinding. Water sprays on each screen washed the material being screened.

Flight Conveyer and Debranner. A flight conveyer driven by a 1 hp Reeves Varimotor through a belt and a set of reduction gears was employed to convey the partially ground grits in the debranner to the mill for further grinding. The linear velocity lay in the range of 1.5 to 9.0 feet per minute. The dimensions of the conveyer were:

Width of flight	5 inches
Depth of flight	2-7/16 inches
Interval of flight	5 inches
Width of trough	5-1/2 inches
Depth of trough	3-1/2 inches
Length of trough	75 inches
Slope of trough	45°

A detailed drawing of the debranner is shown on Plate VI. The debranner, which was in the lower end of the conveyer, served to separate the lighter bran from the partially ground grits by a flotation process. Compressed air was used to bubble the bran portion which was pumped by a gear pump to a 200-mesh screen. Finally, the bran was washed and dried.

Control Panel. There were five flowrators (Fischer and Porter Company's Series 700, Master-Enclosed Type) and seven switches arranged on a control panel as shown in Plate VII. The various rates of water flow as well as the starch tabling operation were measured and controlled by the flowrators and switches.

Tabling Equipment

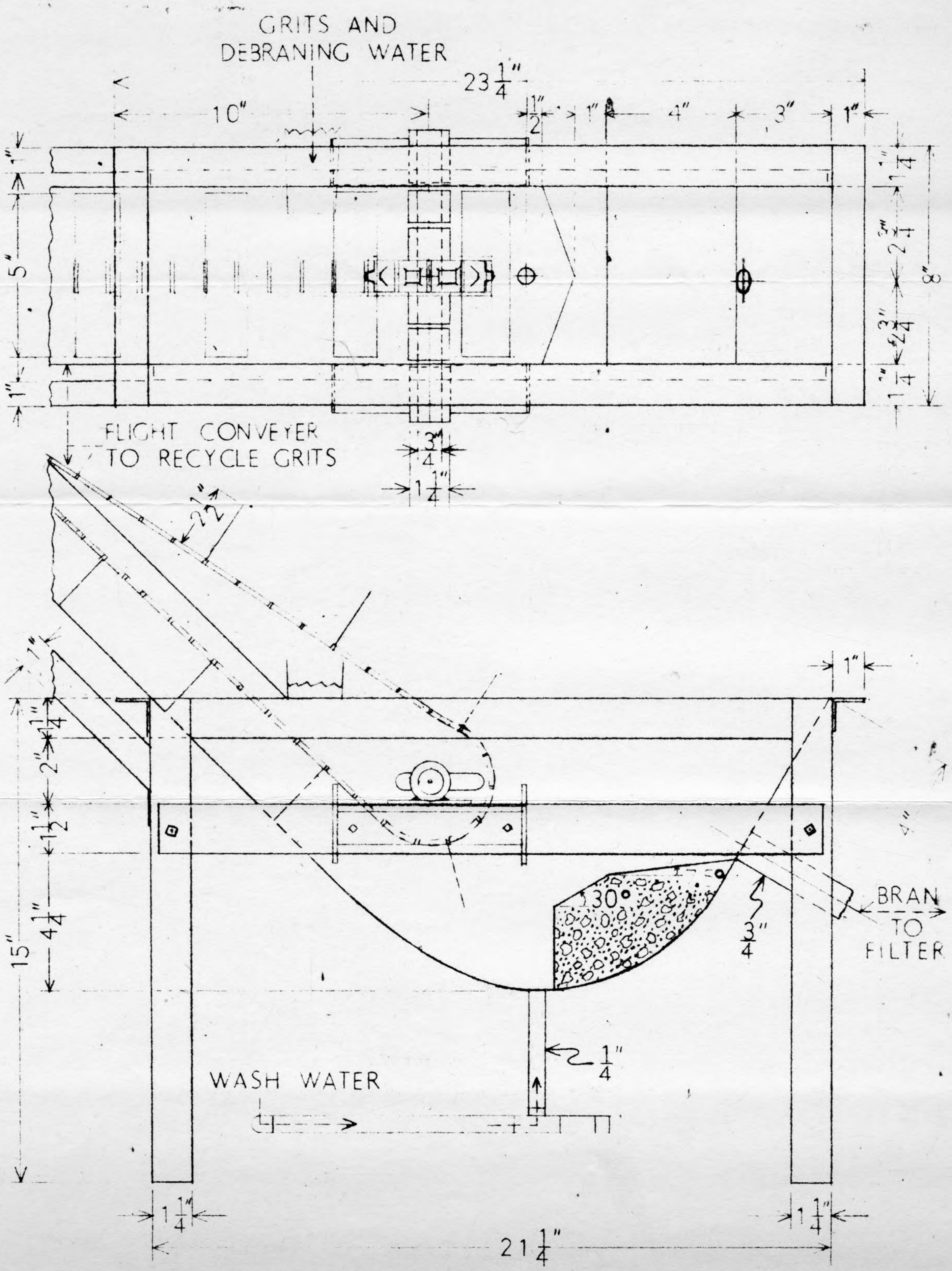
Storage Tanks. A 50-gallon, cone-bottom, stainless steel tank was used to store the starch milk from the 200-mesh screens before tabling. A 1/4 hp lightning mixer, Model D-1A, was used to keep the starch milk in suspension. Another 100-gallon, cone-bottom, stainless steel tank was used to hold the gluten solution which overflowed from the starch tables.

Starch Tables. Four starch tables with a pitch of one inch per 10 feet alternately in opposite directions were used to separate the starch from the gluten. The dimensions of the tables were 27 feet long, 5-3/4 inches wide, and 2-1/2 inches deep.

EXPLANATION OF PLATE VI

Drawing of Debranner

PLATE VI.



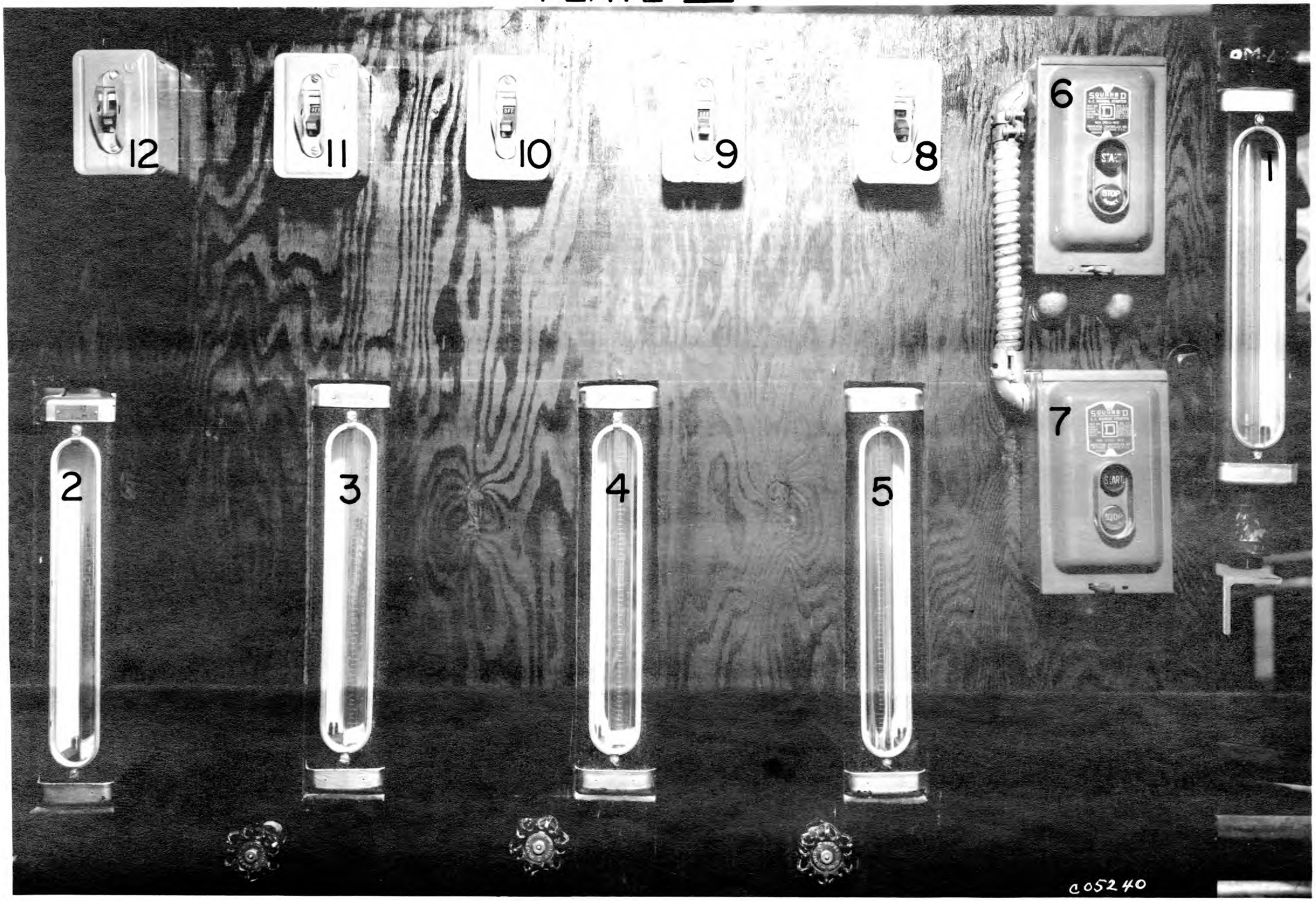
GRITS AND
DEBRANING WATER
23 1/4"
10"
1/2"
1"
4"
3"
1"
1"
5"
1"
8"
FLIGHT CONVEYER
TO RECYCLE GRITS
3/4"
1 1/4"
2 1/2"
1"
30°
3/4"
BRAN
TO
FILTER
15"
1 1/4"
2"
1 1/2"
4 1/4"
1/4"
WASH WATER
1 1/4"
1 1/4"
21 1/4"

EXPLANATION OF PLATE VII

Control Panel

1. Flowrator for Feed Water
2. Flowrator for Grits Recycling Water
3. Flowrator for Water to Screens
4. Flowrator of Debranning Water
5. Flowrator for Starch Milk
6. Starter for Starch Milk Pump to Table
7. Starter for Motor for Flight Conveyer
8. Starter for feed Water Pump
9. Starter for Motor for Screen-Shaker
10. Starter for Recycling Pump
11. Starter for Starch Milk Pump to Storage
12. Starter for Starch Milk Pump to Storage

PLATE VII



Filter. A nutsch-type filter and a vacuum pump (F. J. Stokes Machine Company, Model 33275 reciprocating vacuum pump) were used to filter the gluten slurry and the bran fraction. The area of the filter was four square feet.

Dryer. A compartment dryer made by George Koch Sons Company was used to dry the final products. Air was heated by a steam coil and circulated by a blower. The temperature was controlled at 120-130° F. and recorded by a Bristol pneumatic temperature controller-recorder.

MATERIALS

The raw material used in this experiment was milo sorghum grits of both waxy and non-waxy types. The grits were supplied by Grain Products, Incorporated, of Dodge City, Kansas, and stored in 55-gallon, open-head barrels.

The composition of the grits as analyzed by the Chemical Service Laboratory of Kansas State University, are shown in Table 1.

Table 1. Chemical analysis of sorghum grits.

Component	Weight per cent		
	Batch 1	Batch 2	Batch 3
Type	Waxy	Non-waxy	Waxy
Protein	9.38	10.44	11.44
Ether extract	0.92	1.66	0.98
Crude fiber	0.84	0.89	0.82
Moisture	11.04	10.91	10.81
Ash	0.65	0.86	0.68
N-free extract	77.17	75.24	75.27
Carbohydrate	78.01	76.13	76.09
Starch	71.07	68.70	69.45

All the steeping and processing water was the tap water of Manhattan city. The analysis of the water is shown in Table 2.

Table 2. Analysis of Manhattan city water.

Total hardness as $CaCO_3$, ppm	127.00
HCO_3 as $CaCO_3$, ppm	59.30
Calcium as $CaCO_3$, ppm	80.65
Magnesium as $CaCO_3$, ppm	46.35
pH	8.97

EXPERIMENTAL PROCEDURE

Thirty-nine separate runs were performed for this experiment in three classifications. Series I, runs 1 to 5, using non-waxy grits served as general investigation runs. Series I, runs 6 and 7 were used to test sampling techniques, material balances, and to serve as comparison standards for operations using waxy grits. Series II, runs 1 to 24, investigated the milling of waxy sorghum grits. Series III, runs 1 to 4, investigated the effect of high temperatures in steeping on regular (non-waxy) grits, and series III, runs 5 to 8, investigated the effect of pH in the steeping water on regular grits.

For continuous processes, equilibrium or steady state condition is defined as the state at which the properties of all of the streams in the process are constant. In order to determine if the equilibrium state was attained in this work, four quantities, the mill temperature, the mill overflow rate (measured by the tipper rate), the starch milk density, and the rate of revolution of the KWH meter were measured at certain time intervals (usually 15 minutes) for each run. When these became constant, equilibrium was considered to have been reached. A graphical interpretation of the attainment of equilibrium is shown in Figs. 1 and 2.

Thirty to eighty pounds of sorghum grits were steeped, at a time, depending upon the feed rate to be used. Except for the runs in series III, the steeping temperature was kept at 125 to 130° F. The steeping water, which was ordinary tap water was used at the rate of 0.25 to 0.35 gallons per pound of grits. The steeping time was kept at one hour. After steeping, the water was drained off and discarded.

The pH of the steeping water for runs III-5 to III-8 was controlled, by adding 0.1 N HCl to the steeping water before the hot water was pumped into the grain. The pH of the steeping water was checked every fifteen minutes, and acid was added if the pH rose.

The steeped grits were charged into the feed hopper by hand, and the screw conveyer, the feed water, and the hydraulic mill were started simultaneously. When overflow from the mill began, the shaking screen motor and the screening water were started. Then the pumps for underflow streams and recycling stream were started. As the partially ground grits accumulated to a considerable amount in the debranner, the debranning water, the recycling water, and the flight conveyer were started.

The screening water rate, the recycling water rate, and the debranning water rate were kept at the lowest possible effective rates in most of the runs, i.e., 0.2, 0.2, and 0.3 gpm respectively. The starch milk density, the rpm of the KWH meter, the mill temperature, and the tipper rate were recorded every fifteen minutes. As pointed out in the previous section, the attainment of the equilibrium state was determined by the measurement of these four quantities.

Before the equilibrium state was reached, the starch milk was discharged to the sewer, while the bran fraction was caught in a bucket for disposal.

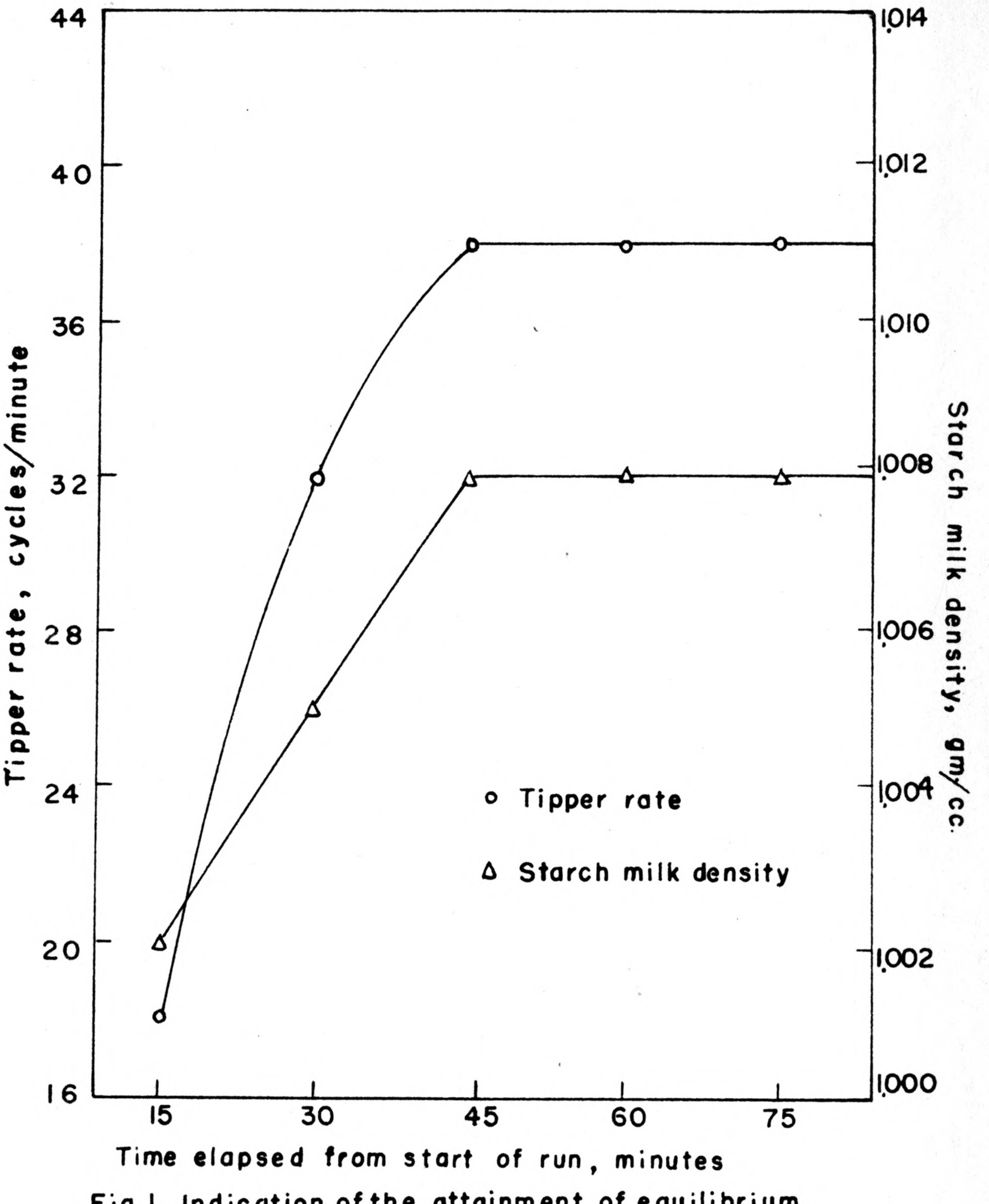


Fig. I. Indication of the attainment of equilibrium.

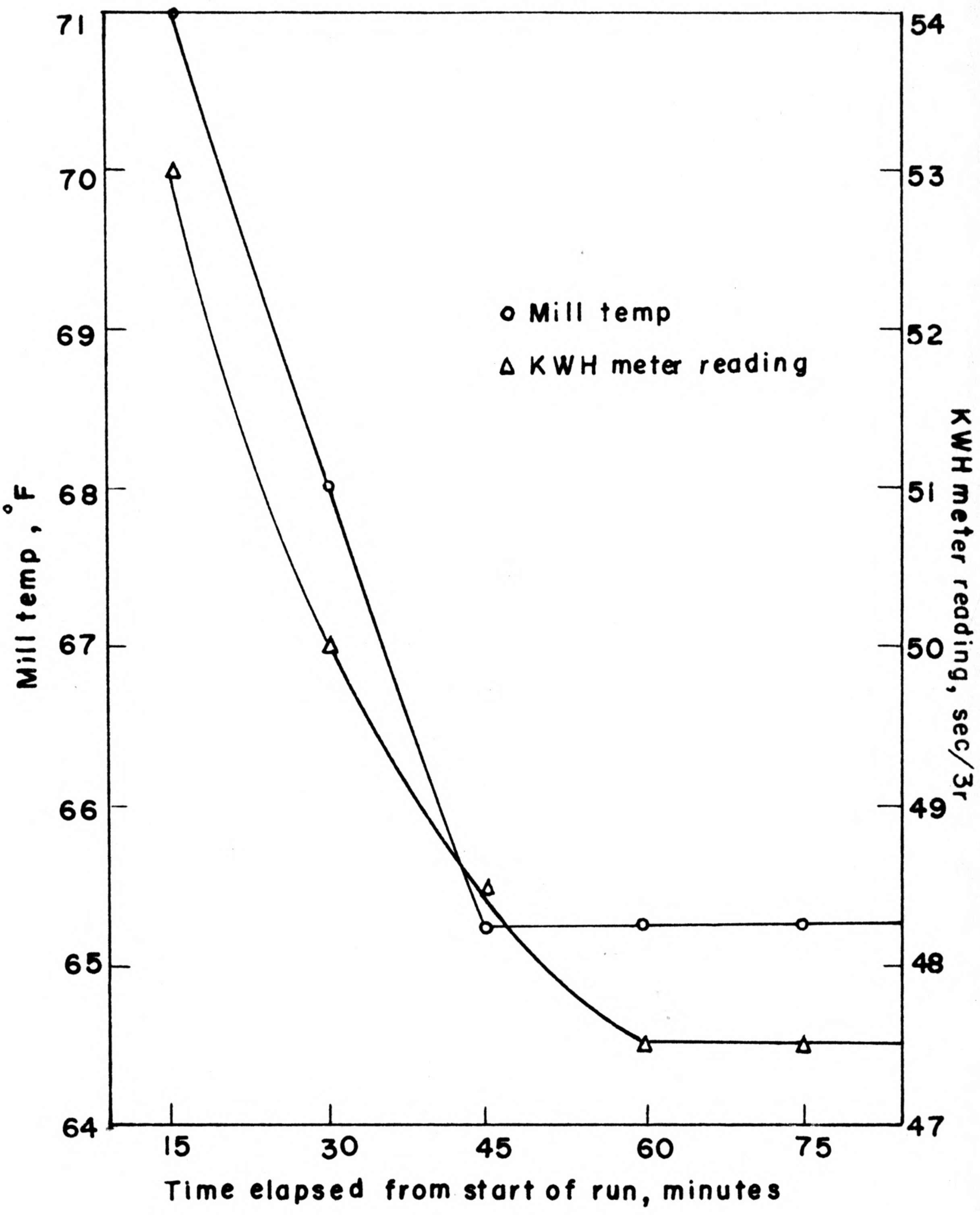


Fig. 2. Indication of the attainment of equilibrium.

After the equilibrium state was reached, the mill overflow rate was measured by catching the flow for a given time interval, usually one minute. Then, the flow of starch milk was changed from the sewer to the storage tank. Meanwhile the bran was also collected in a bucket. The starch milk and bran were collected for a certain time interval, usually 15 minutes, and this served as the basis for the material balance.

After sampling, the starch milk was pumped from the storage tank to the head of the first table through a 1/4-inch galvanized pipe, and the starch settled out on the table while the gluten in suspension passed over the tables and was pumped to another storage tank. The tabling rate was kept at 0.6 gpm, and washing water at a rate of 1.0 gpm was introduced to the starch table immediately after tabling to remove any gluten from the surface of the starch. The washing time was kept at 20 minutes in most of the runs.

After 12 to 24 hours settling, the gluten was deposited at the bottom of the storage tank. The upper clear solution was syphoned off, and the gluten slurry was filtered on the nutsch filter.

The starch was removed from the tables manually and dried together with the bran slurry and the gluten for about 24 hours at a temperature of 130° F. The final products were sent to the Chemical Service Laboratory of Kansas State University for analysis.

Because of the nature of pilot plant experimentation, a factorial design was used for part of this work. In the classical design of experiments, variables are studied one by one. In the factorial design, each variable is evaluated at several levels of all other variables. In other words, the factorial design views the process as a whole and the interactions between variables can be estimated only from factorially designed experiments. The factorial design is particularly useful when data are subject to fluctuations or errors of the same order of magnitude as the effect.

Further, in laboratory experiments, the worker is generally in the fortunate position of being able to have all of his independent variables under complete control. However, in pilot plant scale experiments, the worker often cannot obtain complete control of all his variables. Therefore, experiments on the pilot plant scale generally have a much larger error than laboratory work. Under these conditions it is sometimes difficult to decide whether a particular result is genuine or due to error, and this calls for a statistical test of significance.

There were 14 independent variables in this investigation as follows:

Grain feed rate

Feed water rate

Rpm of mill

Steeping time

Steeping temperature

pH of steeping water

Screen capacity

Quantity of steeping water per unit feed

Recycling water rate

Screening water rate

Debranning water rate

Washing water time

Starch tabling rate

Construction of mill

If all of these variables had been investigated, there would have been an impossible number of runs to be done. However, among these variables, some have little significance in affecting the starch recovery, the water consumption, or the energy consumption.

Hence, only the important variables, the grits feed rate, the feed water rate, the rpm of the mill, the steeping temperature, and the pH of the steeping water were studied. A factorial design was developed for the grain feed rate, feed water rate, and rpm of mill on waxy sorghum grits. Steeping temperature and pH of steeping water were studied by classical methods with non-waxy sorghum grits.

The level of a variable is a value of the variable such that the increments between levels is uniform. The levels of each variable were selected within the capacities of mill and screens, so that the equilibrium state could be reached in a reasonable time. The test conditions for the factorial experiment are listed in Table 3.

Table 3. Levels used in factorial design of series II experiments.

Variable	Level	Value	Symbol
Grits feed rate (dry basis)	0	15 lb/hr	x_1
	1	25 lb/hr	
	2	35 lb/hr	
Feed water rate	0	10 gal/hr	x_2
	1	20 gal/hr	
Rpm of mill	0	1500 rpm	x_3
	1	2125 rpm	

The factorial design for this 2 × 2 × 3 analysis of levels is shown in Plate VIII.

EXPLANATION OF PLATE VIII

Graphical Interpretation of 2 × 2 × 3 Factorial Design

x_1, Feed Grain Rate

x_2, Feed Water Rate

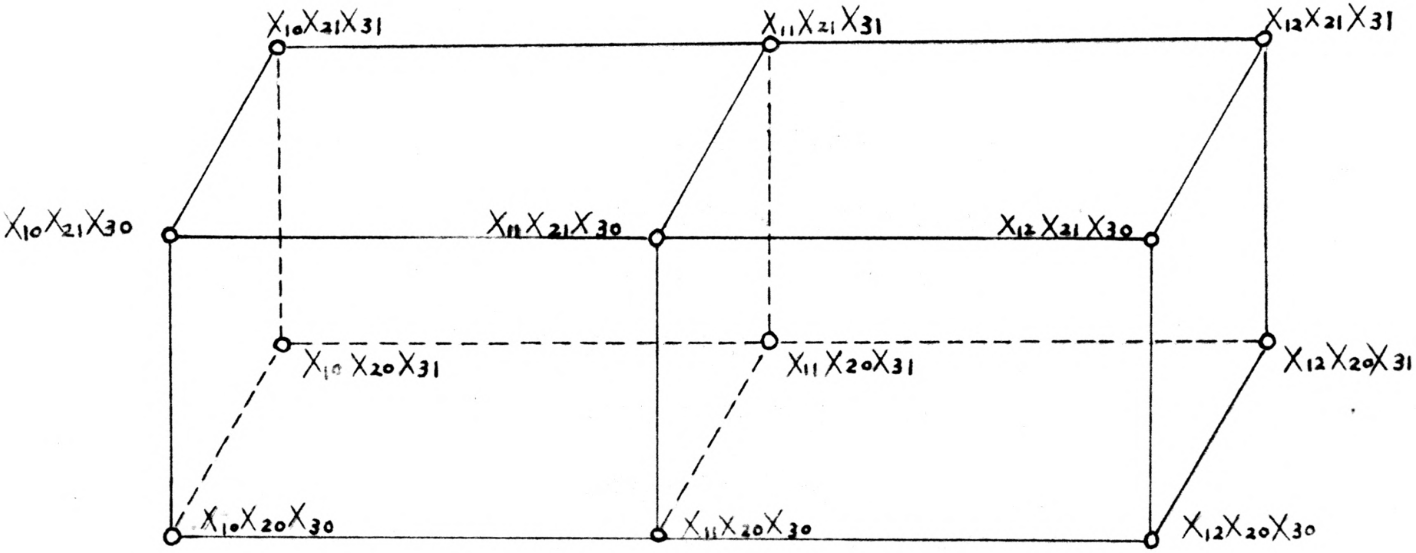
x_3, Rpm of Mill

0, Variable at Low Level

1, Variable at Medium Level

2, Variable at High Level

PLATE VIII


$X_{10}X_{21}X_{31}$
$X_{11}X_{21}X_{31}$
$X_{12}X_{21}X_{31}$
$X_{10}X_{21}X_{30}$
$X_{11}X_{21}X_{30}$
$X_{12}X_{21}X_{30}$
$X_{10}X_{20}X_{31}$
$X_{11}X_{20}X_{31}$
$X_{12}X_{20}X_{31}$
$X_{10}X_{20}X_{30}$
$X_{11}X_{20}X_{30}$
$X_{12}X_{20}X_{30}$

EXPERIMENTAL DATA

The experimental data as well as the experimental results are presented in Tables 4 to 10. Tables 4, 5, and 6 present the processing conditions for series I, II and III, respectively. The process results for these three series are given in Tables 7, 8 and 9. The chemical analysis of the products is listed in Table 10.

All the feed and yield quantities are expressed as rates on a dry basis. The feed rate was determined from the time required to feed 10 pounds of grits. The various water rates and the tabling rate were recorded directly from the flowrators, and the shaft speed of the mill was adjusted by varying the ratio of pulleys. The starch milk density was expressed in degrees Beaumé, and the temperature of the mill was recorded directly from the Bristol temperature recorder. The net power consumption of the mill was evaluated from the following equation:

$$KW = \frac{(60)(7.2)(R_f - R_i)}{1,000}$$

Where R_f = the rpm of the watt-hour meter during the equilibrium state of the run.

R_i = the rpm of the watt-hour meter when the mill was run without load.

For a shaft speed of 2125 rpm, R_i was 1.410; at 1500 rpm R_i was 1.365. Both R_f and R_i were recorded in terms of seconds per three revolutions, and were converted into rpm units.

The starch recovery, starch yield, the starch and protein accounted for in the products, and the water and energy consumed per pound of starch produced were all computed from the chemical analysis of the products and

Table 4. Process conditions for series I, using non-waxy grits.

Run number		1	2	3	4	5	6	7
Steeping temperature(1)	°F	--	--	--	--	130	130	130
Mill speed	rpm	2125	2125	2125	2125	2125	2125	2125
Mill temperature	°F	78.8	78	74	78	78	79	80
Feed rate, wet basis	lb/hr	85.71	79.75	62.72	50.80	42.60	41.72	30.91
Feed rate, dry basis	lb/hr	76.25	60.45	55.80	45.20	37.90	36.85	27.50
Mill concentration	Wt%	--	--	--	--	24.82	24.80	21.20
Overflow rate from mill, dry basis	lb/hr	128.50	109.20	102.30	85.20	68.60	62.55	49.60
Grits recycling rate, dry basis	lb/hr	52.25	48.75	46.50	40.00	30.70	25.70	22.10
Power consumption	KW	1.250	1.210	1.194	1.152	1.082	1.080	1.022
Specific gravity of starch milk	°Be	2.84	2.56	2.43	2.28	1.72	1.58	1.29
Water consumption								
for feeding	gal/hr	20.0	20.0	20.0	20.0	20.0	20.0	20.0
for screening	gal/hr	12.0	12.0	12.0	12.0	12.0	12.0	12.0
for debranning	gal/hr	18.0	18.0	18.0	18.0	18.0	18.0	18.0
for recycling	gal/hr	12.0	12.0	12.0	12.0	12.0	12.0	12.0
for washing	gal/hr	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Starch tabling rate	gal/hr	36.00	36.00	36.00	36.00	36.00	36.00	36.00

(1) Runs 1 to 4 were ground with no previous steeping.

Table 5. Process conditions for series II, using waxy grits. All runs were steeped one hour at 125-130°F.

Run number		1	2	3	4	5	6	7	8	9	10	11	12
Mill speed	rpm	2125	2125	2125	2125	2125	2125	2125	2125	2125	2125	2125	2125
Mill temperature	°F	77	78	77	74	65	65	65	70	74	74	72	72
Feed rate, wet basis	lb/hr	16.88	16.83	16.82	16.83	28.05	28.03	28.06	28.06	39.28	39.29	39.30	39.29
Feed rate, dry basis	lb/hr	15.04	14.98	14.99	14.99	24.99	24.97	25.00	25.00	35.00	35.00	35.01	35.00
Mill concentration	Wt%	14.50	----	17.26	----	18.52	----	20.21	----	22.01	----	24.23	----
Overflow rate from mill, dry basis	lb/hr	27.50	27.00	28.10	28.15	49.50	49.60	49.50	49.80	72.00	70.98	71.25	71.50
Grits recycling rate, dry basis	lb/hr	12.46	12.02	13.11	13.16	24.51	24.63	24.50	24.80	37.00	35.98	36.24	36.49
Power consumption	Kw	0.916	0.904	1.010	1.008	0.994	0.994	1.064	1.070	1.050	1.030	1.085	1.075
Specific gravity of starch milk	°Be	0.72	0.72	0.72	0.72	1.15	1.15	1.15	1.15	1.44	1.44	1.44	1.44
Water consumption													
for feeding	gal/hr	20.0	20.0	10.0	10.0	20.0	20.0	10.0	10.0	20.0	20.0	10.0	10.0
for screening	gal/hr	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
for debranning	gal/hr	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
for recycling	gal/hr	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
for washing	gal/hr	60.0	60.0	60,0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Starch tabling rate	gal/hr	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00

Run number		13	14	15	16	17	18	19	20	21	22	23	24
Mill speed	rpm	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Mill temperature	°F	68	67	66	68	66	63	60	64	66	67	67	66
Feed rate, wet basis	lb/hr	16.82	16.81	16.81	16.81	28.03	28.03	28.03	28.02	39.26	39.20	39.29	39.20
Feed rate, dry basis	lb/hr	14.98	14.99	14.99	14.99	25.00	25.00	25.00	24.99	35.01	34.96	35.04	34.96
Mill concentration	Wt%	14.02	----	17.56	----	19.24	----	20.81	----	23.03	----	24.52	----
Overflow rate from mill, dry basis	lb/hr	28.20	28.50	28.15	28.24	51.50	51.65	51.45	51.30	72.45	72.30	72.28	72.10
Grits recycling rate, dry basis	lb/hr	13.22	13.51	13.16	13.25	26.50	26.65	26.45	26.31	37.44	37.34	37.24	37.14
Power consumption	Kw	0.590	0.581	0.728	0.724	0.718	0.718	0.824	0.821	0.810	0.798	0.875	0.873
Specific gravity of starch milk	°Be	0.72	0.72	0.72	0.72	1.15	1.15	1.15	1.15	1.29	1.29	1.45	1.45
Water consumption													
for feeding	gal/hr	20.0	20.0	10.0	10.0	20.0	20.0	10.0	10.0	20.0	20.0	10.0	10.0
for screening	gal/hr	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
for debranning	gal/hr	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
for recycling	gal/hr	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
for washing	gal/hr	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Starch tabling rate	gal/hr	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00

Table 6. Process conditions for series III, using non-waxy grits.

Run number		1	2	3	4	5	6	7	8
Steeping temperature	°F	130	140	150	160	130	130	130	130
pH of steeping water		8.97	8.97	8.97	8.97	4.00	5.00	6.00	8.97
Mill speed	rpm	2125	2125	2125	2125	2125	2125	2125	2125
Mill temperature	°F	84	82	84	84	82	85	84	81
Feed rate, wet basis	lb/hr	24.98	25.01	25.00	25.00	18.99	19.16	19.05	18.99
Feed rate, dry basis	lb/hr	22.22	22.25	22.24	22.24	16.90	17.05	16.95	16.90
Mill concentration	Wt%	18.00	17.80	17.25	17.50	15.20	15.50	15.20	14.90
Overflow rate from mill, dry basis	lb/hr	40.20	38.16	41.25	38.96	28.20	27.39	28.50	28.45
Grits recycling rate, dry basis	lb/hr	17.98	15.91	19.01	16.72	11.30	10.34	11.55	11.55
Power consumption	KW	1.011	1.011	0.912	0.885	0.864	0.889	0.898	0.985
Specific gravity of starch milk	°Be	1.01	1.01	1.01	1.01	0.72	0.72	0.58	0.58
Water consumption									
for feeding	gal/hr	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
for screening	gal/hr	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
for debranning	gal/hr	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00
for recycling	gal/hr	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
for washing	gal/hr	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00
Starch tabling rate	gal/hr	36.00	36.00	36.00	36.00	36.00	36.00	36.00	36.00

Table 7. Process results for series I. All yields are reported on the dry basis.

Run number		1	2	3	4	5	6	7
Yields of products								
Starch	lb/hr	23.24	23.91	25.85	24.91	23.18	22.46	17.24
	%	30.49	39.55	46.32	55.11	61.16	60.94	62.69
Gluten	lb/hr	7.86	7.47	7.95	6.55	6.16	6.35	4.97
	%	10.31	12.35	14.25	14.50	16.26	17.25	18.10
Bran	lb/hr	4.66	4.00	4.60	4.52	3.56	3.61	2.85
	%	6.11	6.62	8.25	10.00	9.38	9.80	10.20
Total	lb/hr	35.77	35.37	38.40	35.98	32.90	32.42	25.06
	%	46.91	58.42	68.80	79.60	86.81	87.90	91.12
Starch recovery								
Starch in feed	lb/hr	60.91	48.29	44.57	36.10	30.27	29.43	21.96
Recovery	%	38.17	49.51	58.00	69.00	76.59	76.34	78.50
Starch balance								
In starch	lb/hr	23.14	23.74	25.67	24.76	22.94	22.28	17.11
	%	37.99	49.16	57.59	68.58	75.78	75.70	77.91
In gluten	lb/hr	5.14	4.15	4.26	3.23	2.60	3.36	2.65
	%	8.44	8.59	9.56	8.95	11.89	11.41	12.06
In bran	lb/hr	1.51	2.36	1.25	1.33	0.96	0.96	0.58
	%	2.48	4.89	2.80	3.68	3.17	3.26	2.64
Total	lb/hr	29.79	30.25	31.18	29.32	26.50	26.60	20.34
Starch accounted for	%	48.90	62.64	69.95	81.21	87.54	90.38	92.62
Protein accounted for								
In starch	lb/hr	0.109	0.167	0.160	0.154	0.238	0.179	0.127
	%	1.27	2.45	2.72	3.23	5.96	4.57	4.38
In gluten	lb/hr	1.42	1.97	2.47	1.88	2.57	2.11	1.67
	%	16.56	29.01	42.00	39.49	64.41	53.96	57.58
In bran	lb/hr	0.57	0.68	0.79	0.87	0.57	0.61	0.48
	%	6.66	10.00	13.43	18.27	14.28	15.60	16.55
Total	lb/hr	2.10	2.71	3.42	2.90	3.38	2.90	2.27
Total in feed	lb/hr	8.57	6.79	5.88	4.76	3.99	3.91	2.90
Protein accounted for	%	24.50	40.01	58.16	61.00	34.66	74.17	78.51
Net energy consumption for grinding	KWH/lb							
Per pound of feed		0.0164	0.0200	0.0213	0.0255	0.0285	0.0293	0.0371
Per pound of starch		0.0538	0.0506	0.0309	0.0462	0.0467	0.0481	0.0593
Water consumption	gal/lb							
Processing water per pound of feed		0.813	1.025	1.111	1.371	1.636	1.682	2.254
Processing water per pound of starch		2.66	2.59	2.40	2.49	0.0285	0.0293	0.0371

Table 8. Process results for series II. All yields are reported on the dry basis.

Run number		1	2	3	4	5	6	7	8	9	10	11	12
Yields of products													
Starch	lb/hr	7.36	7.40	7.35	7.45	12.90	12.70	12.50	12.30	16.75	16.65	16.60	16.40
	%	49.06	49.33	49.00	49166	51.60	50.80	50.00	49.20	47.85	47.57	47.43	49.71
Gluten	lb/hr	4.52	4.48	4.50	4.51	7.52	7.48	7.45	7.48	9.98	10.00	10.10	10.05
	%	30.13	29.86	30.00	30.06	30.08	29.92	29.80	29.92	28.51	28.57	28.85	28.71
Bran	lb/hr	1.85	1.90	1.92	1.89	3.00	2.89	3.12	2.99	3.75	3.69	3.68	3.78
	%	12.33	12.66	12.80	12.60	12.00	11.56	12.48	11.96	10.71	10.54	10.51	10.80
Total	lb/hr	13.73	13.78	13.77	13.85	23.42	23.07	23.07	22.77	30.48	30.34	30.38	30.23
	%	91.52	91.85	91.80	84.72	93.68	92.28	91.28	91.08	87.07	86.68	86.79	89.22
Starch Recovery													
Starch in feed	lb/hr	11.56	11.56	11.56	11.56	19.27	19.27	19.27	19.27	26.98	26.98	26.98	26.98
Recovery	%	63.66	64.01	63.58	64.44	66.94	65.90	64.86	63.82	62.08	61.71	61.52	60.78
Starch accounted for													
In starch	lb/hr	7.33	7.36	7.32	7.41	12.84	12.65	12.45	12.24	16.66	16.56	16.53	16.32
	%	63.40	63.66	63.32	64.10	66.63	65.64	64.60	63.51	61.52	61.37	61.26	60.48
In gluten	lb/hr	2.99	2.86	2.71	2.75	5.09	5.04	4.21	4.52	7.38	6.97	6.75	7.31
	%	25.86	24.74	23.44	23.78	26.41	26.15	21.84	23.45	27.35	25.83	25.02	27.09
In bran	lb/hr	0.809	0.789	0.562	0.723	1.186	1.418	1.538	1.284	1.957	1.986	1.700	1.693
	%	6.98	6.82	4.86	6.25	6.15	7.35	7.98	6.66	7.25	7.36	6.30	6.27
Total	lb/hr	11.12	11.00	10.59	10.88	19.11	19.10	18.19	18.04	25.99	25.51	24.98	25.32
Starch accounted for	%	96.24	95.22	91.62	94.13	99.13	99.14	94.42	93.62	96.12	94.56	92.58	93.84
Protein accounted for													
In starch	lb/hr	0.030	0.035	0.029	0.034	0.046	0.043	0.049	0.048	0.075	0.074	0.068	0.067
	%	1.71	2.00	1.65	1.94	1.57	1.47	1.67	1.64	1.83	1.80	1.66	1.63
In gluten	lb/hr	1.075	1.087	1.159	1.167	1.649	1.710	1.812	1.850	2.384	2.424	2.584	2.570
	%	61.42	62.11	66.22	66.68	56.28	58.36	61.84	63.14	58.14	59.12	63.02	62.68
In bran	lb/hr	0.387	0.399	0.363	0.358	0.586	0.595	0.601	0.573	0.775	0.766	0.652	0.670
	%	22.11	22.80	20.74	20.45	20.00	20.30	20.51	19.55	18.90	18.68	15.90	16.34
Total	lb/hr	1.492	1.521	1.551	1.559	2.281	2.348	2.462	2.471	3.234	3.264	3.304	3.307
Total in feed	lb/hr	1.750	1.750	1.750	1.750	2.930	2.930	2.930	2.930	4.100	4.100	4.100	4.100
Protein accounted for	%	85.24	86.91	88.61	89.07	77.85	80.13	84.02	84.33	78.87	79.60	80.58	80.65
Net energy consumption for grinding	KWH/lb												
Per pound of feed		0.0610	0.0602	0.0674	0.0670	0.0397	0.0397	0.0422	0.0428	0.0300	0.0294	0.0310	0.0307
Per pound of starch		0.1240	0.1220	0.1370	0.1350	0.0770	0.0783	0.0852	0.0870	0.0626	0.0619	0.0654	0.0655
Water consumption	gal/lb												
Processing water per pound of feed		4.13	4.13	3.47	3.47	2.48	2.48	2.08	2.08	1.77	1.77	1.49	1.49
Processing water per pound of starch		8.42	8.37	7.08	6.98	4.81	4.88	4.16	4.23	3.70	3.72	3.13	3.17

Run number		13	14	15	16	17	18	19	20	21	22	23	24
Yields of products													
Starch	lb/hr	6.78	6.74	7.10	7.20	11.52	11.18	12.05	12.15	16.40	16.30	15.30	15.20
	%	45.20	44.93	47.33	48.00	46.08	44.72	48.20	48.60	46.85	46.57	43.71	43.43
Gluten	lb/hr	4.54	4.51	4.56	4.50	7.54	7.53	7.53	7.49	9.89	10.00	9.95	9.88
	%	30.26	30.06	30.40	30.00	30.16	30.12	30.12	29.96	28.25	28.57	28.71	28.22
Bran	lb/hr	1.92	1.89	1.89	1.90	2.89	2.80	2.93	2.90	3.81	3.85	3.78	3.79
	%	12.80	12.60	12.60	12.66	11.56	11.20	11.72	11.60	10.88	11.00	10.80	10.82
Total	lb/hr	13.24	13.14	13.55	13.60	21.95	21.51	21.51	22.54	30.13	30.15	29.03	28.87
	%	88.26	87.59	90.33	90.66	87.80	86.04	90.04	90.16	85.95	86.14	83.22	82.47
Starch Recovery													
Starch in feed	lb/hr	11.56	11.67	11.67	11.67	19.46	19.46	19.46	19.46	27.25	27.25	27.25	27.25
Recovery	%	58.65	57.75	60.83	61.69	59.19	57.45	61.92	62.43	60.18	59.81	56.14	55.77
Starch accounted for													
In starch	lb/hr	6.75	6.72	7.07	7.18	11.58	11.14	11.99	12.10	16.34	16.23	15.25	15.16
	%	58.39	57.58	60.58	61.52	59.50	57.24	61.61	62.17	59.96	59.55	55.96	55.63
In gluten	lb/hr	2.56	2.57	2.81	2.81	4.57	5.22	5.23	5.17	5.83	6.34	6.78	6.49
	%	22.14	22.02	24.07	24.07	23.48	26.82	26.87	26.56	21.39	23.26	24.88	23.81
In bran	lb/hr	1.076	0.639	0.742	1.211	1.425	1.145	1.227	1.413	2.286	2.088	1.465	1.115
	%	9.31	5.47	6.36	10.37	7.32	5.88	6.30	7.26	8.38	7.66	5.37	4.09
Total	lb/hr	10.38	9.93	10.62	11.20	17.57	17.50	18.44	18.68	25.54	24.66	23.49	22.76
Starch accounted for	%	89.84	85.07	91.01	95.96	90.30	89.94	94.78	95.99	89.73	90.47	86.21	83.53
Protein accounted for													
In starch	lb/hr	0.023	0.019	0.022	0.019	0.030	0.036	0.39	0.040	0.054	0.053	0.042	0.031
	%	1.31	0.98	1.14	0.93	0.93	1.12	1.21	1.24	1.20	1.18	0.94	0.69
In gluten	lb/hr	1.269	1.214	1.115	1.099	1.829	1.700	1.532	1.538	2.303	2.323	2.212	2.215
	%	72.51	63.23	58.07	57.23	56.97	52.95	47.72	47.91	51.29	51.73	49.26	49.33
In bran	lb/hr	0.330	0.352	0.349	0.323	0.480	0.460	0.504	0.506	0.643	0.641	0.738	0.732
	%	18.85	18.33	18.18	16.82	14.95	14.33	15.70	15.76	14.32	14.27	16.43	16.30
Total	lb/hr	1.622	1.585	1.486	1.414	2.339	2.196	2.075	2.084	3.000	3.017	2.992	2.978
Total in feed	lb/hr	1.75	1.92	1.92	1.92	3.21	3.21	3.21	3.21	4.49	4.49	4.49	4.49
Protein accounted for	%	92.67	82.54	77.39	74.98	72.85	68.40	64.63	64.91	66.81	67.18	65.69	66.32
Net energy consumption for grinding	KWH/lb												
Per pound of feed		0.0393	0.0387	0.0485	0.0482	0.0287	0.0287	0.0330	0.0329	0.232	0.0228	0.0250	0.0249
Per pound of starch		0.0871	0.0862	0.1025	0.1004	0.0623	0.0643	0.0683	0.0676	0.0494	0.0490	0.0571	0.0574
Water consumption	gal/lb												
Processing water per pound of feed		4.13	4.13	3.47	3.47	2.48	2.48	2.08	2.08	1.77	1.77	1.49	1.49
Processing water per pound of starch		9.14	9.20	7.33	7.21	5.38	5.55	4.32	4.28	3.78	3.80	3.40	3.42

Table 9. Process results for series III. All yields are reported on the dry basis.

Run number		1	2	3	4	5	6	7	8
Yields of products									
Starch	lb/hr	13.53	13.86	14.23	14.59	10.52	10.41	10.21	10.37
	%	60.89	62.29	63.98	65.60	62.24	61.05	60.23	61.36
Gluten	lb/hr	4.00	3.44	3.60	3.52	3.15	3.20	3.15	3.10
	%	18.00	15.46	16.18	15.82	18.64	18.76	18.58	18.34
Bran	lb/hr	2.60	2.00	2.00	2.20	1.62	1.65	1.59	1.60
	%	11.70	8.99	8.99	9.89	9.58	9.67	9.38	9.46
Total	lb/hr	20.13	19.30	19.83	20.31	15.29	15.26	14.95	15.07
	%	90.59	86.74	89.15	91.31	90.47	89.50	88.20	89.17
Starch recovery									
Starch in feed	lb/hr	17.75	17.77	17.76	17.76	13.49	13.61	13.54	13.49
Recovery	%	76.20	78.00	80.10	82.25	78.00	76.50	75.40	76.87
Starch accounted for									
In starch	lb/hr	13.44	13.76	14.16	14.49	10.48	9.61	9.79	10.28
	%	75.72	77.43	79.72	81.52	77.68	70.60	72.30	76.25
In gluten	lb/hr	2.13	1.74	2.07	1.99	2.03	1.93	1.70	1.60
	%	12.00	9.79	11.65	11.20	15.04	14.18	12.55	11.86
In bran	lb/hr	0.71	0.56	0.30	0.63	0.32	0.31	0.35	0.32
	%	4.00	3.15	1.68	3.55	2.37	2.27	2.58	2.37
Total	lb/hr	16.28	16.06	16.53	17.11	12.83	11.85	11.84	12.20
Starch accounted for	%	91.78	90.37	93.07	96.34	95.09	87.05	87.43	90.47
Protein accounted for									
In starch	lb/hr	0.089	0.098	0.075	0.097	0.028	0.028	0.046	0.072
	%	3.80	4.17	3.19	4.13	1.57	1.56	2.57	4.04
In gluten	lb/hr	1.31	1.24	1.07	1.09	0.72	0.85	0.98	0.99
	%	55.98	52.76	45.53	46.38	40.44	47.48	54.74	55.61
In bran	lb/hr	0.47	0.42	0.46	0.45	0.36	0.29	0.25	0.26
	%	20.08	17.87	19.57	19.14	20.22	16.20	13.96	14.60
Total	lb/hr	1.869	1.758	1.605	1.637	1.108	1.168	1.276	1.322
Total in feed	lb/hr	2.34	2.35	2.35	2.35	1.780	1.790	1.790	1.780
Protein accounted for	%	79.87	74.80	68.30	69.65	62.23	65.24	71.27	74.25
Net energy consumption for grinding	KWH/lb								
Per pound of feed		0.0455	0.0454	0.0410	0.0398	0.0511	0.0521	0.0530	0.0616
Per pound of starch		0.0747	0.0729	0.0641	0.0607	0.0821	0.0854	0.0879	0.0950
Water consumption	gal/lb								
Processing water per pound of feed		2.79	2.78	2.78	2.78	3.66	3.64	3.66	3.66
Processing water per pound of starch		4.58	4.47	4.36	4.25	5.89	5.96	6.07	5.98

Table 10. Analysis of products, dry basis.

Run number	Starch protein content %	Gluten		Bran	
		Starch content %	Protein content %	Starch content %	Protein content %
I -1	0.47	65.43	18.14	32.40	12.26
I -2	0.70	55.52	26.40	59.17	16.97
I -3	0.62	53.57	31.15	27.14	17.11
I -4	0.62	49.37	28.85	29.32	19.42
I -5	1.03	42.20	41.80	26.95	16.24
I -6	0.80	52.92	33.22	26.60	16.81
I -7	0.74	53.29	33.58	20.50	16.91
II -1	0.41	66.22	23.82	43.84	21.00
II -2	0.48	63.80	24.27	41.66	21.06
II -3	0.40	60.23	25.77	29.31	18.96
II -4	0.46	61.06	25.93	38.19	18.96
II -5	0.35	67.67	21.93	39.61	19.58
II -6	0.34	67.40	22.85	49.00	20.55
II -7	0.40	56.49	24.42	49.28	19.26
II -8	0.40	60.37	24.73	42.94	19.18
II -9	0.45	74.00	23.90	52.32	20.73
II-10	0.45	69.72	24.26	53.90	20.79
II-11	0.41	66.88	25.60	46.21	17.71
II-12	0.41	72.35	25.42	44.80	17.72
II-13	0.34	56.38	27.95	56.10	17.19
II-14	0.28	57.02	26.97	33.90	18.63
II-15	0.33	61.61	24.44	39.39	18.53
II-16	0.27	62.40	24.43	63.93	17.03
II-17	0.26	60.71	24.28	49.32	16.61
II-18	0.33	65.70	22.58	40.94	16.41
II-19	0.33	64.96	20.35	41.94	17.24
II-20	0.33	68.98	20.34	48.46	17.37
II-21	0.33	59.01	23.31	60.12	16.92
II-22	0.33	63.38	23.24	54.26	16.67
II-23	0.27	68.18	22.24	38.75	19.51
II-24	0.21	65.68	22.44	29.44	19.31
III -1	0.66	53.31	32.65	27.28	18.03
III -2	0.70	50.57	36.09	27.82	20.99
III -3	0.53	57.48	29.69	15.02	22.83
III -4	0.67	56.57	31.08	28.51	20.23
III -5	0.27	64.32	22.91	19.84	22.16
III -6	0.27	60.27	26.44	19.02	17.82
III -7	0.46	55.77	31.19	22.17	15.84
III -8	0.71	53.65	31.94	20.78	16.46

the process results. The starch yield is defined as

$$\frac{\text{Weight of starch obtained as product, dry basis}}{\text{Weight of grain used, dry basis}} \times 100.$$

Starch recovery is defined as

$$\frac{\text{Weight of starch obtained, dry basis}}{\text{Weight of starch in grain charged, dry basis}} \times 100.$$

DISCUSSION OF RESULTS

General Investigation Runs (series I)

At high feed rates, the time required to reach a steady state became excessive, so that the material balances obtained were poor. Runs I-1 to I-3 indicate that equilibrium was not reached. As the feed rate dropped from about 75 pounds per hour to less than 40 pounds per hour, satisfactory material balances were obtained. Runs I-5, 6 and 7, together with runs III-1 and III-8, served to compare the milling of waxy sorghum grits (series II) and non-waxy grits.

Waxy Sorghum Grits (series II)

Waxy starch of high purity (protein percentage smaller than 0.5%) with a starch recovery up to 67%, power consumption down to 0.5 KW, energy consumption and water consumption as low as 0.05 KWH and 3.2 gallon per pound of starch was produced within the selected ranges under various processing conditions. The significant effects as well as the experimental equations for the dependent variables were evaluated by the analysis of variance and regression.

The starch production rate, the net power consumption for grinding, the energy and water consumed per pound of starch were considered as the dependent variables with the independent variables being the grits feed rate, feed water rate, and rpm of mill. The analysis of these dependent variables is shown in Table 11. The mean square for effects, the mean square for error, and the F values were calculated by the Statistical Laboratory of Kansas State University. The significant effects at the 95%, 99% and 99.9% level of probability are shown.

The effects A_1BC, A_qC, A_qB, and A BC did not affect the net power consumption significantly, while all the other terms had significant effects on net power consumption at the 99.9% level. This means there is a 99.9% chance of being correct to report that the net power consumption was a function of feed grain rate, the feed water rate, and the rpm of mill. The equation derived from this analysis for net power consumption as a function of feed rate (x_1), feed water rate (x_2), and rpm of mill (x_3) is:

$$(1) \quad y_1 = 0.885 + 0.131x_3 - 0.044x_2 + 0.009x_2x_3 + 0.071x_1 - 0.021x_1x_3 + 0.016x_1x_2 - 0.022(x_1^2 - 2/3)$$

This equation is still in the coded form where the values of x_1, x_2 and x_3 are still the level values given in Table 1. y_1 is the net power consumption in kilowatts. The corresponding equation in terms of the actual values of the variables is:

$$(2) \quad y_1 = 0.8858 + 0.0004187(x_3' - 1812.5) - 0.008783(x_2' - 15) + 0.00000549(x_2' - 15)(x_3' - 1812.5) + 0.007094(x_1' - 25) - 0.00000662(x_1' - 25)(x_3' - 1812.5) + 0.0003238(x_1' - 25)(x_2' - 15) - 0.0002181\left[(x_1' - 25)^2 - 66.67\right]$$

Here x_1', x_2' and x_3' stand for actual numerical values of feed rate, feed water rate, and mill rpm, respectively.

Table 11. Analysis of variance for effects in series II.

Effect	Factor	Net power consumption, KW			Starch production rate, lb/hr			Energy consumption, KWH/lb starch			Water consumption, gal/lb		
		Sum of effect	Mean square	F value	Sum of effect	Mean square	F value	Sum of effect	Mean square	F value	Sum of effect	Mean square	F value
T	24	21.260	18.832817		284.28	3367.2966		1.9525	0.15884401		129.45	698.2209	
C	24	3.140	0.410817	10533.77***	8.44	2.9681	239.36***	0.2493	0.00258960	2669.69***	-4.17	0.7245	241.50***
B	24	-1.054	0.046288	1186.87***	1.08	0.0486	3.92 n.s.	-0.1043	0.00045327	467.29 ***	12.03	6.0300	2010.00***
BC	24	0.206	0.001768	45.33***	1.24	0.0641	5.17*	0.0057	0.00000135	1.39 n.s.	-1.75	0.1276	42.53**
A_1	16	1.135	0.080514	2064.46***	72.22	325.9830	26288.95***	-0.4259	0.01133693	11687.56***	-35.60	79.2100	26403.33***
A_1C	16	-0.331	0.006848	175.59***	1.46	0.1332	10.74**	-0.0993	0.00061628	635.34***	1.36	0.1156	38.53***
A_1B	16	0.259	0.004193	107.51***	3 .42	0.7310	58.95***	0.0331	0.00006848	70.60***	-4.64	1.3456	448.53***
A_1BC	16	-0.023	0.000033	0.85 n.s.	- 2.54	0.4032	32.52***	0.0061	0.00000233	2.40 n.s.	1.44	0.1296	43.20***
A_q	48	-0.349	0.002538	65.08***	-7.62	1.2097	97.56***	0.1825	0.00069388	715.34***	16.62	5.7547	1918.23***
A_qC	48	0.017	0.000006	0.15 n.s.	-2.06	0.0884	7.13*	0.0543	0.00006143	63.33***	0.18	0.0007	0.23 n.s.
A_qB	48	0.011	0.000003	0.08 n.s.	3.18	0.2107	16.99**	-0.0257	0.00001376	14.19**	1.14	0.0271	9.03*
A_qBC	48	0.017	0.000006	0.15 n.s.	-5.66	0.6674	53.82***	0.0285	0.00001692	17.44**	1.34	0.0374	12.47**

	Net power consumption, KW	Starch production rate, lb/hr	Energy consumption, KWH/lb starch	Water consumption, gal/lb
Sum of mean square	19.385831	3699.8040	0.17469824	791.7237
Sum of mean square for error	0.000467	0.1494	0.00001169	0.0364
Sum of square	19.386298	3699.9534	0.17470993	791.7601
Mean square for error	0.000039	0.0124	0.00000097	0.0030

* Significant at 95% level
** Significant at 99% level
*** Significant at 99.9% level
n.s. - not significant

Note: T refers to the total effect
C refers to the effect of rpm of mill
B refers to the effect of feed water rate
A_1 refers to the linear effect of feed grain rate
A_q refers to the quadratic effect of feed grain rate

From Table 11, it appears that for all terms except B affect the starch yield with the different probability levels indicated. The equation expressing starch production rate as a function of x_1, x_2 and x_3 is

$$(3)\quad y_2 = 11.845 + 0.351x_3 + 0.051x_2x_3 + 4.514x_1 + 0.091x_1x_3 + 0.214x_1x_2 - 0.158x_1x_2x_3 - 0.476(x_1^2 - 2/3) - 0.129(x_1^2 - 2/3)x_3 + 0.199(x_1^2 - 2/3)x_2 - 0.354(x_1^2 - 2/3)x_2x_3.$$

where y_2 is the starch production rate, lbs per hr. In the uncoded form, this equation becomes

$$\begin{aligned}(4)\quad y_2 = {} & 11.845 + 0.00112533(x_3' - 1812.5) + 0.00003306(x_2' - 15)(x_3' - 1812.5) \\ & + 0.451375(x_1' - 25) + 0.00002920(x_1' - 25)(x_3' - 1812.5) \\ & + 0.004275(x_1' - 25)(x_2' - 15) \\ & - 0.00001016(x_1' - 25)(x_2' - 15)(x_3' - 1812.5) \\ & - 0.0047625\left[(x_1' - 25)^2 - 66.67\right] \\ & - 0.0000412\left[(x_1' - 25)^2 - 66.67\right](x_3' - 1812.5) \\ & + 0.0003975\left[(x_1' - 25)^2 - 66.67\right](x_2' - 15) \\ & - 0.00000226\left[(x_1' - 25)^2 - 66.67\right](x_2' - 15)(x_3' - 1812.5)\end{aligned}$$

From this analysis, it appears that the starch production rate was chiefly affected by the feed rate (x_1). However, the relationship between the feed rate and the starch production rate was not a linear one, since both A_1 and A_q were significant at the 99.9% probability level. From the regression equation (3), the slope constant for x_1 is + 4.514, while for $(x_1^2 - 2/3)$ the slope was -0.476. This means that the linear effect of the feed rate would control the starch yield at low values of the feed rate, and at higher values the quadratic effect would become more important. Since there is a difference in sign between these, an optimum value of feed rate should exist at which the starch production rate would be a maximum. This effect was found to exist experimentally by Fan (7) and Chiang (4).

Further, this analysis showed that the feed water rate (x_2) did not significantly affect the starch production rate. The interaction effect of feed water rate and rpm of the mill (x_3) had a relatively small slope constant (-0.158) and a low probability level (95%). The grits feed rate (x_1) and the feed water rate (x_2) formed a new independent variable, the mill concentration, and it was pointed out by Chiang (4) that the mill concentration seemed to have a linear relationship with feed rate when feed water rate was constant. So, the relationship between the mill concentration and the starch production rate would be in the same form as with feed rate provided that the feed water rate was constant. Since the determination of the mill concentration could not be done accurately enough, the more easily measured variables, grits feed rate and feed water rate were used.

The speed of the shaft in the mill (x_3) had a significant effect on the starch production rate at the 99.9% probability level. However, the slope constant for x_3 in equation (3) was smaller than for feed rate, x_1 (4.514 and 0.351). This means that increasing the shaft speed in the mill increased the yield of starch. Though the total production rate was independent of the shaft speed, the proportion of the feed ground per pass increased with the shaft speed, and the recycle rate consequently decreased.

The energy and water consumed for producing one pound of starch were studied in the same way as above. The terms BC and A_1BC had no significant effects on the energy consumption per pound of starch, while the terms A_qC had no significant effect on the water consumption per pound of starch.

The equations were as follows:

$$(5)\quad y_3 = 0.081 + 0.010x_3 - 0.004x_2 - 0.026x_1 - 0.006x_1x_3 + 0.002x_1x_2 + 0.011(x_1^2 - 2/3) + 0.003(x_1^2 - 2/3)x_3 - 0.002(x_1^2 - 2/3)x_2 + 0.002(x_1^2 - 2/3)x_2x_3$$

$$(6)\quad y_4 = 5.394 - 0.174x_3 + 0.501x_2 - 0.073x_2x_3 - 2.225x_1 + 0.085x_1x_3 - 0.290x_1x_2 + 0.090x_1x_2x_3 + 1.039(x_1^2 - 2/3) + 0.071(x_1^2 - 2/3)x_2 + 0.084(x_1^2 - 2/3)x_2x_3$$

Where y_3 is the energy consumption in KWH per pound of starch and y_4 is the water consumption in gallons per pound of starch. The corresponding equations in the uncoded form are:

$$(7)\quad y_3 = 0.0814 + 0.00003324(x_3' - 1812.5) - 0.0008692(x_2' - 15) - 0.002662(x_1' - 25) - 0.00000199(x_1' - 25)(x_3' - 1812.5) + 0.00004137(x_1' - 25)(x_2' - 15) + 0.0001141\left[(x_1' - 25)^2 - 200/3\right] + 0.00000011\left[(x_1' - 25)^2 - 200/3\right](x_3' - 1812.5) - 0.00000321\left[(x_1' - 25)^2 - 200/3\right](x_2' - 15) + 0.00000001\left[(x_1' - 25)^2 - 200/3\right](x_2' - 15)(x_3' - 1812.5)$$

$$(8)\quad y_4 = 5.3938 - 0.0005560(x_3' - 1812.5) + 0.1003(x_2' - 15) - 0.00004666(x_2' - 15)(x_3' - 1812.5) - 0.2225(x_1' - 25) + 0.00002720(x_1' - 25)(x_3' - 1812.5) - 0.005800(x_1' - 25)(x_2' - 15) + 0.00000576(x_1' - 25)(x_2' - 15)(x_3' - 1812.5) + 0.01038750\left[(x_1' - 25)^2 - 200/3\right] + 0.0001425\left[(x_1' - 25)^2 - 200/3\right](x_2' - 15) + 0.00000054\left[(x - 25) - 200/3\right](x - 15)(x - 1812.5)$$

The feed rate (x_1) and the shaft speed (x_3) have larger slope constants and greater probability levels of significance in equation (5) than feed water rate (x_2)or any of the interaction terms. In equation (6) the feed rate (x_1) and feed water rate (x_2) had the largest slope constants as well as greater probability levels of significance.

Comparison of the Milling of Waxy and Non-Waxy Sorghum Grits

The recovery of starch, the net power consumed for grinding and the energy and water consumed per pound of starch produced are plotted against feed rate for these two types of sorghum grits on Figs. 3, 4, 5, and 6. The non-waxy sorghum grits had a considerably greater starch recovery and consumed a little more power than the waxy sorghum grits. Both the energy and the water consumed per pound of starch for waxy sorghum grits were higher than for non-waxy grits. A numerical comparison of the two types of sorghum grits at a moderate feed rate, i.e., 25 pounds per hour is shown in Table 12.

Table 12. Milling characteristics of waxy and non-waxy sorghum grits at a feed rate of 25 lbs. per hour.

Type	Recovery %	Energy consumption KWH/lb. starch	Water consumption Gal/lb. starch	Protein in starch, %
Non-waxy	78.30	0.0685	4.050	0.70
Waxy	66.42	0.0776	4.845	0.35

Further, the protein content of the waxy starch was about one-half that of the non-waxy starch. The average value of the protein content in the waxy starches was 0.36 percent, while in the non-waxy starches it was 0.76 percent.

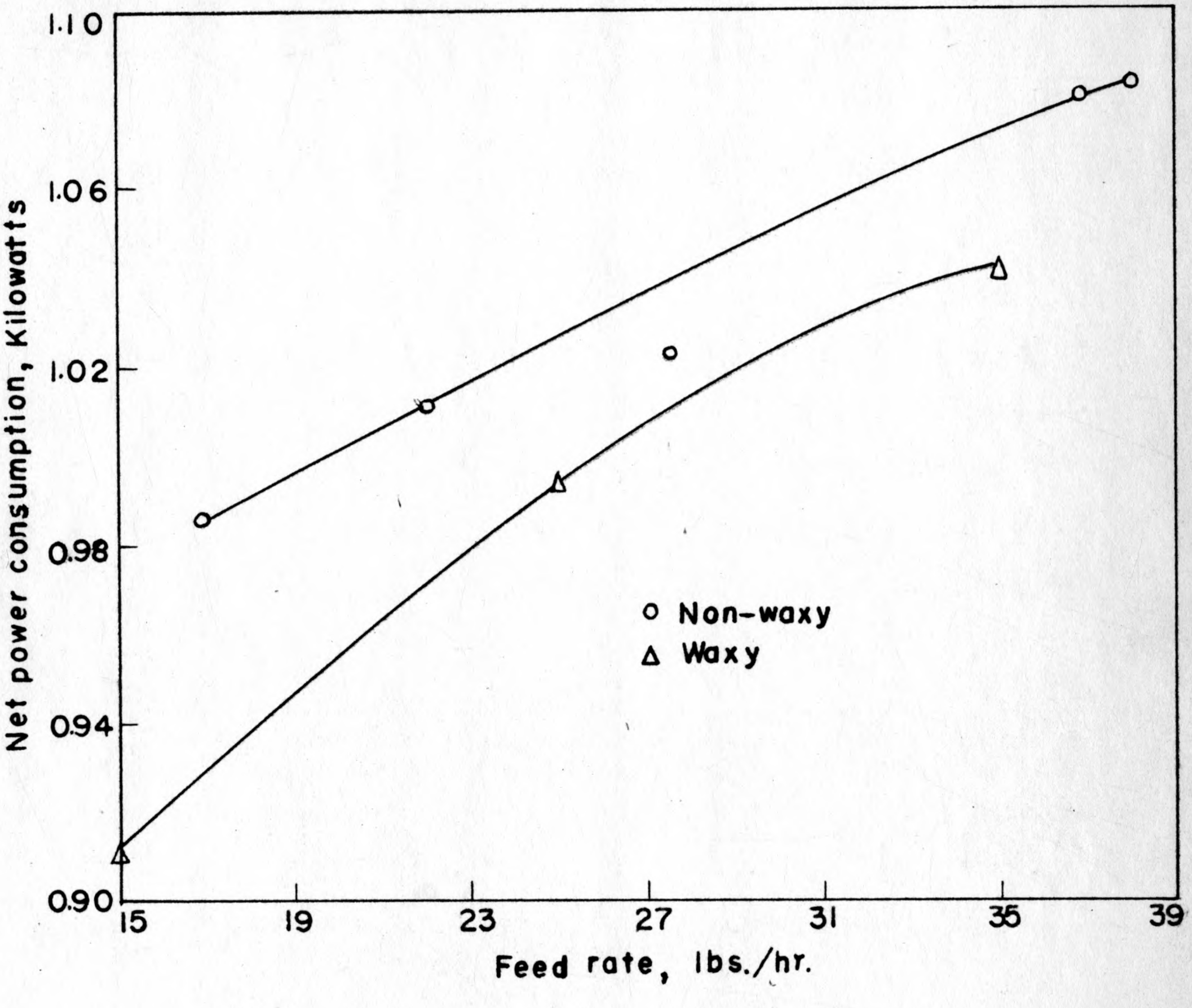


Fig. 3. Comparision of power consumption for waxy and non waxy sorghum grits.

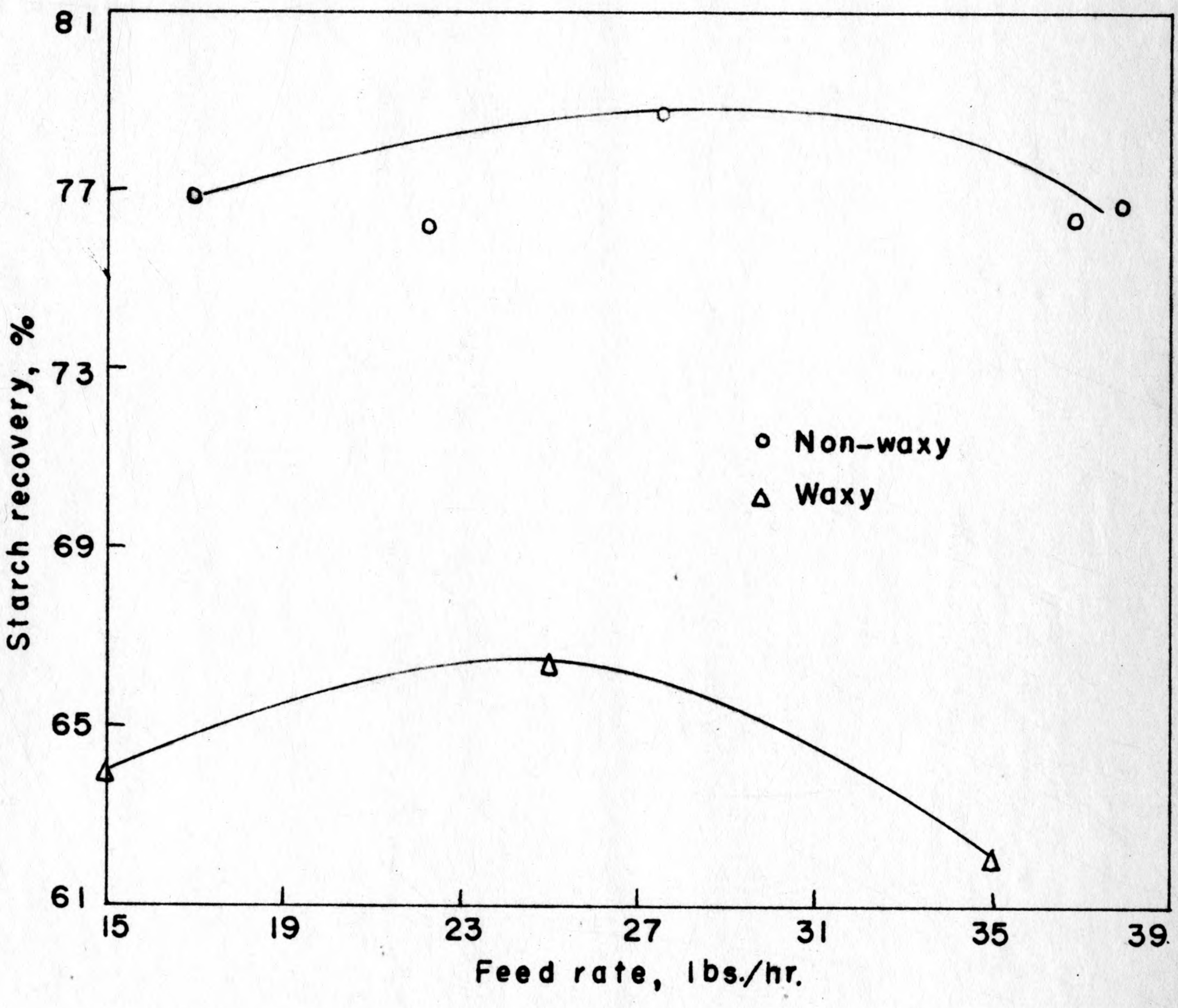


Fig. 4. Comparision of starch recovery for waxy and non waxy sorghum grits.

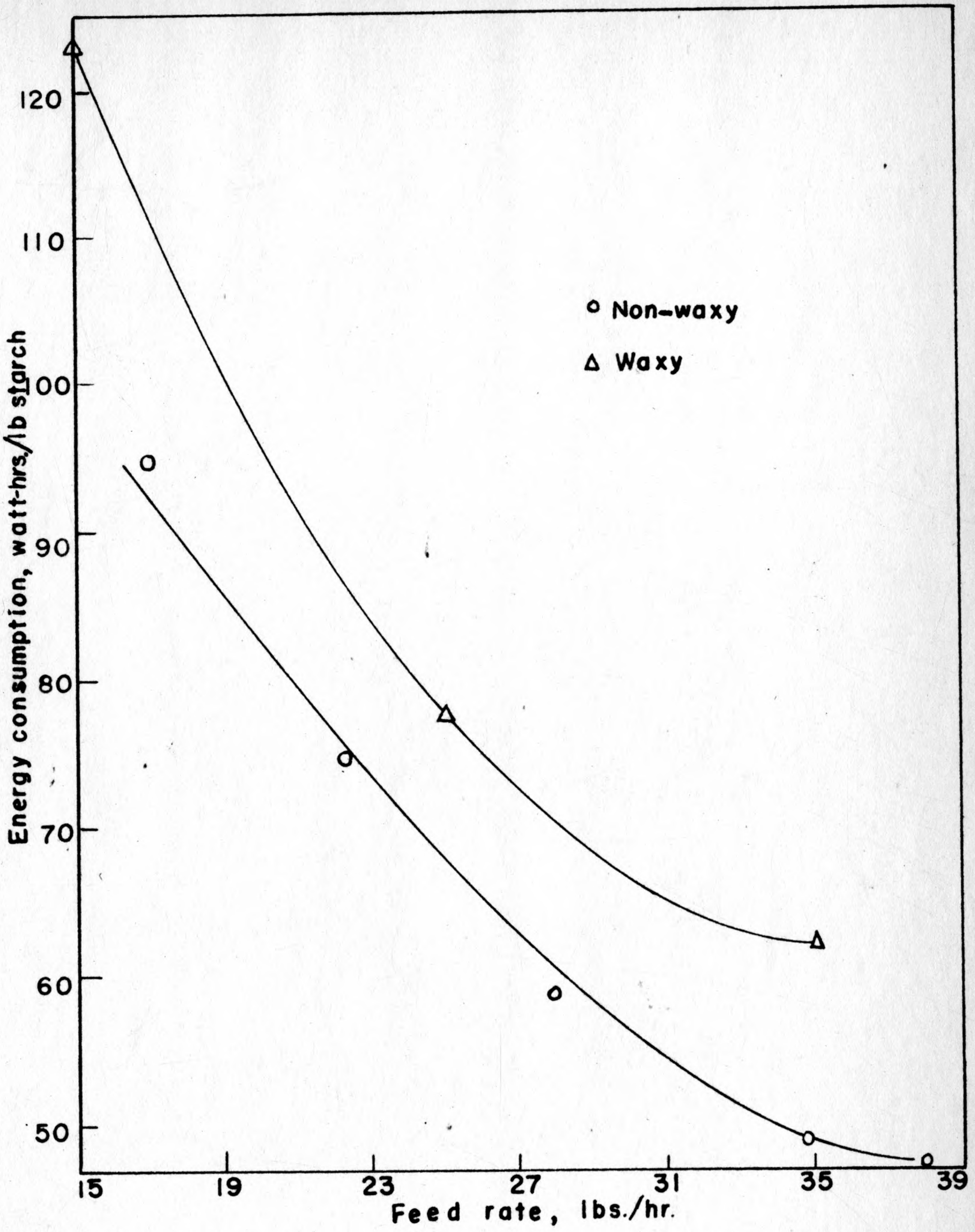


Fig. 5. Comparision of energy consumption for waxy and non waxy sorghum grits.

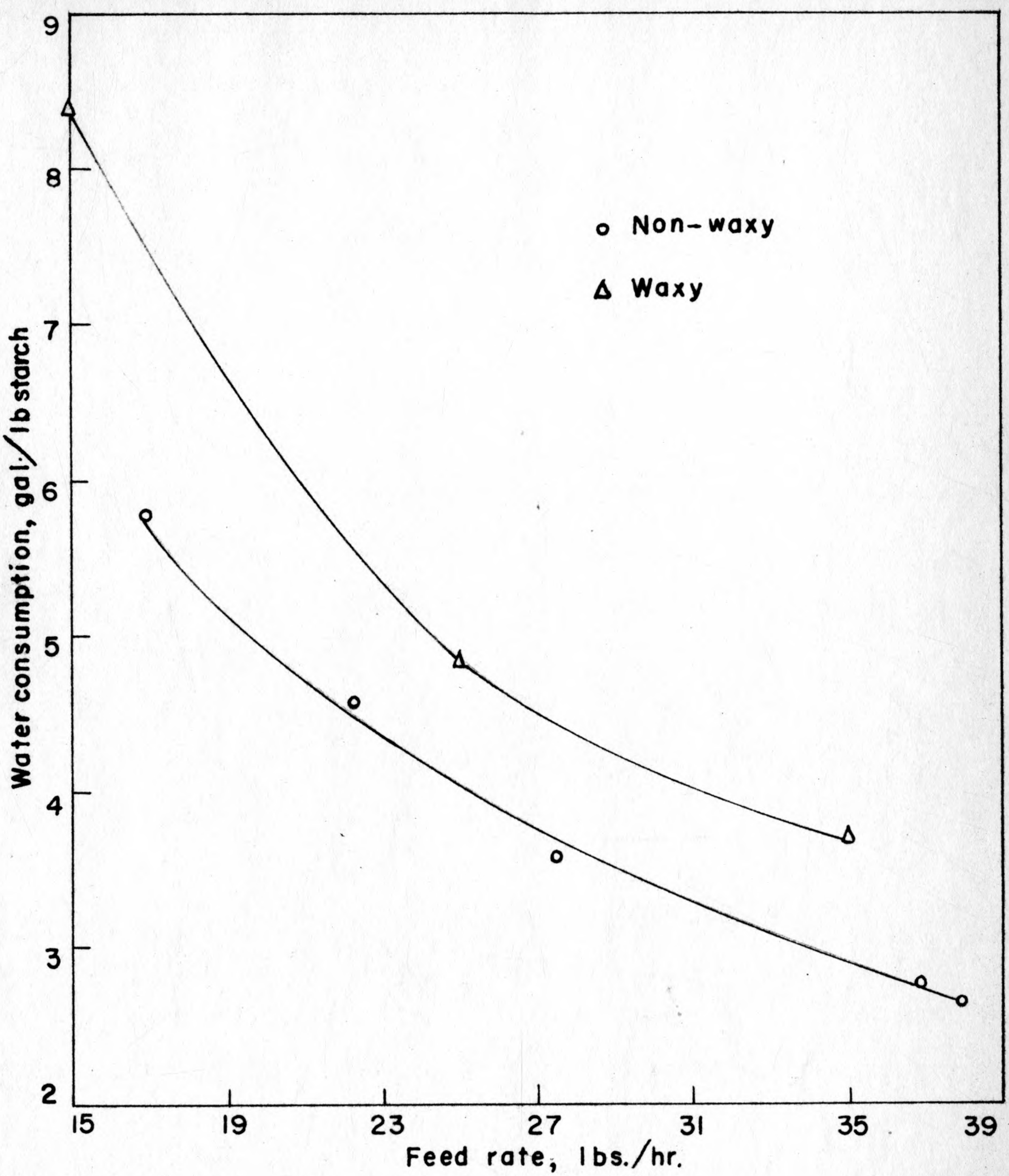


Fig. 6. Comparision of water consumption for waxy and non waxy sorghum grits.

The starch lost in the gluten and the total starch lost is plotted against feed rate in Fig. 7. Both losses were larger for waxy sorghum grits than for non-waxy sorghum grits.

In all of these comparisons the waxy sorghum grits had a greater slope than the non-waxy grits, showing that the waxy sorghum grits were more sensitive to processing conditions.

Steeping Temperature and pH (series III)

Every 10 degree increase in steeping water temperature from 130° F. to 160° F. increased the starch recovery about two percent. Also, the net energy consumed decreased as the steeping temperature increased. This is shown graphically in Fig. 8.

A plot of steeping temperature versus the percent of starch lost in the gluten and bran is given in Fig. 9. This shows that the starch lost in the gluten and bran portions was lowest in the temperature range from 140° F. to 150° F. No obvious change in quality resulted from the use of these higher steeping temperatures.

The pH of the steeping water had little effect on the starch recovery in the range from four to nine. However, the energy consumption per pound of starch was slightly lower at the lower pH values as shown in Fig. 10. At a pH between four and five, the net energy consumption was 0.0113 KWH less per pound of starch than when tap water (pH = 8.97) was used. The starch lost in the gluten and bran increased as the pH of steeping water decreased as shown in Fig. 11. However, the percentage of protein in the starch was very low at the lower pH values. At pH values of four and five, only 0.27 percent of protein was found in the starch.

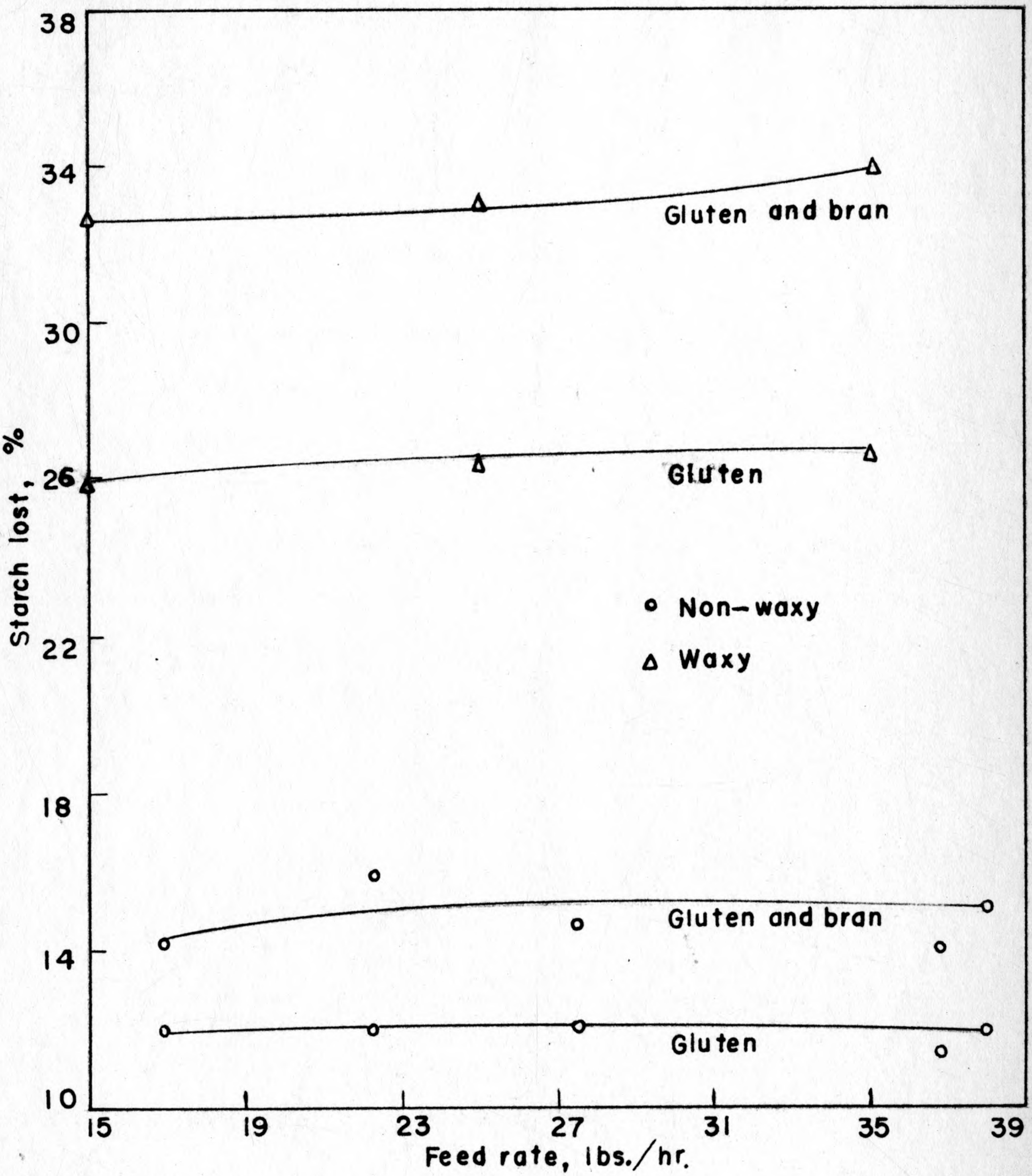


Fig.7. Comparision of the loss of starch in gluten and bran for waxy and non waxy sorghum grits.

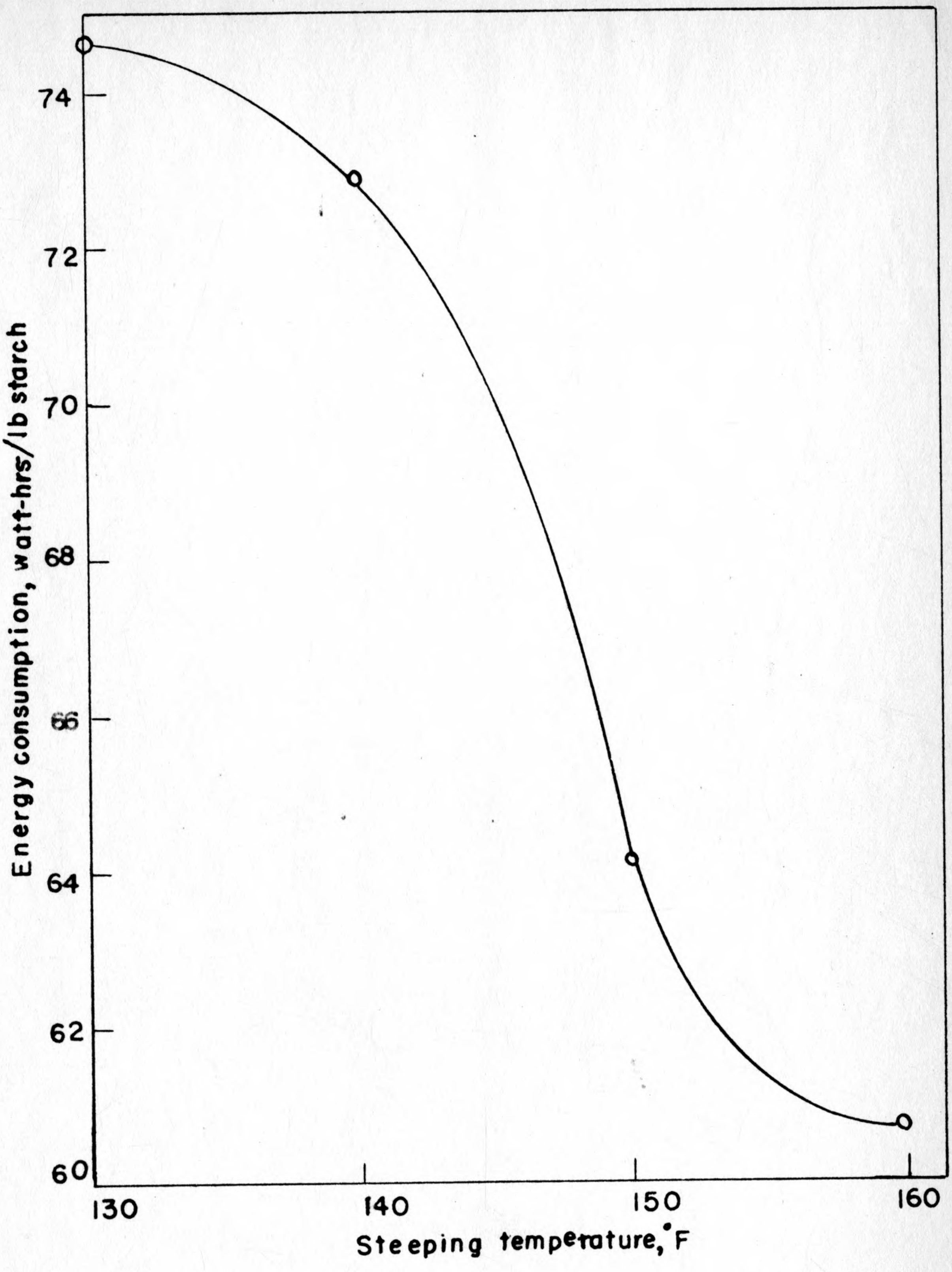


Fig. 8. Effect of steeping temperature on energy cosumption.

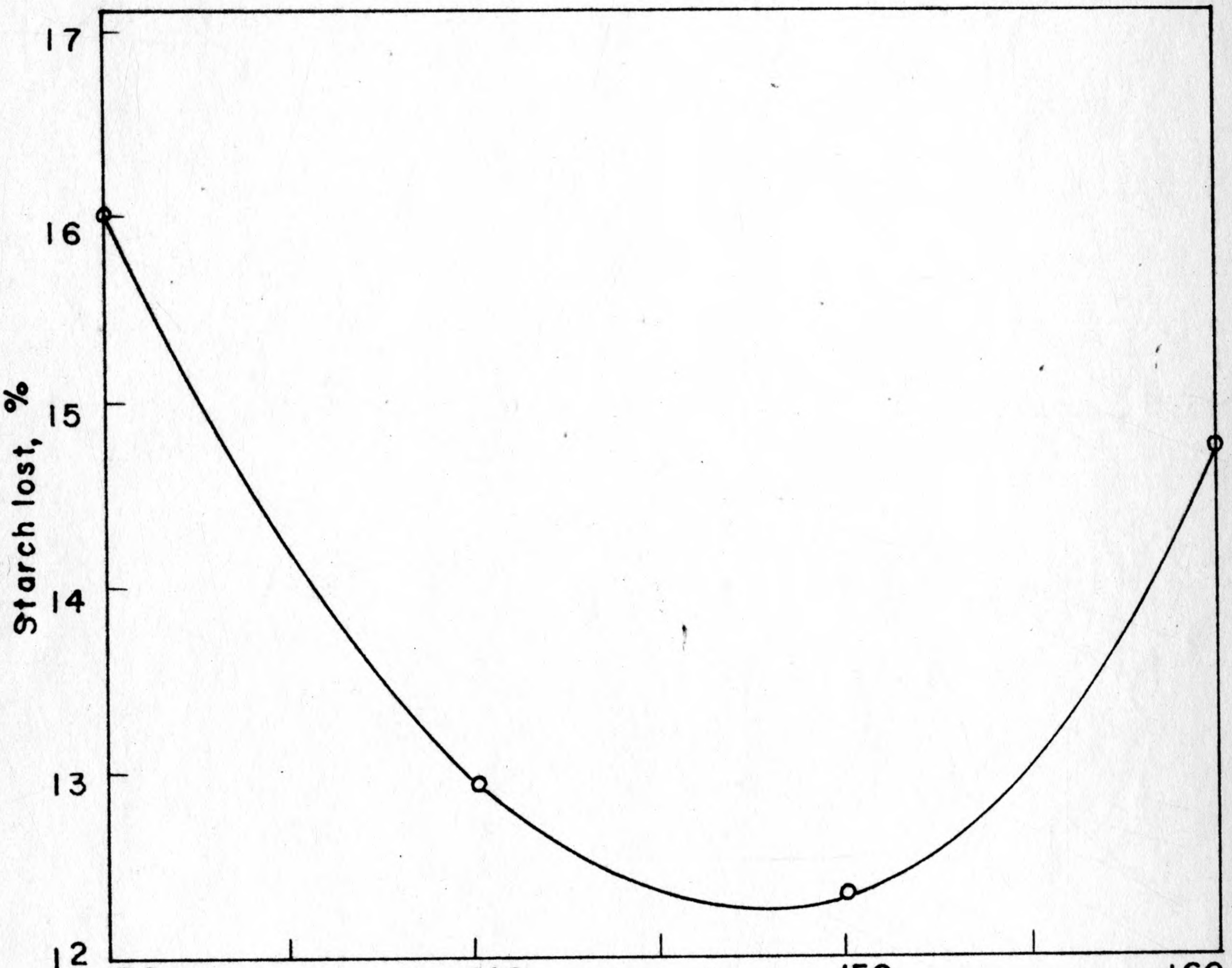


Fig. 9. Efeect of steeping temperature on starch lost in gluten and bran.

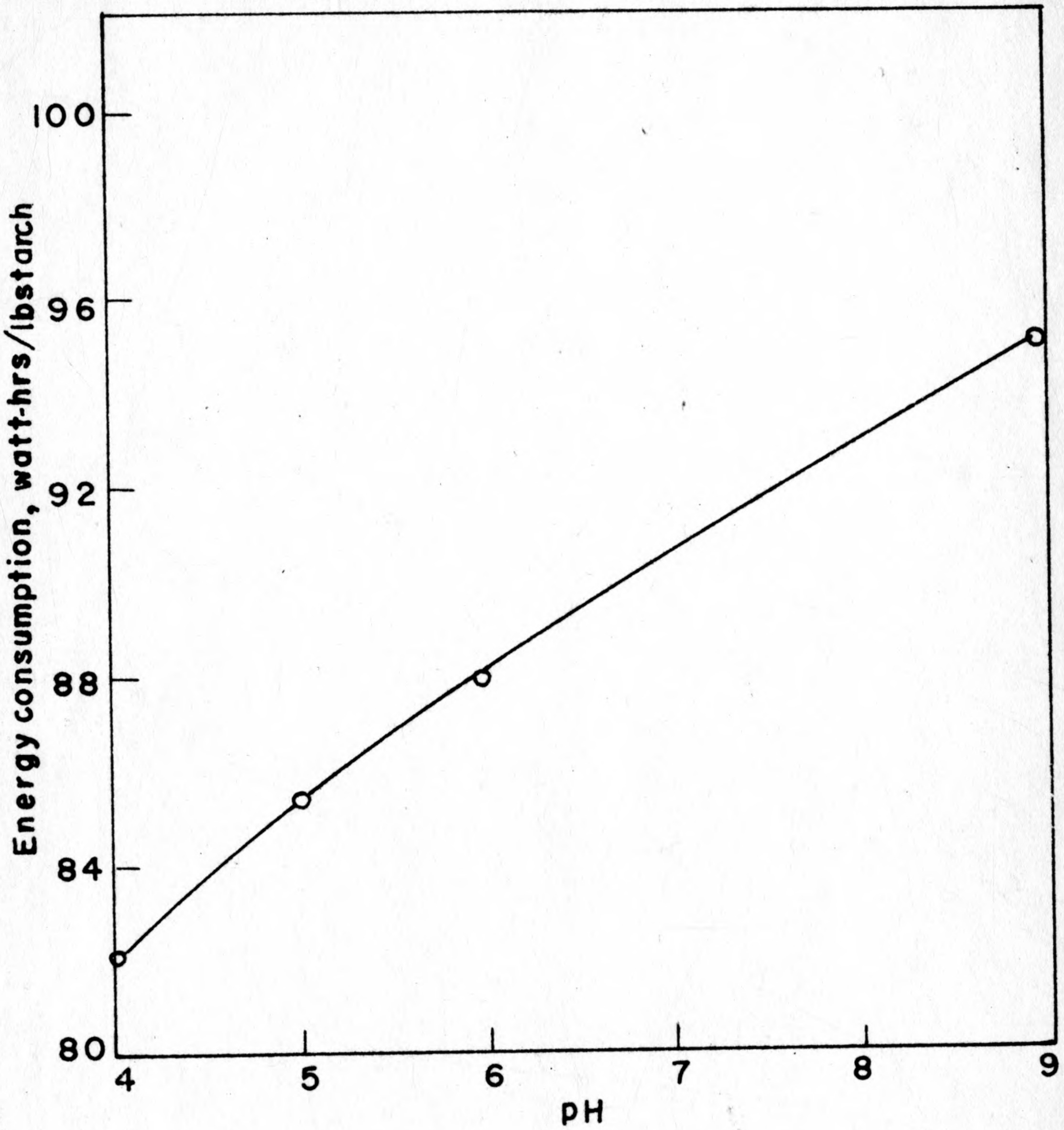


Fig. 10. Effect of pH of steeping water on energy consumption.

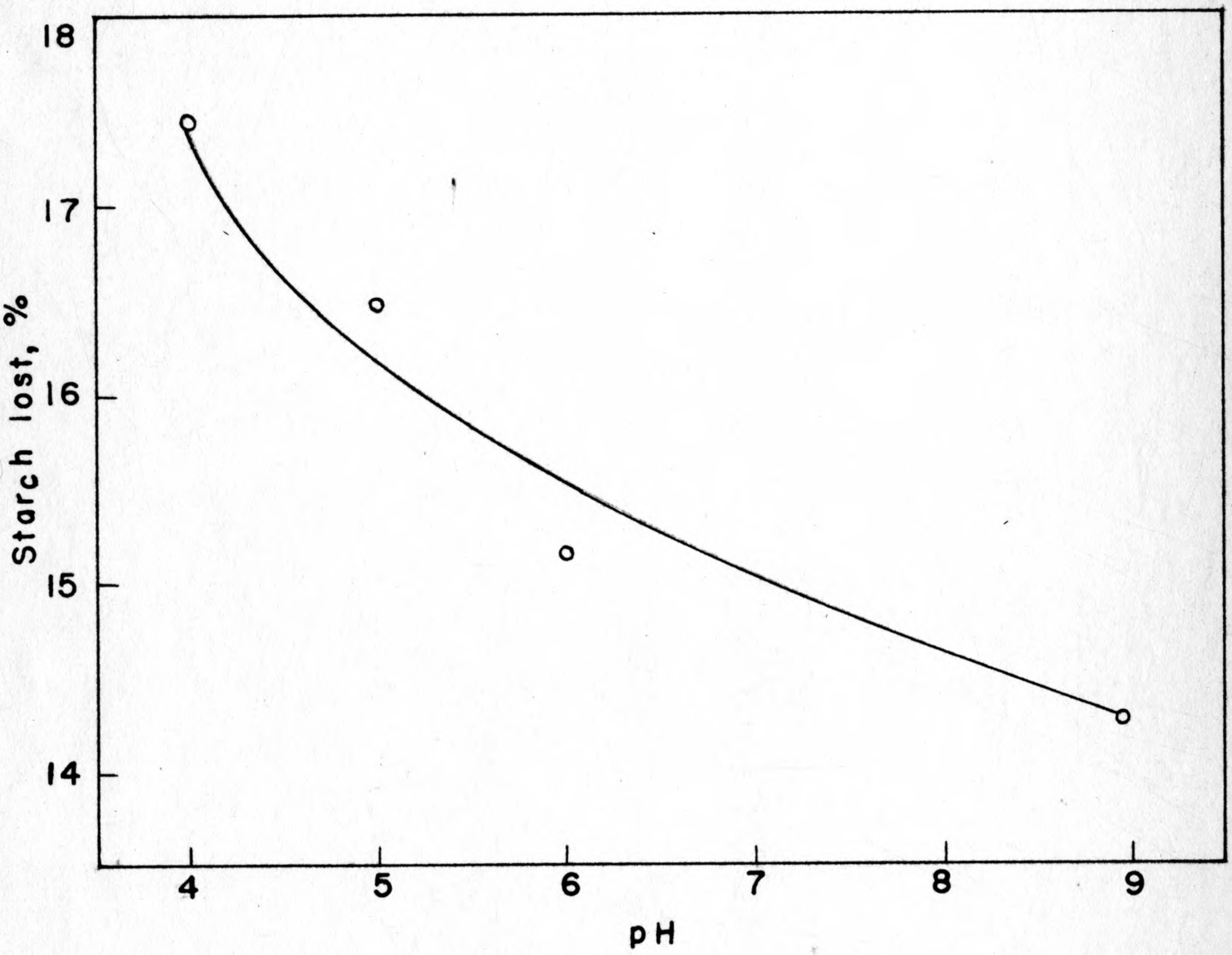


Fig.11. Effect of pH of steeping water on starch lost in gluten and bran.

CONCLUSIONS

It was difficult to get a satisfactory material balance at feed rates above about 40 pounds per hour because of the excessive time required to reach equilibrium. At feed rates below 40 pounds per hour, dry basis, reasonable results were obtained.

Waxy starch of high purity (protein percentage smaller than 0.5%) was produced with a starch recovery up to 67 percent, energy consumption as low as 0.05 KWH per pound of starch, and water consumption as low as 3.2 gallon per pound of starch. By a statistical analysis of variance as well as regression, experimental equations together with the significant effects were evaluated.

The net power consumption was affected significantly by the grits feed rate, the feed water rate, and the rpm of mill. Of these independent variables, the rpm of mill had the greatest influence on the net power consumption.

The starch production rate was chiefly affected by the grits feed rate, and was not significantly affected by the feed water rate. The linear effect of the feed rate would control the starch yield at low values of the feed rate, while at higher values the quadratic effect would become more important. The rpm of the mill also affected the starch production rate significantly. Since the total through put was independent of the shaft speed, this effect was caused by the effect of rpm of the mill on the distribution of starch in the output stream.

The energy and water consumed to produce one pound of starch were affected significantly by the feed grain rate, feed water rate, and rpm of the mill.

A comparison of the milling characteristics of waxy and non-waxy sorghum grits showed that the non-waxy type had a considerable greater starch recovery and consumed a little more power to produce starch than the waxy type. Hence, both the energy and the water consumption per pound of starch for the waxy sorghum were higher than for non-waxy. The protein content of the waxy starch was about one half of that of the non-waxy starch, and the starch lost in the gluten and bran in this process for waxy type was larger than for non-waxy type. The waxy sorghum grits were more sensitive to processing conditions than the non-waxy one.

Several runs were made to evaluate the effect of high temperature steeping and the pH of steeping water. It was shown that every ten degree increase in steeping water temperature from 130° F. to 160° F. increased the starch recovery about two percent. Also, the net energy consumed decreased as the steeping temperature decreased.

The pH of the steeping water had little effect on the starch recovery in the range from four to nine. However, the energy consumption per pound of starch was slightly lower at the lower pH range. The starch lost in gluten and bran increased as the pH of steeping water decreased, but the protein percentage in the starch was very low at the lower pH values.

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PRODUCTION OF STARCH FROM WAXY SORGHUM GRITS

by

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The hydraulic milling process employed in this research was a process to liberate starch by physical disruption in the presence of water from the endosperm of sorghum grains. The purpose of this thesis was the evaluation of the milling characteristics of waxy sorghum grits, a comparison of the milling of waxy and non-waxy types of sorghum grits, and the determination of the effect of the temperature of steeping water and the pH of steeping water.

A 2 × 2 × 3 factorial design was used for the experiments on waxy sorghum grits with the independent variables, grits feed rate, feed water rate, and rpm of the mill.

Sorghum grits were steeped first for one hour, and then fed continuously into the hydraulic mill through a V-shaped hopper for grinding. The ground grits were separated by successive passes over a 40-mesh and a 200-mesh screen. The fine particles which passed through the 200-mesh screen were stored as starch milk which was pumped to four starch tables where the gluten was separated. The starch was collected from the table, while the gluten was obtained by sedimentation and filtration. The particles coarser than 40-mesh ran into the debranner where the bran was separated by flotation and the partially-ground material was recycled by a flight conveyer for further grinding. The fraction which overflowed from the 200-mesh screen was also recycled to the mill.

Waxy starch of high purity (protein percentage smaller than 0.5%) with starch recovery up to 67%, power consumption as low as 0.5 KW, energy and water consumptions down to 0.05 KWH and 3.2 gallon per pound of starch, was produced. The grits feed rate, feed water rate, and rpm of mill affected the results significantly up to 99.9% level.

In comparison with the non-waxy sorghum grits, the waxy type had a smaller starch recovery and consumed a little less power under the same processing conditions. Both the energy and the water consumed to produce one pound of starch were greater for the waxy type than for the non-waxy. The starch lost in the gluten and bran was greater for the waxy type than for the non-waxy. The waxy sorghum grits were more sensitive to processing conditions than the non-waxy.

High temperature steeping increased the recovery of starch. Every 10 degree increase in steeping from 130° F. to 160° F. increased the starch recovery about two percent.

The pH of the steeping water had little effect on the starch recovery in the range from four to nine. The energy consumed per pound of starch was slightly lower at the lower pH range. The starch lost in bran and gluten increased as the pH of steeping water decreased, but the protein percentage in the starch was much lower at the lower pH values.