VARIABLES IN THE DESIGN OF A HYDRAULIC MILL FOR THE PRODUCTION OF STARCH FROM SORGHUM GRITS

by

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INTRODUCTION AND REVIEW OF LITERATURE

Grain sorghums have certain advantages as a crop in the Great Plains area. They are able to withstand the prolonged periods of hot, dry weather common in the area; they yield better, or at least give a more reliable yield than other crops over a period of years; and they afford protection against wind erosion which other crops may not provide. For these reasons grain sorghums have become one of the favorite crops in the Great Plains area. The production of sorghum grains in Kansas was 31,878,000 bushels in 1955 (10).

Since sorghum grains contain about 70 per cent starch, and since the starch from sorghum grain is comparable to corn starch, the utilization of sorghum grains for starch production is of interest. The value of the sorghum crop would be greatly enhanced by its use for this purpose. The oil, wax, and protein by-products from the starch production may be used either as stock feed or as raw material for further industrial processes.

For this reason much attention has been paid to the utilization of sorghum grains industrially. In 1949 a plant designed for the production of starch and dextrose from milo maize, as well as corn, was constructed at Corpus Christie, Texas by the Corn Products Refining Company. The novel features of the plant, as reported by Hightower (8) and Taylor (15), included the use of Rietz mills in place of the Buhr stone mills employed by the conventional plant for the fine grinding of steeped grains, and the application of the Merco centrifugal system to separate the gluten from the starch in lieu of conventional starch tables.

Research on the wet milling of sorghum grains was reported by Zipf, et al. (17), Watson, et al. (16), and Kerr (11). The conventional Buhr stone mill was used by both Watson, et al. and Zipf, et al. Most of this work was concerned with the effect of steeping conditions on the quality and yield of starch.

Swanson and Laude (14) reported that the use of starch from waxy sorghum grains as a substitute for tapioca is feasible.

The properties of starches from both glutinous corn and glutinous sorghum and their dependence on the processing conditions were reported by Macmasters and Hilbert (12).

A procedure similar to the conventional process for the production of corn starch was adapted by Johnston (9). The grinding was carried out by using a disc grinder for coarse grinding and a Buhr stone mill for fine grinding, both in the presence of water. Starch of high purity and quality was obtained from several varieties of sorghum grains; however, yields obtained were unsatisfactory. This was attributed to the small-scale batch process employed.

A dry-milling process for sorghum grain was then developed which removed the outer bran covering of the grain, cracked the grain, and separated the germ from the endosperm. The resulting grits, which are the starch-bearing, endosperm portion of sorghum grains, were used by several investigators as the raw material for starch production.

Banowetz (1) studied the recovery of starch from sorghum grits by means of batch grinding process. The grits in the form of a slurry, were ground in a so-called "hydraulic mill." Operating speed, duration of grinding, and initial sorghum concentration were investigated for their effect on quality and yield of starch. Though the starch obtained was of good quality, the yields were lower than those obtained by the Johnston process. These yields were explained as being caused by overgrinding. That is, some of the starch was reduced to a fineness too great for separation on the starch tables and therefore, was lost. Similar results have been described by Brown, et al. (3) in other grinding processes. To overcome this disadvantage, the later part of Banowetz's work was done by periodically removing a fraction of the milling mixture, screening and returning the coarse fraction to the mill. The results indicated the possibility of an optimum exposure time to the hydraulic milling process.

Drobot (6) continued the study and by the periodic removal of starch milk, starch of higher yield and quality was obtained.

An entirely continuous process using the closed circuit principle of operation was carried out by Fan (7). Higher recovery of starch, lower power consumption, smaller units for a given capacity, more uniform particle sizes, lower labor requirements, and good quality starch were reported.

Further research using the hydraulic mill for continuous milling was accomplished by Chiang (5) and Chai (4). Chiang studied factors which affected the yield and quality of the product, such as steeping conditions, feeding rate, water rate, and screen capacity. Chai compared the use of sulfur dioxide solutions with plain water in steeping the grits, and also the operation of the hydraulic mill with a Buhr stone mill in the grinding process. He concluded that the use of sulfur dioxide in steeping sorghum grits was of little value.

This work was a continuation of this series of studies at Kansas State College. The purpose was to determine the effect of several design variables in the hydraulic mill on the production of starch from sorghum grits.

As described by Stewart (13), the methods of grinding that apply direct compressing and shearing force in the cracking of the grain cause the oil to be pressed out of the germ and contaminate the endosperm, and also result in overgrinding which causes difficulties in the separation of starch from gluten, thus lowering the yield and quality of the starch. Therefore, the grinding of grain for good quality starch production should be performed by a mechanism other than a positive compressing action. Hydraulic milling utilizes the principle of physical disruption in the presence of water to remove the starch from the grit structure. Mechanical pressure is not applied directly to the grits, instead, breakdown is induced by the action of high speed rotating blades through a slurry of grits and water contained in a mill casing. The grit particles are abraded as they strike the casing wall, rub each other and undergo exposure to a rapidly rotating liquid stream. It is believed that the advantages of the process are less tendency for local overheating of the slurry, less rupture of the starch granules, and more efficient removal of protein from the starch granules. These combine to produce a higher quality starch. For this reason, this work was devoted entirely to the design variables in the hydraulic mill.

Since no theories for the operation of this type of grinding device were available, trial and error methods were used here. Different sizes and shapes of mill casings and different sizes and pitch of blades for milling have been used at various shaft speeds and at various feeding rates to the mill. A series of runs was carried out in pilot plant scale, and the effects were studied systematically.

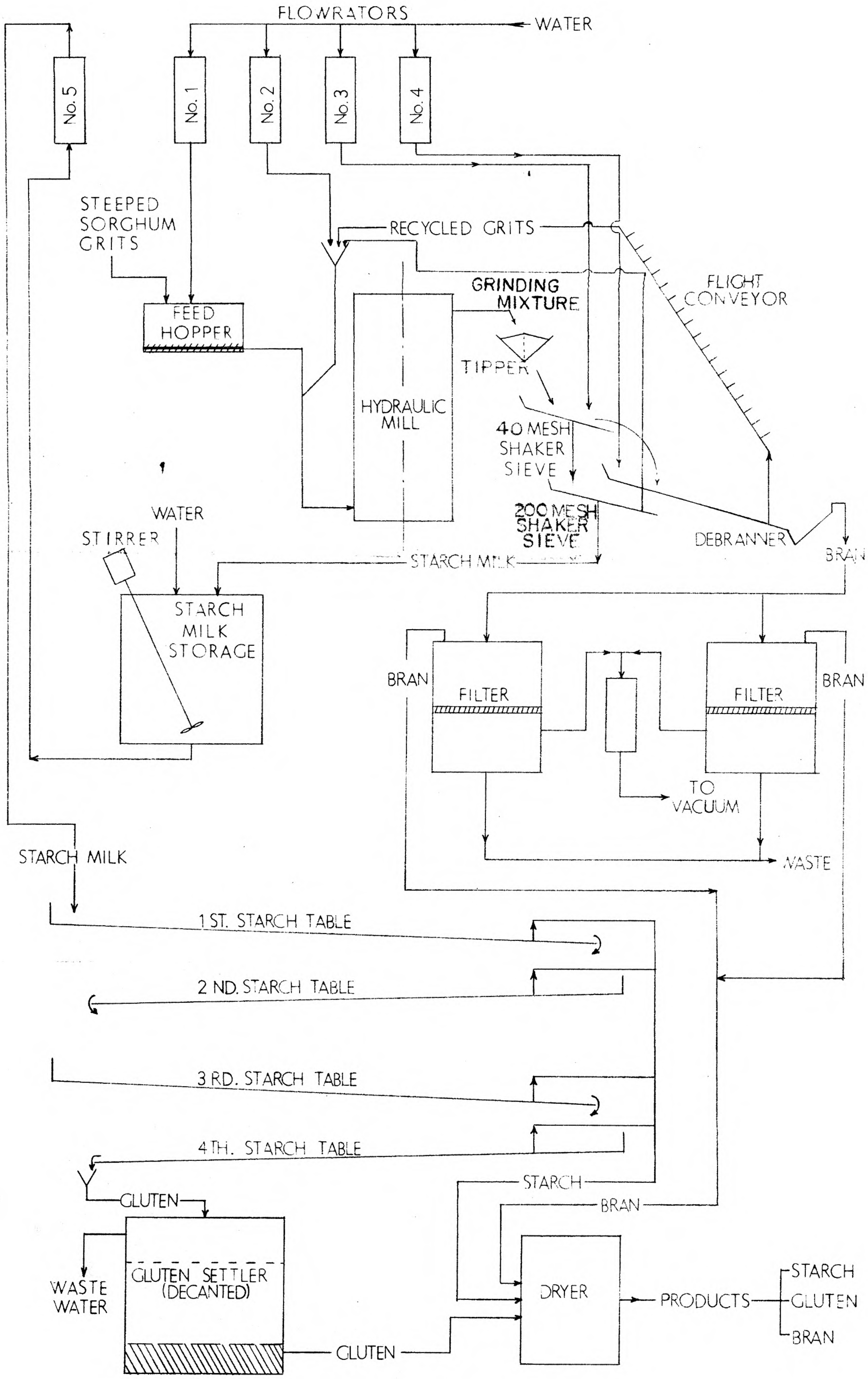
EQUIPMENT

Except for some minor modifications, the same equipment used by Chai (4) was used in this work. The flow diagram and a view of the pilot plant are shown in Plates I and II. A modification of the screening operation is shown in Plate III. This was used on only the last few runs.

EXPLANATION OF PLATE I

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

PLATE I

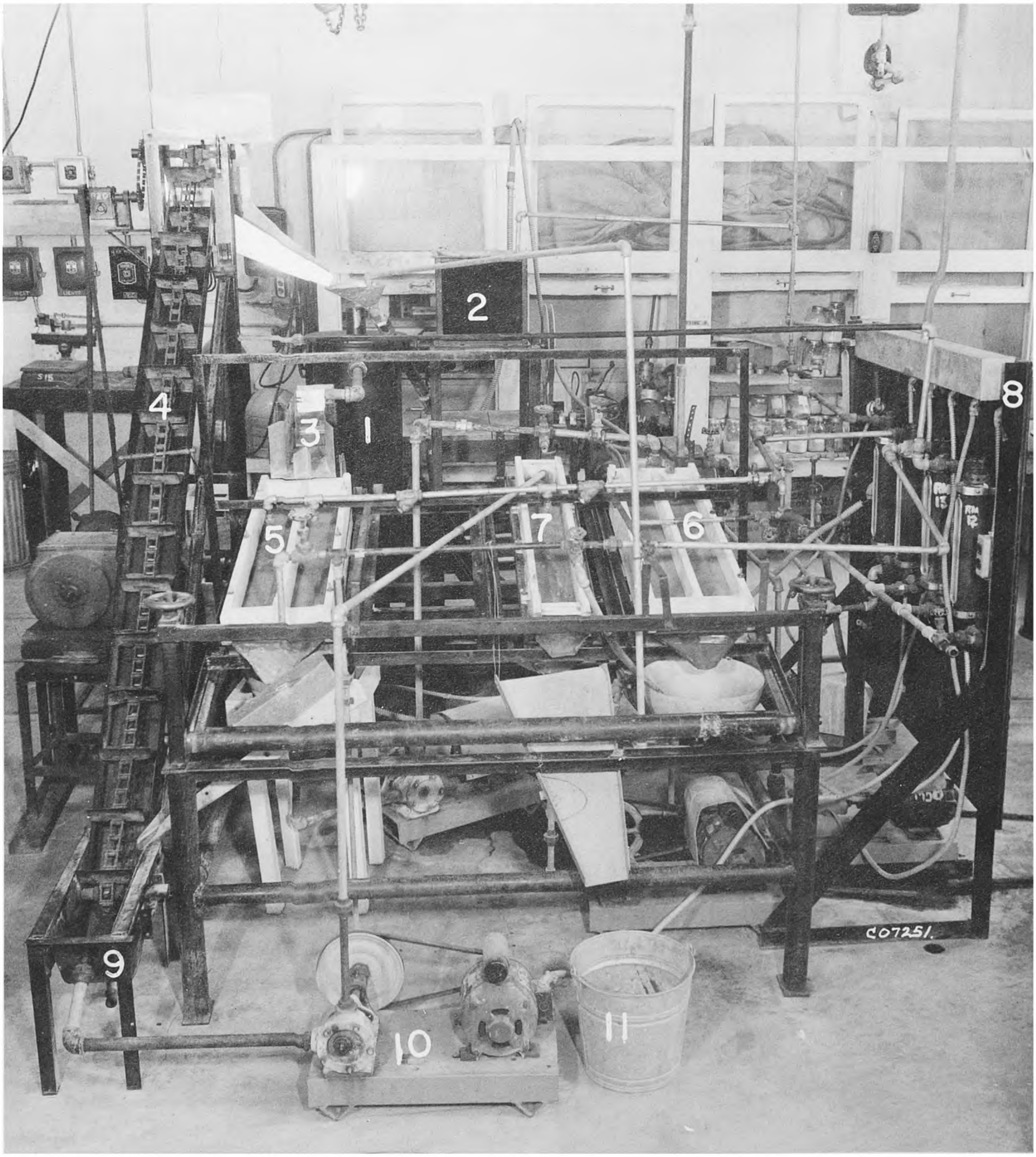

FLOWRATORS
WATER
No. 5
No. 1
No. 2
No. 3
No. 4
STEEPED SORGHUM GRITS
RECYCLED GRITS
FLIGHT CONVEYOR
GRINDING MIXTURE
FEED HOPPER
TIPPER
HYDRAULIC MILL
40 MESH SHAKER SIEVE
200 MESH SHAKER SIEVE
DEBRANNER
BRAN
WATER
STIRRER
STARCH MILK
STARCH MILK STORAGE
BRAN
FILTER
FILTER
BRAN
TO VACUUM
WASTE
STARCH MILK
1 ST. STARCH TABLE
2 ND. STARCH TABLE
3 RD. STARCH TABLE
4 TH. STARCH TABLE
STARCH
BRAN
GLUTEN
WASTE WATER
GLUTEN SETTLER (DECANTED)
GLUTEN
DRYER
PRODUCTS
STARCH
GLUTEN
BRAN

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

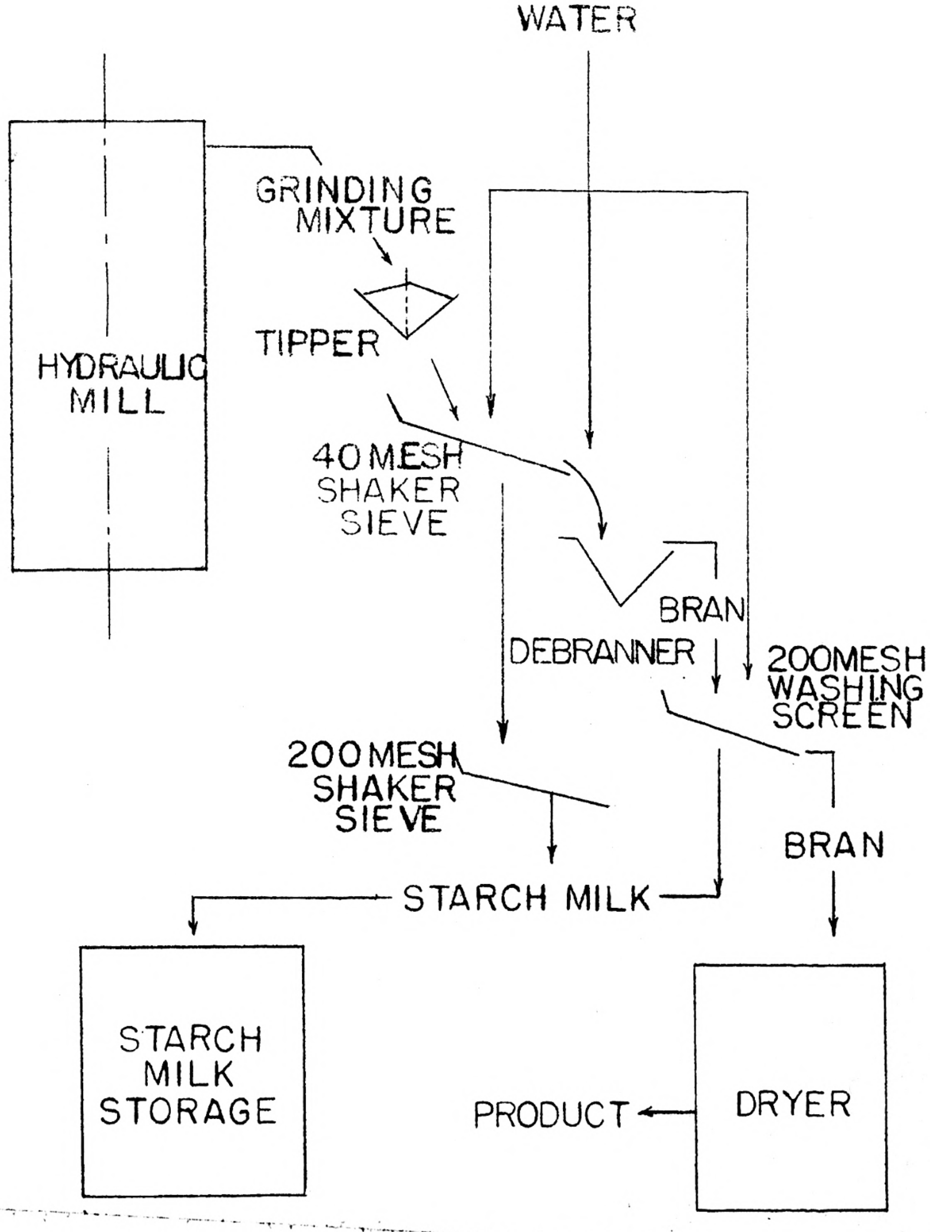
PLATE II



EXPLANATION OF PLATE III

Flow Diagram of the Modified Starch Recovery Process from Bran

PLATE III


WATER
HYDRAULIC MILL
GRINDING MIXTURE
TIPPER
40 MESH SHAKER SIEVE
BRAN
DEBRANNER
200MESH WASHING SCREEN
200 MESH SHAKER SIEVE
BRAN
STARCH MILK
STARCH MILK STORAGE
PRODUCT
DRYER

Steeping Equipment

Four 15-gallon stainless steel tanks arranged as shown in Plate IV were used. One of these was used as a steep-water heating tank. The heating was done by passing low-pressure steam through a copper coil in the tank. The water temperature was controlled at 125° ± 5° F. by use of a Taylor self-acting steam regulator. A centrifugal pump (Eastern Industries, Model D-6, 1/30 hp., 3450 rpm) was used to pump the hot water through a 1/4 inch galvanized iron pipe to the top of each of the three steeping tanks. The water flowed through the grits in the steeping tanks and then back into the heating tank. A 1/4 inch tube was installed near the top of each steeping tank to carry the overflow, if any, from each of the steep tanks back to the heating tank, thus making exact adjustment of the pumping rate of the steep water unnecessary. The temperature was recorded by a Bristol temperature recorder.

Grinding Equipment

Feeding Device. A V-shaped feed hopper whose capacity was about 20 pounds of grits was used. The steeped grits were fed to the mill by a 1 1/2 inch by 12 inch screw conveyer which was driven by a 1 hp Reeves Varimotor with adjustable speeds from 26 to 156 rpm. A 1 1/2 inch standard iron pipe was connected at the outlet of the screw conveyer to the bottom of the hydraulic mill in order to lead the feed grits into the mill for grinding. Feed water was introduced into the feed hopper through a 1/4 inch galvanized iron pipe.

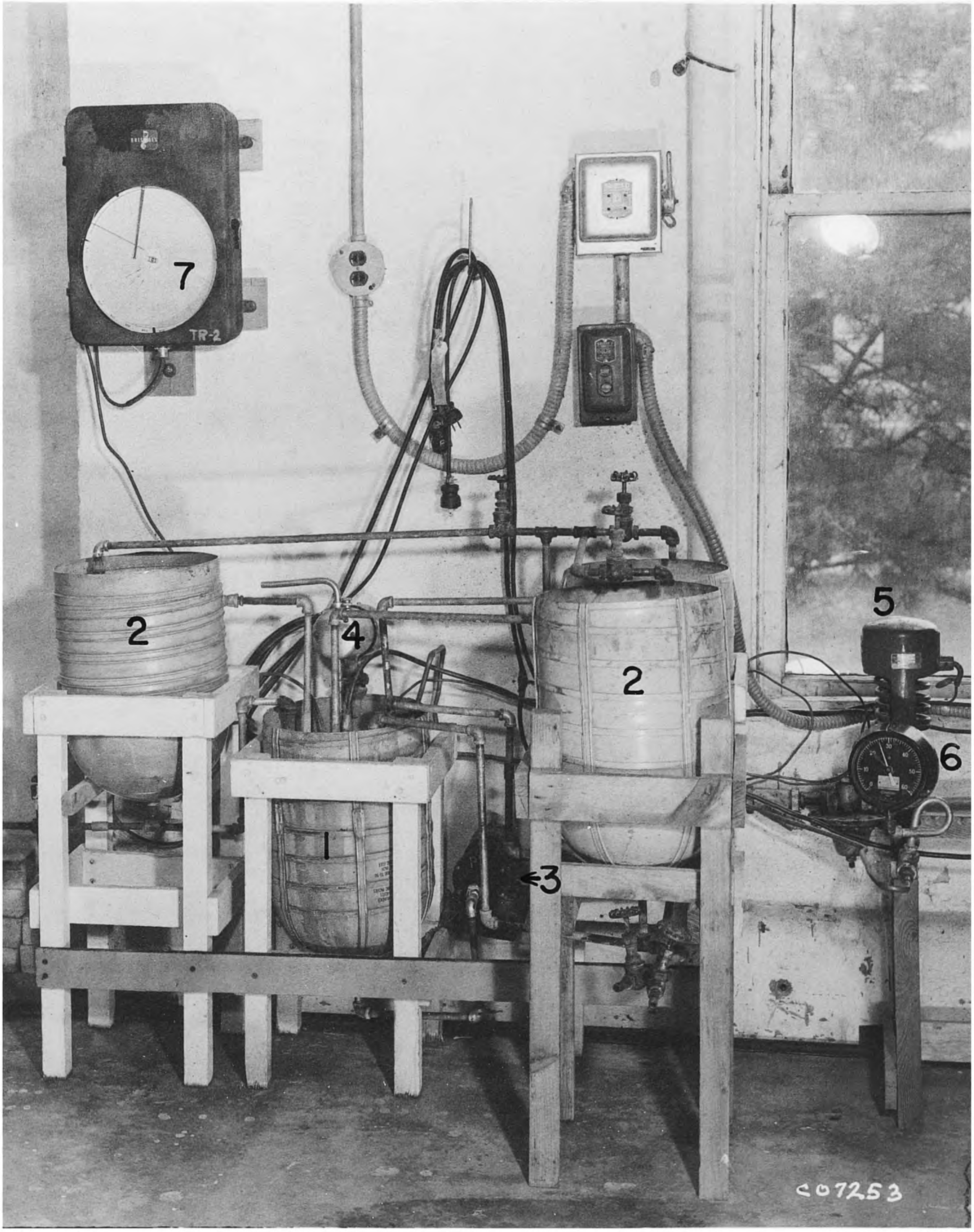
Hydraulic Mill. Three different casings, designated C, S-R, and L-R, were used. A photograph of these three casings is shown in Plate V. The C casing was clover-leaf in shape and is shown in Plate VI. The S-R (small,

EXPLANATION OF PLATE IV

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 IV



EXPLANATION OF PLATE V

Three Kinds of Mill Casings

C Clover-leaf type

S-R Small, round casing, 8-inch diameter

L-R Large, round casing, 12-inch diameter

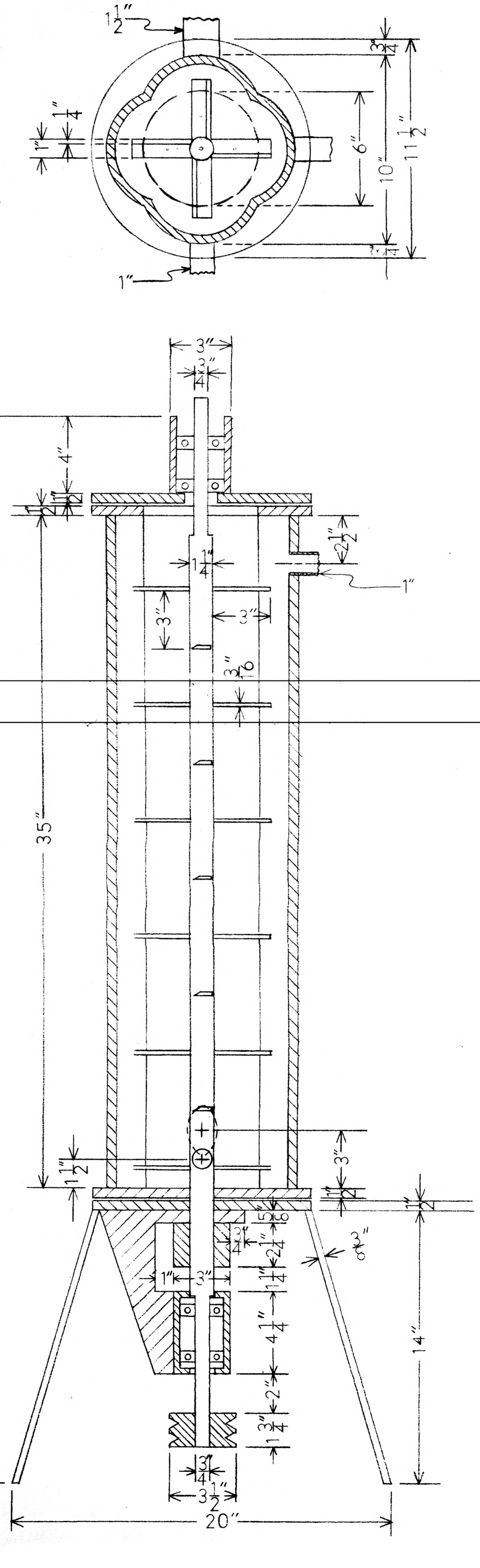
PLATE V

C S-R L-R

EXPLANATION OF PLATE VI

Detailed Drawing of Hydraulic Mill Using C Casing

PLATE VI



round) and L-R (large, round) casings were both circular and are shown in Plates VII and VIII. In each case the casings were mounted on a base carrying a vertical stainless steel shaft, as shown in Plate VI.

The shaft carried horizontal blades and was driven from the bottom. A detailed drawing of the shaft is shown in Plate IX. Two different blades were used. The first, called the A blade, is shown in Plate X. These were made of 1/8 inch by 1 inch stainless steel bar stock and were 2 13/16 inches long. They screwed into threaded holes in the shaft and were held in place by a jam nut. The B blades, shown in Plate XI, were identical to the A blades except that they were 4 15/16 inches long and were not sharpened as were the A blades.

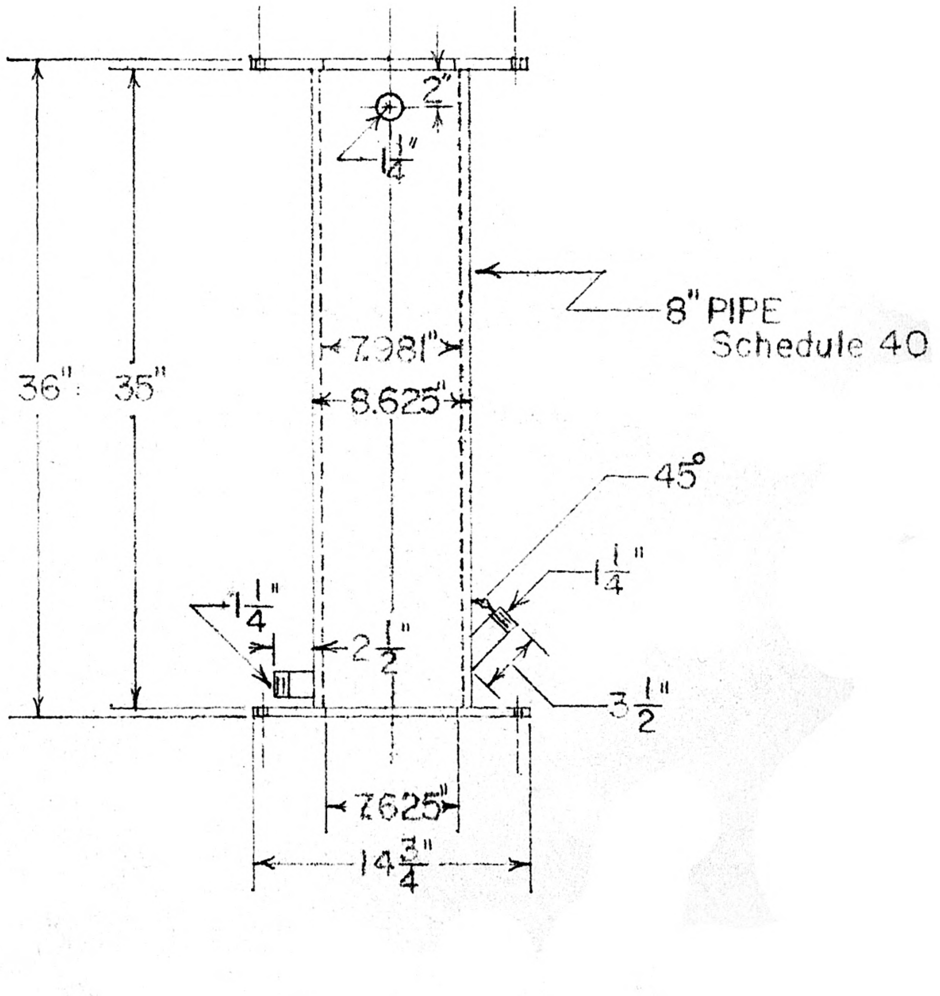
The three casings were interchangeable and were mounted on the base plate carrying the shaft. A cover bolted to the top of the casings carried a second bearing for the shaft. The shaft was driven by a 10 hp, 1170 rpm, Fairbanks-Morse induction motor through two V-belts. Various operating speeds were obtained by varying the ratio of the shaft and motor pulleys. A T-2 Frahm tachometer was used to indicate the shaft speed of the mill for the earlier runs. However, it was found that the driving motor interferred with the tachometer readings so that the readings of the meter were not very reliable. Therefore, a Stewart-Warner portable hand tachometer was used to check the mill rpm for the later runs. The power consumption was measured by a General Electric polyphase watt-hour meter, having a watt-hour constant of 7.2, which was placed in the motor power input circuit.

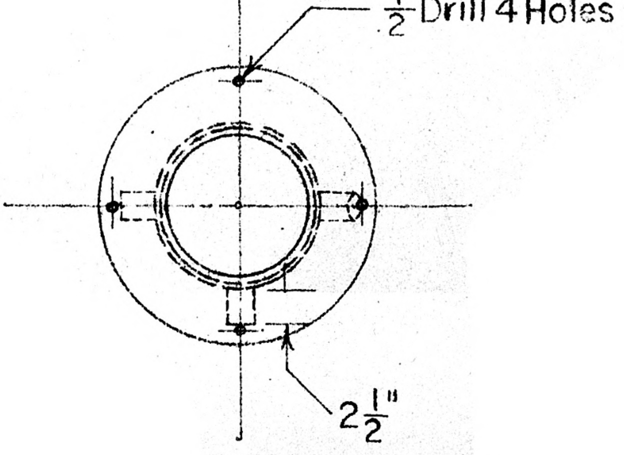
Screens. The ground material overflowed from the mill through a one inch standard pipe near the top of the mill onto a 40-mesh screen. Two screens, both 31 1/2 inches long and 4 inches wide, one of which was 40-mesh and the other 200-mesh, were arranged in series. During the later runs, these screens were replaced by larger screens having twice this width and area, i.e., 31 1/2

EXPLANATION OF PLATE VII

Drawing of S-R Casing

PLATE VII

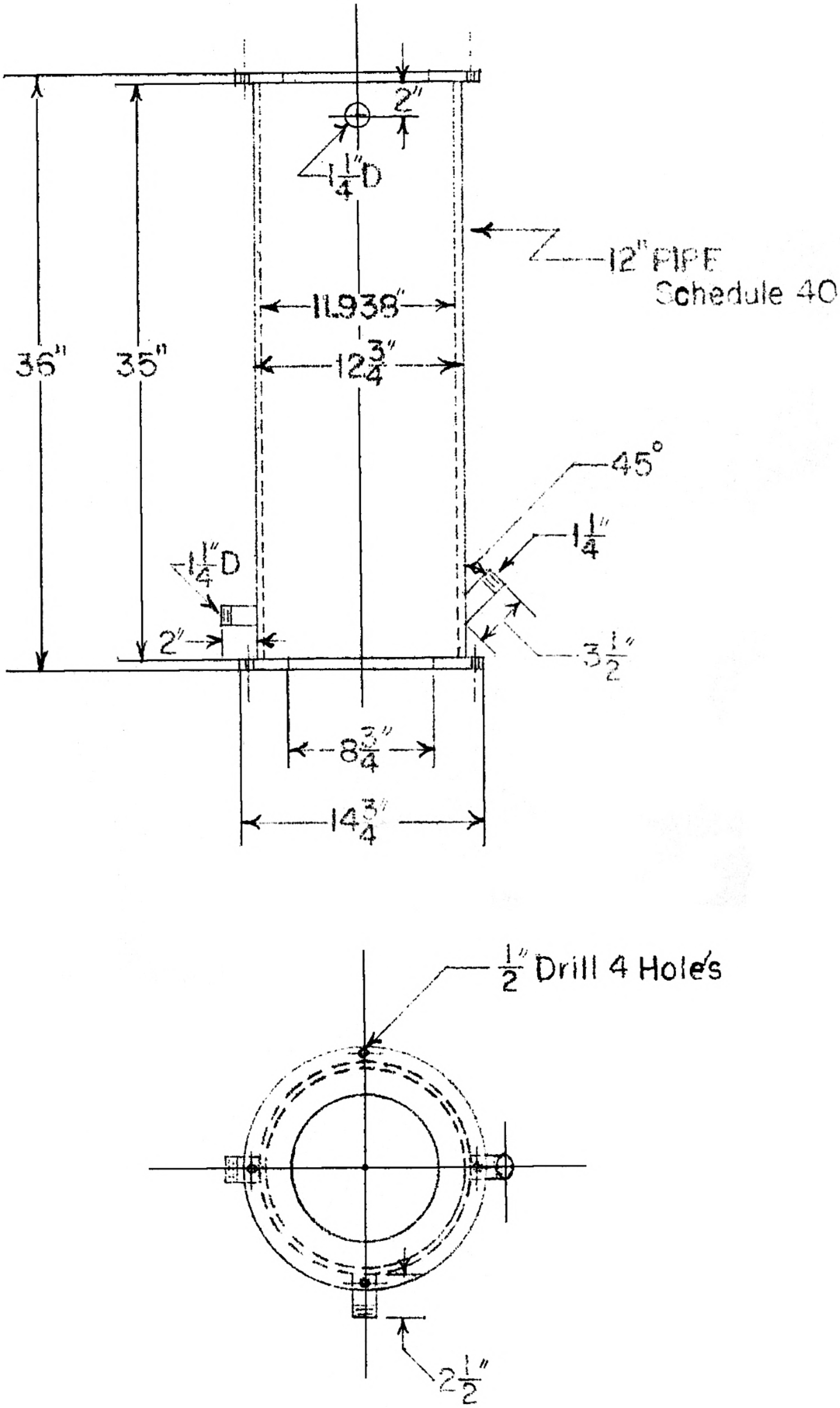

2"
1 1/4"
8" PIPE
Schedule 40
7.981"
8.625"
36"
35"
45°
1 1/4"
1 1/4"
2 1/2"
3 1/2"
7.625"
14 3/4"


1/2" Drill 4 Holes
2 1/2"

EXPLANATION OF PLATE VIII

Drawing of L-R Casing

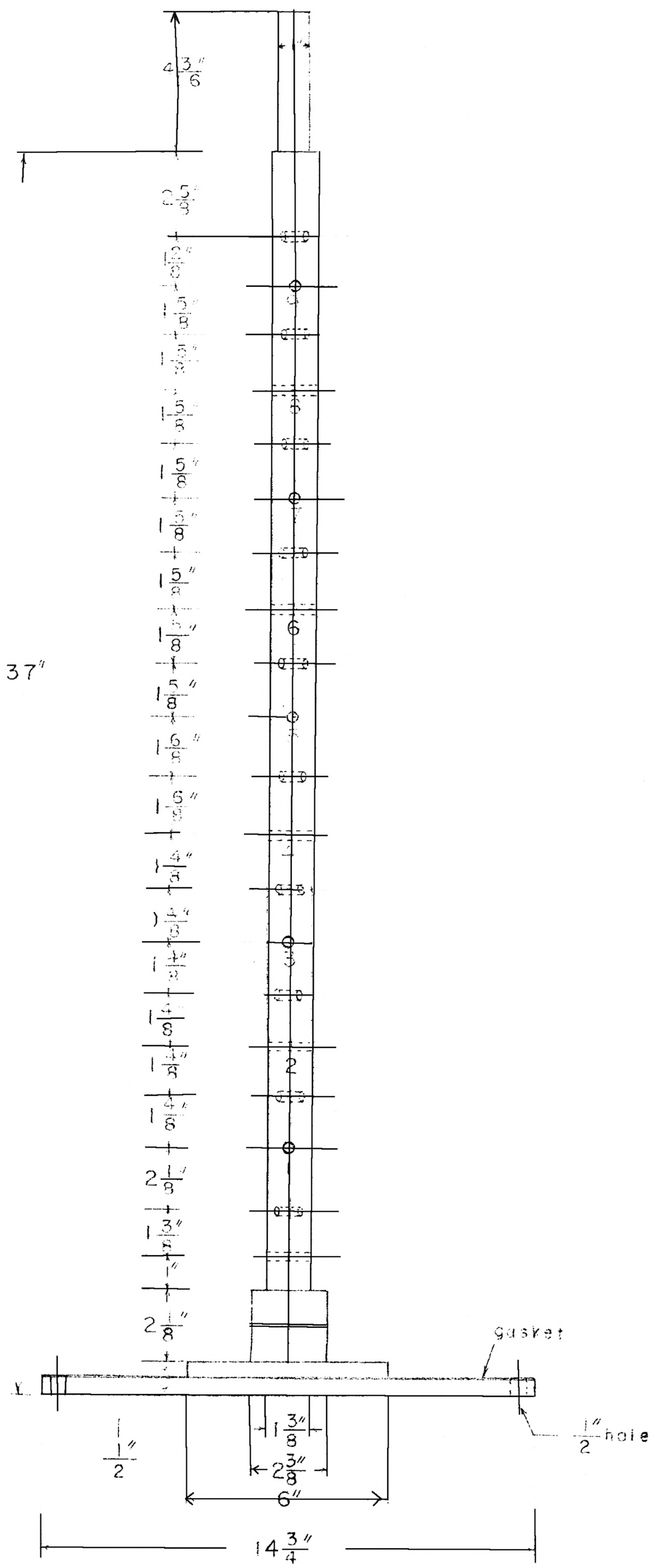
PLATE VIII


2"
$1\frac{1}{4}$"D
12" PIPE
Schedule 40
11.938"
$12\frac{3}{4}$"
36"
35"
45°
$1\frac{1}{4}$"
$1\frac{1}{4}$"D
2"
$3\frac{1}{2}$"
$8\frac{3}{4}$"
$14\frac{3}{4}$"
$\frac{1}{2}$" Drill 4 Hole's
$2\frac{1}{2}$"

EXPLANATION OF PLATE IX

Detailed Drawing of Mill Shaft Showing the Designation of Blade Positions

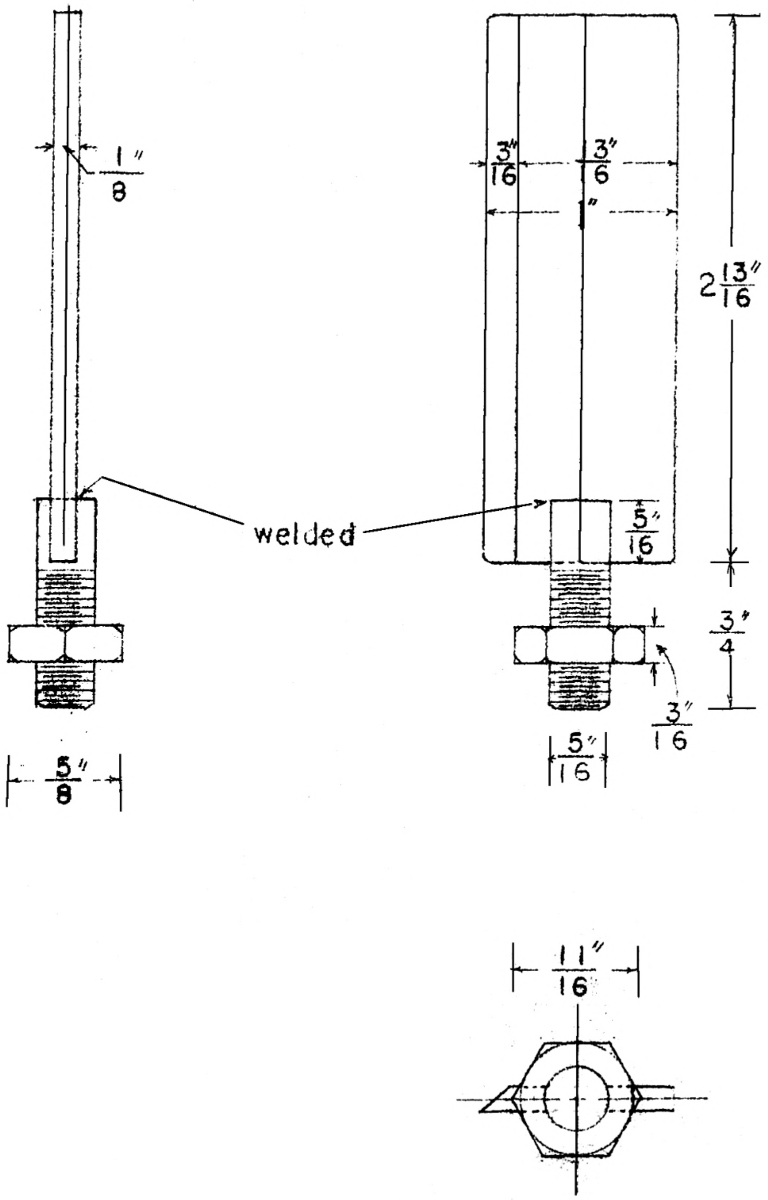
PLATE IX



EXPLANATION OF PLATE X

Detailed Drawing of Blade-A

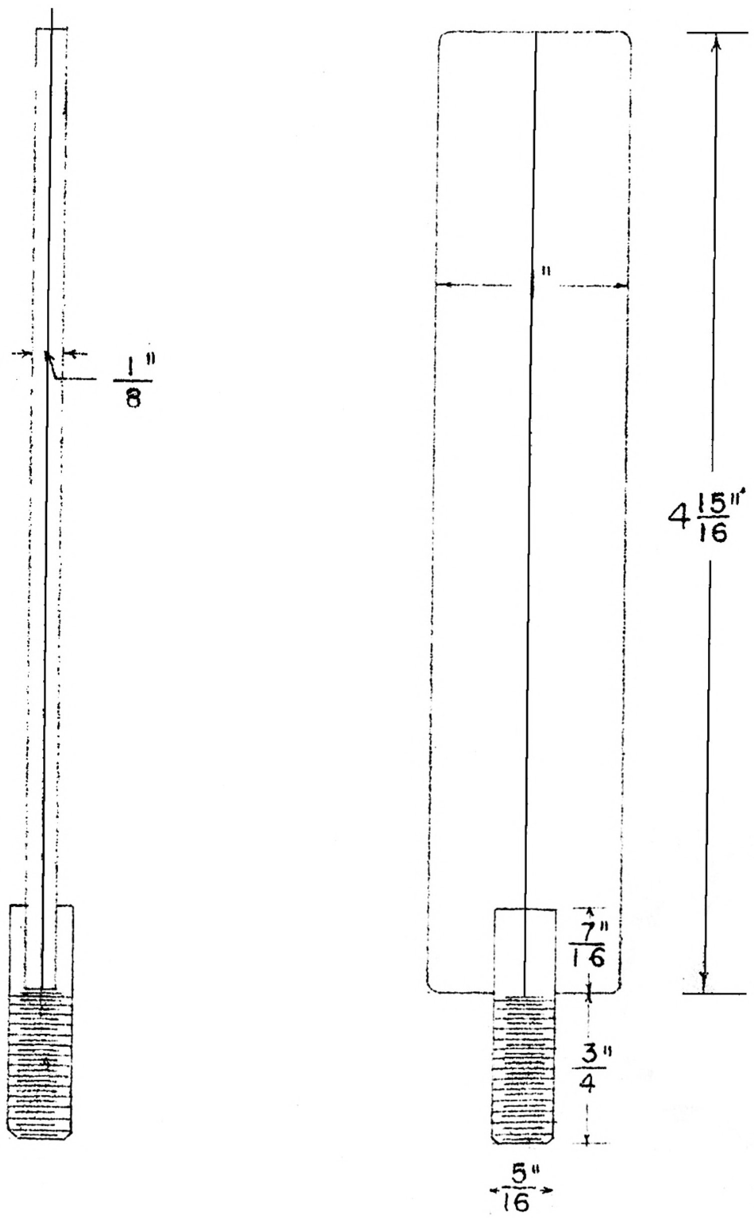
PLATE X



EXPLANATION OF PLATE XI

Detailed Drawing of Blade-B

PLATE XI



inches by 8 inches, to meet the increasing mill capacity. The pitch of the screens was adjustable by varying the height of the supporting stands. The ground material overflowed onto the 40-mesh screen, the overflow from which was washed into the debranner, while the underflow was pumped by a gear pump to the head of the 200-mesh screen. The portion coarser than 200-mesh overflowed from the screen and was pumped back to the mill for further grinding by a gear pump, while the underflow solution was pumped to a storage tank by a gear pump as starch milk for tabling. Both the coarse and the fine screens were mounted on a shaker which provided an oscillating motion by means of an eccentric. The oscillating frequency was 290 cycles per minute with 1/2 inch horizontal displacement.

A stream of water was introduced onto each screen through an overhead spray-nozzle to wash the ground material on the screen.

Flight Conveyer and Debranner. A flight conveyer was employed to convey partially-ground grits back to the mill for further grinding. Its dimensions 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°

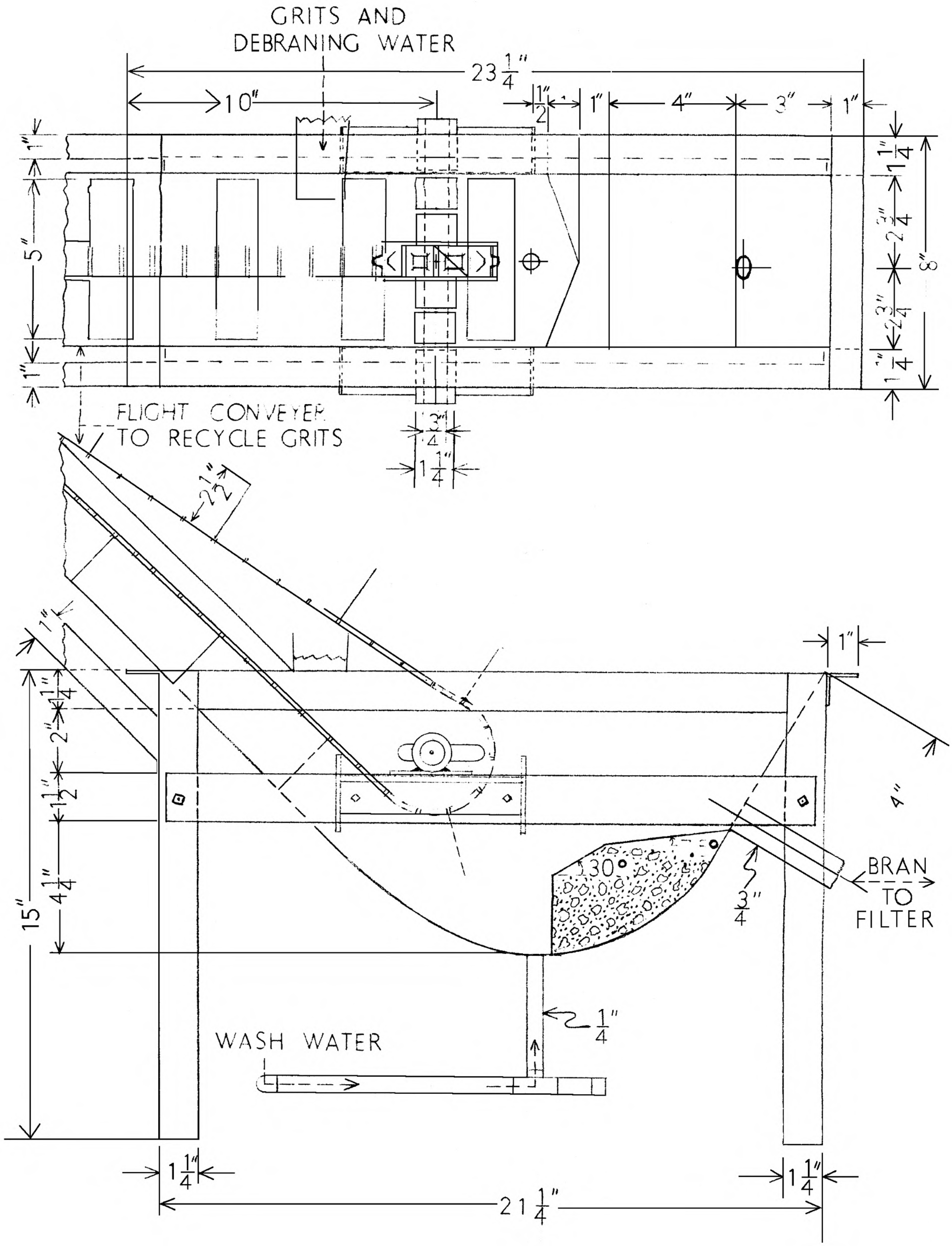
The conveyer was driven by a 1 hp Reeves Varimotor through a belt and a set of reduction gears. The linear velocity of the conveyer was in the range of 1.5 to 9 feet per minute.

The lower end of the conveyer functioned as the debranner which is shown in detail on Plate XII. The overhead coarser fraction washed from the 40-mesh screen passed into the debranner, where the lighter bran was separated from

EXPLANATION OF PLATE XII

Drawing of Debranner

PLATE XII



GRITS AND
DEBRANING WATER
FLIGHT CONVEYER
TO RECYCLE GRITS
WASH WATER
BRAN
TO
FILTER

the partially-ground materials by flotation. The overflow from the debranner was pumped by a gear pump to a nutsch-type filter with an area of four square feet. The filter was furnished with a vacuum pump (F. J. Stokes Machine Company, Model 33275 reciprocating vacuum pump). Partially-ground grits which settled in the bottom of the conveyer boot were carried back to the hydraulic mill for regrinding.

Since it was found that a large amount of starch adhered to the bran and was lost because of incomplete washing on the coarse screen, especially at high feeding rates, the debranning process was modified as shown in Plate III for the later runs (funs L-R, 7, 8, 9, and 10). In these runs the overflow from the debranner was pumped to another 200-mesh screen (32 1/2 inches by 4 inches) which had a pitch of 3.17 inches per foot. Here the bran was washed with a spray of water to separate an additional portion of starch. The bran from this screen was dried while the underflow starch suspension was combined with the starch milk. This modification produced bran almost free of starch, giving appreciably higher starch recoveries.

Starch Tables. Four starch tables, each 27 feet long, 5 3/4 inches wide, and 2 1/2 inches deep were used to separate the starch from the gluten. To save floor space the four tables were arranged in series and each of them had a pitch of 1 inch per 10 feet alternately in opposite directions as shown on Plate I.

Auxiliary Equipment

Control Panel. Five rotameters and seven switches were arranged on a control panel in order to control the various rates of water flow and the starch tabling operation.

Storage Tanks. A 50-gallon, cone-bottom, stainless steel tank was used as a storage for starch milk from the 200-mesh screens before tabling. A 1/4 hp lightning mixer, Model D-1A, was used to keep the starch in suspension.

Another 100-gallon, cone-bottom, stainless tank was used to hold the gluten solution which overflowed from the starch tables. After overnight settling, the upper clear liquor was siphoned out and the thick gluten slurry in the bottom was drained through a 2-inch outlet at the bottom.

Dryer. A tray and compartment dryer made by George Koch Sons Company was used for drying the products. Air was heated by a steam coil and circulated by a blower. The temperature was maintained at 125 $\pm$ 5° F. by a Bristol pneumatic temperature controller-recorder.

Tipper. A tipper made of copper sheet was installed between the overhead of the corase screen and the mill was used to measure the overflow rate from the mill by measuring the time required for a certain number of tilts. The constancy of this rate was taken as the criterion for the attainment of steady state operation.

MATERIAL

The milo sorghum grits used for most of this work were supplied by Grain Products, Inc., Dodge City, Kansas. As the grits arrived at the laboratory, they were stored in 55-gallon, open-head barrels. A 50-cc erlenmeyer flask containing carbon disulfide was placed in each container as an insecticide. The barrels were then covered tightly. Five batches of grits were used. The composition of the grits was analyzed by the Chemical Service Laboratory at Kansas State College. The analyses are shown in Table 1.

Table 1. Chemical analysis of sorghum grits.

Source and type of grits	Component in weight per cent		
	Moisture	Protein	Starch
Batch 1, Grain Products, non-waxy	10.72	11.23	76.47
Batch 2, Grain Products, non-waxy	10.76	10.38	75.19
Batch 3, Grain Products, non-waxy	12.29	10.38	74.04
Batch 4, Grain Products, non-waxy	11.83	9.06	74.38
Batch 5, Grain Products, non-waxy	11.51	9.75	73.66
Batch 6, Harvest Queen, non-waxy	11.49	8.63	78.78
Batch 7, Harvest Queen, waxy	10.51	11.31	74.30

Two other samples of milo grits, one waxy and the other non-waxy, obtained from the Harvest Queen Mill and Elevator Company, Plainview, Texas, were used for long runs of several hours each. The analyses of these grits are shown in Table 1 also.

Both steeping and processing water were taken from the Manhattan City system. The analysis of water was reported as shown in Table 2.

Table 2. Analysis of Manhattan City water.

Total hardness (parts of calcium carbonate per million)	76
Non-carbonate hardness (parts of calcium carbonate per million)	45
Total dissolved (parts per million)	218
pH value	8.97

EXPERIMENTAL PROCEDURE

Steeping, grinding, and tabling were the three main steps of the operation. Each step is described in detail in the following:

Steeping

Thirty to 200 pounds of grits, depending on the feed rate to be used, were weighed and charged into the steeping tanks. The hot steeping water prepared in the heating tank was supplied separately to the steeping tanks by a 1/30 hp centrifugal gear pump. The steeping temperature was held constant at 125 ± 5° F. Plain water with no steeping agent such as sulfur dioxide was used through all runs. Except for Run C-1, a steeping time of one hour was adopted for all runs. The work of Chai (4) and Chiang (5) showed this time to be sufficient. After steeping, the steeping liquor was drained and discarded. The steeped grits were carried to the feeding hopper manually.

The purposes of steeping were to soften the grain and to extract the soluble proteins and minerals which act as binders between the starch granules and gluten. Removal of the soluble proteins also aids in reducing the nitrogen content in the final product.

Milling

The flow diagram for the milling operation is shown in Plate I. The feed rate, the water rate, and the speed of the mill shaft were set for each run. In order to compute the net power consumption for milling, a power consumption reading was taken on the mill running empty prior to the time feeding was started. The shaft rpm was checked and recorded simultaneously. Then the feed water, the screw conveyer in the hopper, and the mill were turned on simultaneously. The total time of feeding was measured by a Kodak stop clock.

When the mill solution began to overflow through the overflow pipe onto the screen, the screen shaker was started, and the wash water to the screens turned on. The pumps for pumping the underflow from the 40-mesh screen to the

200-mesh screen, for the starch milk underflow from the 200-mesh screen, and for pumping the overflow from the 200-mesh screen back to the mill for re-grinding, were turned on successively. Meanwhile, as the coarse, partially-ground grits and bran overflowed from the 40-mesh screen into the boot of the flight conveyer, the flight conveyer was started and the water for debranning and for washing the recycled grits into the mill was turned on. The starch milk and bran were pumped into the sewer and discarded until steady state operation was reached.

In the early runs the steady state was assumed to be reached within one hour after the run was started. This assumption was verified when overflow rates from the mill, in terms of the time required for five complete cycles of the tipper, at different times after starting of the runs were plotted for three runs having the highest feed rates used, as shown in Fig. 1. When the overflow from the mill reached a constant rate, as measured by the tipper, the starch milk was collected in the storage tank, and the bran was pumped to the vacuum filter. The run was continued for 30 minutes after the steady state was reached. During this time the power consumption, the mill shaft rpm, the mill temperature, the starch milk specific gravity, and the rate of each stream of water were taken and recorded. The slurry overflowing from the mill was also collected for a measured length of time. This sample was weighed and its solid content determined. The recycle rate was computed from this data by making a material balance around the mill. All the calculations were based on this steady state interval.

The run was continued until all the grits were fed into the mill in order that the feed rate could be computed in terms of dry grits. The starch milk and bran streams were again discarded after the expiration of the 30-minute sampling period.

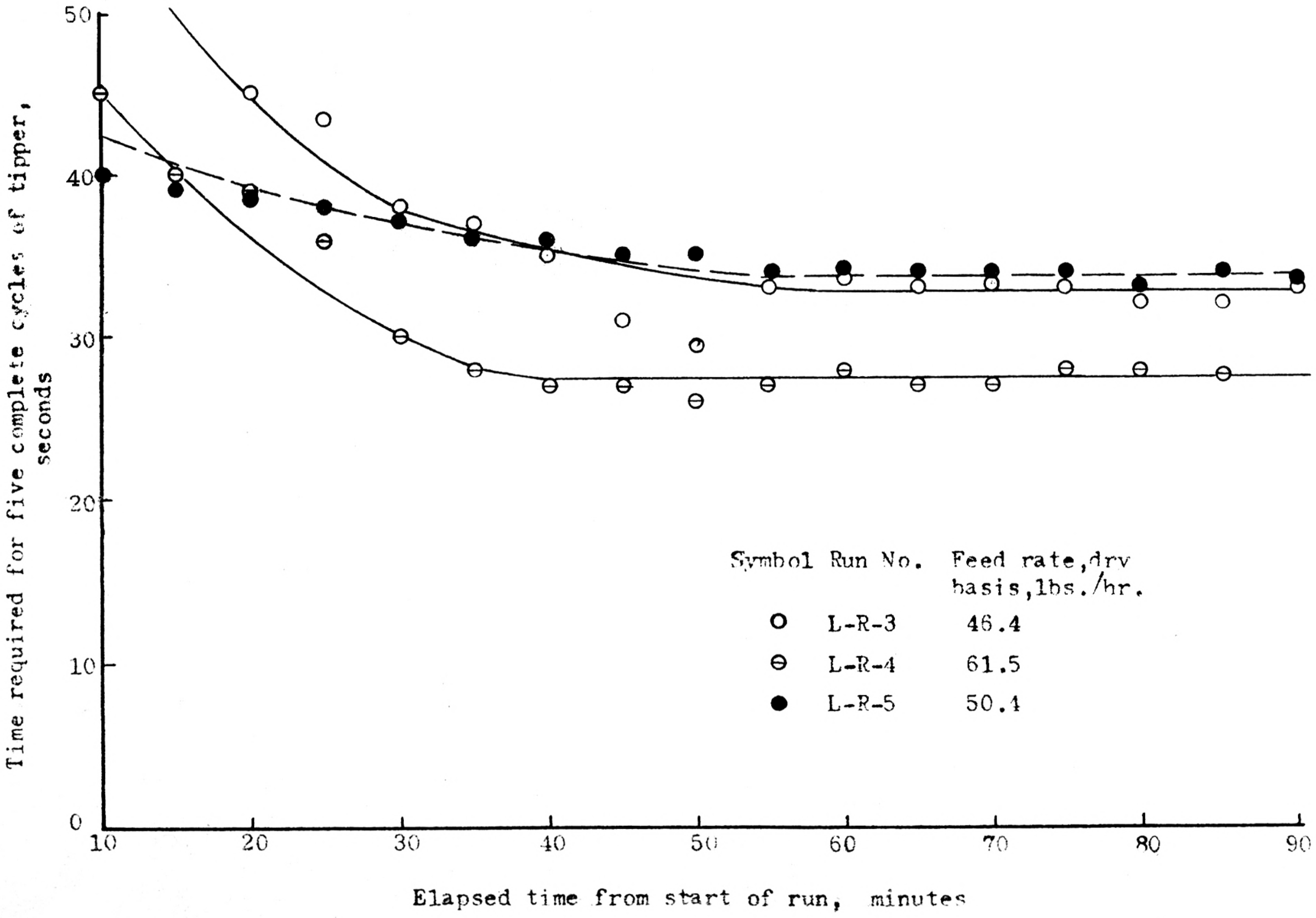


Fig. 1. Time required to reach a steady flow rate at the mill overflow.

Tabling

After the sample was taken, the starch milk was pumped through a 1/4 inch galvanized pipe to the head of the starch tables by a 1/3 hp centrifugal pump, Eastern Industries, Model 2-F. The tabling rate of starch milk was controlled by a rotameter at 0.8 gpm, which was determined to be the optimum by Chiang (5), and was used by Chai (4) throughout his work. The starch settled out on the tables while the gluten remained suspended in the overflow and passed from table to table. The gluten slurry was finally pumped by a 1/2 hp gear pump to a 100-gallon conical-bottom stainless steel tank, where the gluten was allowed to settle overnight. A small amount of sulfur dioxide was added to prevent fermentation. After settling, the upper clear liquor was decanted by means of a siphon. Because of the difficulty of filtering the gluten slurry, it was sent to a tray dryer for direct drying.

After all the starch milk was pumped onto the table, the starch on the tables was washed with a stream of water introduced through the same pipe as for the starch milk. The washing water rate was one gallon per minute for 30 minutes which was also determined to be most effective by Chiang (5) and also was used by Chai (4). The washing liquor was collected with the gluten suspension.

When the starch on the tables became nearly dry (usually six to eight hours, depending on the thickness of starch layer) it was scooped out manually and placed on a tray in the dryer. The starch, bran, and gluten were dried at 125° ± 5° F. for 24 hours or more until completely dry. The weights of the materials after drying were the basis for the material balance, starch yield, and recovery calculations.

DATA

The process data for all runs are presented in Tables 3 through 11. The processing conditions are listed in Tables 3, 4, and 5; the chemical analysis of the products is given in Table 6; and the calculated results, including the yield and recovery of starch, and the consumption of power and of water, are given in Tables 7, 8, and 9. The runs for long test periods with both waxy and non-waxy varieties of grits from Texas are presented in Tables 10 and 11.

The amount of steeping water used was about 0.3 gallon per pound of grits. This was, however, highly flexible depending on whether batch or continuous steeping was being used. In the case of continuous steeping, the water used per pound of grits was much lower, because most of the water could be reused.

The symbols C, S-R, and L-R stand for the clover-leaf type; small, round type; and large, round type casings of the mill, respectively (Plate V), and A and B stand for the kind of blades used (Plates X and XI). The locations of the blades were expressed by numbers to show the positions on the shaft as shown in Plate IX. Blades at positions 1, 3, 5, 7, and 9 are parallel, while 2, 4, 6, and 8 are parallel to each other, but perpendicular to 1, 3, 5, 6, and 9.

Because of the nature of the process, all grits and yield quantities are expressed as rates and calculated on the dry basis. The water consumptions and tabling rates were recorded directly from flowrators. Tabling rate and table washing rate were fixed through all runs conducted. The feed rate was determined from the total length of time required to transfer all the steeped grits (which had been weighed before steeping) from the screw conveyer into the mill. The feed rate was calculated by first dividing the total weight of grits before steeping by the total feeding time to get the feed rate of unsteeped grits. This was then corrected for the moisture content in the original grits to obtain the feed rate on the dry basis.

The net power consumption of the mill was estimated from the following equation:

$$KW = \frac{60 \times 7.2}{1,000} (Rf - Ri)$$

where Rf = the rpm of the watt-hour meter during the steady state of the run.

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

$\frac{60 \times 7.2}{1,000}$ = the conversion factor for the watt-hour meter.

The fraction ground per pass was considered to be a measure of the effectiveness of the different milling conditions. This was computed by dividing the feed rate of dry grits by the total flow rate of dry solid matter overflowing from the mill. The recycling rate was calculated by subtracting the feed rate from total solid overflow rate from the mill. These definitions are derived by consideration of a material balance on dry solids around the mill. The input to the mill consisted of fresh feed and a recycle stream of partly-ground grits, while the output from the mill was the solid portion of the overflow stream. From this definition the more effective the mill, the less the recycling rate and the higher the grinding efficiency.

Starch yield is defined as:

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

while the starch recovery was defined as:

$$\frac{\text{Weight of starch as product, dry basis}}{\text{Weight of starch in the grain used, dry basis}}$$

Table 3. Summary of process conditions for runs using the clover-leaf casing with nine pairs of A-blades.

Run number		C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9[1]	C-10[2]	C-11[2]	C-12[3]	C-13[4]
Room temperature	° F	71	71	73	88	73	88	82	92	91	96	93	94	93
Grinding conditions														
Blade pitch	degree	0	0	30	30	45	45	60	60		90	90	90	
Mill speed, no load	rpm	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400
with load	rpm	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,300	2,250	2,200	2,200	1,900	
Mill temperature	° F	84	89	88	93	91	99	130	124	131	136	125	170	
Feed rate, wet basis	lb/hr	25.2	24	23	22.9	24	25.4	24	21.7	22.6	24	23.4		
dry basis	lb/hr	22.5	21.43	20.53	20.45	21.43	22.68	21.43	19.37	20.18	21.43	20.9		
Mill concentration	wt %	16.5	17.4	22.5	21.5	24.5	23.2	24.6	23.2	24.3	26.7	23.2	Mill temperature too	
Overflow rate from mill, dry basis	lb/hr	41.1	38.4	45.7	42.2	48.6	55	53.7	50.2	46.3	52	55.3	high. Starch pasted	
Grits recycling rate, dry basis	lb/hr	18.6	17.0	25.2	21.75	27.2	32.3	32.3	30.8	26.1	30.6	34.3	in mill.	
Fraction ground per pass	%	54.7	55.8	44.9	48.4	44.1	41.3	40	38.2	43.6	41.3	37.8		
Power consumption	KW	1.805	1.705	1.745	1.70	2.146	2.12	4.0	4.47	5.35	4.94	4.88		
Specific gravity of starch milk	° Be	1.4	2.2	2.0	2.1	2.2	2.1	1.9	1.9	2.1	1.8	1.7		
Slope of screens														
Coarse screen (single width)	in/ft	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Fine screen (single width)	in/ft	0.55	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		
Water consumption														
for feeding	gal/hr	17.90	15.4	15.9	15.1	15.7	17.7	14.3	8.16	9.95	8.85	8.16		
for screening	gal/hr	9.60	4.2	4.5	7.2	5.4	6.34	3.0	3.6	4.2	3.0	5.4		
for debranning	gal/hr	4.80	4.8	5.1	5.4	3.6	3.3	14.4	21.6	16.2	20.4	16.8		
for recycling	gal/hr	11.40	11.4	8.4	8.4	10.8	10.8	9.0	10.2	12.6	14.4	12.6		

1. Blade arrangement: five pairs at positions 1, 3, 5, 7, and 9, 45° pitch up; four pairs at 2, 4, 5, and 8, 45° pitch down.
2. Blade arrangement: eight pairs, position 8 vacant.
3. Blade arrangement: seven pairs, positions 8 and 9 vacant.
4. Blade arrangement: nine pairs, 1 to 7, pitch 90°; 8 and 9, 45° pitch down.

Table 4. Summary of process conditions for runs using the small, round casing with nine pairs of A-blades.

Run number		S-R-1	S-R-2	S-R-3	S-R-4	S-R-5	S-R-6	S-R-7	S-R-8	S-R-9	S-R-10	S-R-11	S-R-12	S-R-13	S-R-14	S-R-15	S-R-16	S-R-17	S-R-18	S-R-19	S-R-20	S-R-21
Room temperature	° F	79	76	80	74	70	71	68	73	74	79	68	72	75	76	78	71	68	68	79	68	74
Grinding conditions																						
Blade pitch	degree	0	0	0	0	45	90	0	0	0	0	0	0	0	0	0	0	0	45	45	90	90
Mill speed, no load	rpm	1,850	1,850	1,850	1,850	1,850	1,850	2,300	2,300	2,300	2,300	2,300	2,450	2,450	2,450	2,150	2,150	2,150	2,150	2,150	2,150	2,150
with load	rpm	1,850	1,850	1,850	1,850	1,850	1,300	2,300	2,300	2,300	2,300	2,300	2,450	2,450	2,450	2,150	2,150	2,150	2,150	2,150	2,100	2,000
Mill temperature	° F	83	85	84	84	86	94	88	87	88	94	88	87	90	86	90	84	82	82	85	95	96
Feed rate, wet basis	lb/hr	29.4	36.2	49.6	45.8	42.4	35.3	36	50	44.7	63.8	53.1	66.3	52.5	43.3	44.8	62.5	50.6	51.2	43	43.2	51.8
dry basis	lb/hr	26.2	32.3	44.24	40.85	37.82	31.5	32.11	44.6	39.87	56.91	47.37	59.14	46.04	39.97	39.3	54.81	44.38	44.9	37.7	37.89	45.43
Mill concentration	wt %	14	14.8	17.0	21.6	19.9	25.9	13.9	25.6	17.0	23.5	20.6	22.8	18.5	15.8	16.9	25.8	18.85	24	17.9	23.9	23.9
Overflow rate from mill, dry basis	lb/hr	35.4	44.5	93.2	83.4	94.6	124.4	37.0	77.8	70	123	84	147	84.6	66	57	82.2	65.4	126	85.5	106.5	113
Grits recycling rate, dry basis	lb/hr	9.2	12.2	49.0	42.55	56.8	90.9	4.92	33.2	30.1	66.1	36.6	87.9	38.6	28	12.2	27.4	21.0	81.1	47.8	68.6	67.6
Fraction ground per pass	%	74.1	72.64	47.5	49.1	40.0	25.74	86.71	57.3	56.94	46.3	56.43	40.24	54.4	57.5	69	66.7	67.8	35.64	44.17	35.6	40.3
Power consumption	KW	0.58	0.805	0.842	0.64	0.906	1.67	1.03	1.15	1.09	1.05	1.06	1.235	1.19	1.2	1.1	1.28	1.26	1.165	1.16	2.33	2.32
Specific gravity of starch milk	° Be	2.6	3.0	3.0	3.8	2.9	4.0	3.6	5.0	3.9	5.0	5.5	4.6	2.0	2.3	2.3	4.0	2.7	2.7	3.0	3.1	3.6
Slope of screens																						
Coarse screen (single width)	in/ft	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Fine screen (double width)	in/ft	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Water consumption,																						
for feeding	gal/hr	15.95	15.95	17.15	9.4	24.5	7.35	7.5	9.95	8.45	8.58	7.92	7.74	8.04	7.2	7.2	7.2	6.24	7.1	6.8	6.6	6.8
for screening	gal/hr	9.6	19.2	13.2	10.8	15.0	8.4	9.6	9.0	8.4	12.0	10.6	16.2	19.8	18.0	17.4	17.4	18.0	15.6	16.8	14.4	15.6
for debranning	gal/hr	22.2	13.8	26.4	12.0	8.4	16.2	15.0	9.0	15.0	19.8	14.4	6.6	19.2	14.4	13.8	15.6	16.8	17.4	10.8	13.8	15.6
for recycling	gal/hr	0	0	10.4	6.6	7.8	9.0	6.6	6.0	8.4	8.4	6.6	7.8	7.8	7.2	6.0	4.8	6.0	6.0	6.0	4.8	7.8

Table 5. Summary of process conditions for runs using the large, round casing with nine pairs of B-blades.

Run number		L-R-1[1]	L-R-2[1]	L-R-3	L-R-4	L-R-5	L-R-6	L-R-7	L-R-8	L-R-9[2]	L-R-10
Room temperature	° F	79	78	68	75	68	73	74	70	70	76
Grinding conditions											
Blade pitch	degrees	90	0	0	0	0	0	0	0	0	0
Mill speed, no load	rpm	2,150	2,150	2,150	2,150	1,900	2,450	3,100	2,400	2,400	2,450
with load	rpm	2,100	2,150	2,150	2,150	1,900	2,450	2,900	2,100	2,250	2,450
Mill temperature	° F	92	86	100	100	96	105	122	118	105	105
Feed rate, wet basis	lb/hr	62.4	63.18	52.62	69.78	57.12	58.68	56.82	107.88	50.82	97.14
dry basis	lb/hr	55.0	55.44	46.4	61.53	50.36	51.74	50.1	95.12	44.81	85.96
Mill concentration	wt %	30.1	28.2	19.75	22.9	22.8	21.4	18.4	31.5	23.4	26.4
Overflow rate from mill, dry basis	lb/hr	220	209	98.5	173	115	138	106	276	112.5	246
Grits recycling rate, dry basis	lb/hr	157.3	153.5	52.1	111.5	64.6	86.25	55.9	180.9	67.7	160
Fraction ground per pass	%	25.1	26.5	47.1	35.6	43.9	37.5	47.2	34.5	39.8	35.0
Power consumption	KW	1.798	1.171	3.06	3.18	2.60	3.69	5.3	4.53	3.33	4.07
Specific gravity of starch milk	° Be	3.1	3.0	3.6	4.6	4.2	4.5	3.1	7.1	3.2	4.3
Slope of screens											
Coarse screen (single width except run L-R-10 which was double width)	in/ft	2	2	2	2	2	2	2	2	2	2.36
Fine screen (double width)	in/ft	2	2	2	2	2	2	2	2	2	2
Bran washing screen (single width)	in/ft	--	--	--	--	--	--	3.17	3.17	3.17	3.17
Water consumption											
for feeding	gal/hr	11.6	14.0	7.37	8.15	8.1	8.4	7.37	6.74	8.15	10.8
for screening	gal/hr	13.2	17.4	15.0	15.0	14.4	14.4	19.8	19.8	20.4	27.6
for debranning	gal/hr	16.2	17.4	15.6	15.6	14.4	14.4	25.2	10.2	12	7.2
for recycling	gal/hr	9.0	6.0	6.6	8.4	7.8	6.0	9.0	6.0	5.4	7.8

1. 9 pairs A-blade were used.
2. 18 blades, one each at positions 1 to 9; 8 blades between each position 1 to 9; one below 1, 120° to each other.

Table 6. Analysis of products, as received basis.

	Starch	Gluten		Bran	
Run number	Protein content %	Starch content %	Protein content %	Starch content %	Protein content %
C- 1	0.44	50.22	33.00	56.34	18.94
C- 2	0.37	50.57	33.25	57.94	19.19
C- 3	0.37	46.29	37.50	56.02	19.31
C- 4	0.37	45.69	37.56	52.44	19.13
C- 5	0.44	45.30	38.38	53.12	18.06
C- 6	0.44	50.43	34.38	58.20	17.88
C- 7	0.50	33.78	44.19	53.13	20.50
C- 8	0.44	48.38	36.13	47.40	21.19
C- 9	0.37	50.64	32.44	54.70	20.00
C-10	0.37	55.85	24.38	56.62	17.5
C-11	0.44	51.03	33.19	52.56	19.69
S-R- 1	0.37	49.87	36.75	68.23	19.44
S-R- 2	0.50	49.57	36.00	60.93	18.50
S-R- 3	0.37	49.02	37.13	65.72	16.88
S-R- 4	0.37	49.10	37.13	64.78	17.19
S-R- 5	0.50	50.00	34.25	54.53	18.00
S-R- 6	0.50	49.06	34.56	61.92	15.44
S-R- 7	0.56	50.47	34.75	50.86	22.94
S-R- 8	1.12	47.23	37.38	54.57	19.31
S-R- 9	0.62	50.17	36.00	53.59	21.19
S-R-10	0.62	46.88	38.75	61.45	20.50
S-R-11	0.44	52.82	35.06	66.95	16.81
S-R-12	1.12	49.11	36.88	68.62	15.94
S-R-13	1.50	50.25	33.88	53.55	17.25
S-R-14	0.75	52.56	33.63	54.83	17.63
S-R-15	0.81	57.60	29.38	59.94	14.88
S-R-16	0.81	48.51	35.56	64.52	15.25
S-R-17	1.12	50.39	31.63	57.56	15.44
S-R-18	0.94	51.59	32.19	60.25	14.13
S-R-19	0.75	49.53	33.31	56.79	15.19
S-R-20	0.62	54.70	29.44	51.03	17.19
S-R-21	0.87	53.08	32.00	66.14	13.63
L-R- 1	0.56	58.37	58.37	64.09	11.19
L-R- 2	0.68	48.81	30.81	66.74	12.25
L-R- 3	0.56	49.40	35.75	65.16	14.88
L-R- 4	0.44	47.99	37.31	69.81	13.44
L-R- 5	0.63	49.57	35.63	60.46	14.69
L-R- 6	0.56	49.57	35.38	64.95	16.25
L-R- 7	0.63	42.96	40.56	47.74	22.0
L-R- 8	0.56	52.09	32.88	68.36	15.88
L-R- 9	0.81	46.31	36.63	47.01	21.31
L-R-10	0.75	47.91	37.00	64.56	18.50
Non-waxy 1	0.87	46.5	37.31	76.69	10.63
Non-waxy 2	0.50	51.07	34.88	69.39	14.88
Non-waxy 3	0.44	51.54	34.56	71.05	14.13
Waxy 1	0.44	48.51	34.56	72.85	15.13
Waxy 2	0.56	42.61	37.81	61.32	19.19
Waxy 3	0.75	62.21	22.00	73.74	13.63

Table 7. Process results for mill using the clover-leaf casing. All yields are reported on the dry basis.

Run number		C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11
Yields of products												
Starch	lb/hr	10.98	11.38	10.63	11.24	11.49	12.22	13.13	12.28	11.04	9.1	11.58
	%	48.80	53.10	51.78	54.96	53.62	53.88	61.27	63.40	54.71	42.46	55.43
Gluten	lb/hr	2.85	2.96	1.74	2.62	2.51	2.85	2.72	2.83	3.32	3.58	3.07
	%	12.67	13.81	8.48	12.81	11.71	12.57	12.69	14.61	16.45	16.71	14.70
Bran	lb/hr	3.36	3.12	3.47	2.95	2.74	4.56	1.42	1.07	1.06	1.64	0.70
	%	14.93	14.56	16.90	14.43	12.79	20.11	6.63	5.52	5.25	7.65	3.35
Total	lb/hr	17.19	17.46	15.84	16.81	16.74	19.63	17.27	16.18	15.42	11.45	15.35
	%	76.40	81.47	77.16	82.20	78.12	86.56	80.59	83.53	76.41	66.82	73.49
Starch recovery												
Starch extracted	lb/hr	10.98	11.38	10.63	11.24	11.49	12.22	13.13	12.28	11.04	9.1	11.58
Starch in feed	lb/hr	19.27	18.35	17.59	17.51	18.35	19.42	18.04	16.32	16.99	18.05	17.59
Recovery	%	56.98	62.02	60.43	64.19	62.61	62.92	72.78	75.25	64.98	50.42	65.83
Starch accounted for	lb/hr											
In starch		10.93	11.34	10.59	11.20	11.44	12.16	13.06	12.23	11.00	9.06	11.53
In gluten		1.51	1.61	0.87	1.28	1.22	1.51	0.97	1.45	1.77	2.03	1.66
In bran		2.03	1.96	2.10	1.67	1.59	2.83	0.80	0.53	0.62	0.99	0.39
Total		14.47	14.91	13.56	14.15	14.25	16.50	14.83	14.21	13.39	12.08	13.58
Total in feed		19.27	18.35	17.59	17.51	18.35	19.42	18.04	16.32	16.99	18.05	17.59
Starch accounted for	%	75.09	81.25	77.09	80.81	77.66	84.96	82.21	87.07	78.81	66.93	77.20
Protein accounted for	lb/hr											
In starch		0.05	0.04	0.04	0.04	0.05	0.06	0.07	0.05	0.04	0.04	0.05
In gluten		0.99	1.06	0.70	1.06	1.04	1.03	1.27	1.03	1.14	0.88	1.08
In bran		0.68	0.65	0.72	0.61	0.54	0.87	0.31	0.24	0.23	0.31	0.15
Total		1.72	1.75	1.46	1.71	1.63	1.96	1.65	1.32	1.41	1.23	1.28
Total in feed		2.83	2.69	2.58	2.57	2.69	2.85	2.49	2.25	2.35	2.49	2.43
Protein accounted for	%	60.78	65.06	56.59	66.54	60.59	68.77	66.27	58.67	60.00	49.40	52.67
Energy consumption for grinding	KWH/lb											
Per pound of feed		0.0802	0.0796	0.0850	0.0538	0.1001	0.0935	0.1867	0.2308	0.2651	0.2305	0.234
Per pound of starch		0.1644	0.1498	0.1642	0.152	0.1868	0.1735	0.3046	0.3640	0.4846	0.5429	0.422
Water consumption	gal/lb											
Processing water per pound of feed		1.94	1.67	1.65	1.77	1.66	1.68	1.90	2.25	2.13	2.18	2.06
Washing water per pound of feed		2.67	2.80	2.92	2.93	2.80	2.65	2.80	3.10	2.97	2.80	2.87
Total per pound of feed		4.61	4.47	4.57	4.70	4.46	4.33	4.70	5.35	5.10	4.98	4.93
Processing water per pound of starch		3.98	3.16	3.19	3.21	3.09	3.12	3.10	3.56	3.89	5.13	3.71
Washing water per pound of starch		5.48	5.27	5.64	5.34	5.22	4.91	4.57	4.89	5.43	6.59	5.18
Total per pound of starch		9.46	8.43	8.83	8.55	8.31	8.03	7.67	8.45	9.32	11.72	8.89

Table 8. Process results for mill using the small, round casing. All yields are reported on the dry basis.

Run number		S-R-1	S-R-2	S-R-3	S-R-4	S-R-5	S-R-6	S-R-7	S-R-8	S-R-9	S-R-10	S-R-11
Yields of products												
Starch	lb/hr	16.67	19.19	26.67	23.71	20.82	17.60	18.38	25.66	23.08	32.85	25.88
	%	63.58	59.43	60.28	58.04	55.05	55.89	57.24	57.54	57.89	57.72	54.63
Gluten	lb/hr	3.56	4.69	7.38	6.51	6.87	3.85	5.70	7.49	6.94	8.73	7.73
	%	13.57	14.52	16.68	15.94	18.16	12.23	17.75	16.79	17.41	15.34	16.32
Bran	lb/hr	4.43	15.61	6.68	5.87	3.15	3.46	3.21	6.38	4.15	8.74	6.46
	%	16.90	19.11	15.51	14.37	8.33	10.99	10.00	14.30	10.40	15.36	13.64
Total	lb/hr	24.66	30.05	40.91	36.09	30.84	24.91	27.29	39.53	34.17	88.42	84.59
	%	94.05	93.06	92.47	88.35	81.54	79.11	84.99	88.63	85.70	50.32	40.07
Starch recovery												
Starch extracted	lb/hr	16.67	19.19	26.67	23.71	20.82	17.60	18.38	25.66	23.08	32.85	25.88
Starch in feed	lb/hr	22.10	27.22	37.29	34.44	31.88	26.54	27.07	37.59	33.61	47.97	39.93
Recovery	%	75.43	70.50	71.52	68.84	65.31	66.32	67.90	68.26	68.67	68.48	64.81
Starch accounted for	lb/hr											
In starch		16.61	19.09	26.57	23.62	20.71	17.51	18.27	25.36	22.93	32.64	25.76
In gluten		1.87	2.49	3.80	3.31	3.58	1.96	2.97	3.72	3.64	4.22	4.29
In bran		3.16	4.04	4.85	3.98	1.79	2.24	1.72	4.23	2.35	5.84	4.60
Total		21.64	25.62	35.22	30.91	26.08	21.71	22.96	33.31	28.92	42.70	34.65
Total in feed		22.10	27.22	37.29	34.44	31.88	26.54	27.07	37.59	33.61	47.97	39.93
Starch accounted for	%	97.92	94.12	94.45	89.75	81.81	81.80	84.82	88.61	86.05	89.01	86.78
Protein accounted for	lb/hr											
In starch		0.06	0.10	0.10	0.09	0.11	0.09	0.11	0.30	0.15	0.21	0.12
In gluten		1.38	1.80	2.89	2.51	2.49	1.38	2.04	2.94	2.61	3.49	2.85
In bran		0.90	1.23	1.24	1.05	0.59	0.56	0.77	1.50	0.93	1.95	1.16
Total		2.34	3.13	4.23	3.65	3.19	2.03	2.92	4.74	3.69	5.75	4.13
Total in feed		3.05	3.76	5.15	4.75	4.40	3.66	3.74	5.19	4.64	6.62	5.51
Protein accounted for	%	76.72	83.24	82.14	76.84	72.50	55.46	78.07	91.33	79.53	86.86	74.95
Energy consumption for grinding	KWH/lb											
Per pound of feed		0.0221	0.0249	0.0190	0.0157	0.0252	0.0530	0.0321	0.0259	0.0273	0.0185	0.0224
Per pound of starch		0.0348	0.0420	0.0316	0.0270	0.0435	0.0949	0.0560	0.0448	0.0472	0.0320	0.0410
Water consumption	gal/lb											
Process water per pound of feed		1.82	1.52	1.52	0.95	1.47	1.30	1.21	0.76	1.01	0.86	0.83
Washing water per pound of feed		2.29	1.86	1.37	1.47	1.59	1.90	1.89	1.35	1.50	1.05	1.27
Total per pound of feed		4.11	3.38	2.89	2.42	3.06	3.20	3.10	2.11	2.51	1.91	2.10
Process water per pound of starch		2.86	2.55	2.52	1.64	2.68	2.33	2.11	1.32	1.74	1.48	1.53
Washing water per pound of starch		3.60	3.13	2.25	2.53	2.88	3.41	3.26	2.34	2.60	1.83	2.32
Total per pound of starch		6.46	5.68	4.77	4.17	5.56	5.74	5.37	3.66	4.34	3.31	3.85

Run number	S-R-12	S-R-13	S-R-14	S-R-15	S-R-16	S-R-17	S-R-18	S-R-19	S-R-20	S-R-21
Yields of products										
Starch	30.99	25.45	22.59	20.27	27.20	22.79	25.76	21.91	18.18	22.98
	52.40	55.28	59.49	51.59	49.63	51.35	57.37	58.10	47.98	50.58
Gluten	8.34	8.54	7.79	8.41	9.10	8.25	8.80	7.03	8.40	8.03
	14.10	18.55	20.52	21.40	16.60	18.59	19.60	18.64	22.16	17.68
Bran	11.19	4.75	3.52	3.89	7.95	5.76	5.91	3.16	4.14	6.10
	18.92	10.31	9.27	9.90	14.50	12.98	13.16	8.38	10.93	13.43
Total	85.42	84.14	89.28	82.89	80.73	82.92	90.13	85.12	81.07	81.69
	50.52	38.74	33.90	32.57	44.25	36.80	40.47	32.10	30.72	37.11
Starch recovery										
Starch extracted	30.99	25.45	22.59	20.27	27.20	22.79	25.76	21.91	18.18	22.98
Starch in feed	49.85	38.87	32.06	33.17	46.27	37.46	37.91	31.84	31.98	38.35
Recovery	62.17	65.47	70.46	61.11	58.79	60.84	67.95	68.81	56.85	59.92
Starch accounted for										
In starch	30.63	25.05	22.42	20.10	26.96	22.52	25.51	21.74	18.06	22.77
In gluten	4.24	4.52	4.20	4.97	4.61	4.35	4.76	3.71	4.70	4.38
In bran	8.15	2.81	1.99	2.40	5.40	3.45	3.75	1.85	2.17	4.22
Total	43.02	32.38	28.61	27.47	36.97	30.32	34.02	27.30	24.93	31.37
Total in feed	49.85	38.87	32.06	33.17	46.27	37.46	37.91	31.84	31.98	38.35
Starch accounted for	86.30	83.30	89.24	82.82	79.90	80.94	89.74	85.74	77.95	81.80
Protein accounted for										
In starch	0.36	0.40	0.17	0.17	0.24	0.27	0.25	0.17	0.12	0.21
In gluten	3.18	3.05	2.69	2.53	3.38	2.73	2.97	2.50	2.53	2.64
In bran	1.89	0.91	0.64	0.60	1.28	0.93	0.88	0.49	0.73	0.87
Total	5.43	4.36	3.50	3.30	4.90	3.93	4.10	3.16	3.38	3.72
Total in feed	6.88	5.45	4.49	4.65	6.49	5.25	5.31	4.46	4.48	5.38
Protein accounted for	78.92	80.00	77.95	70.97	75.50	74.86	77.21	70.85	75.45	69.15
Energy consumption for grinding										
Per pound of feed	0.0209	0.0259	0.0316	0.0278	0.0234	0.0284	0.0260	0.0281	0.0615	0.0512
Per pound of starch	0.0399	0.0468	0.0531	0.0540	0.0471	0.0553	0.0452	0.0483	0.1282	0.1011
Water consumption										
Process water per pound of feed	0.65	1.20	1.23	1.13	0.82	1.06	1.03	1.07	1.05	1.01
Washing water per pound of feed	1.01	1.30	1.58	1.53	1.09	1.35	1.34	1.59	1.58	1.32
Total per pound of feed	1.66	2.50	2.81	2.66	1.91	2.41	2.37	2.66	2.63	2.33
Process water per pound of starch	1.24	2.17	2.07	2.19	1.65	2.06	1.79	1.84	2.19	1.99
Washing water per pound of starch	1.94	2.38	2.67	2.96	2.21	2.63	2.33	2.74	3.30	2.61
Total per pound of starch	3.18	4.55	4.74	5.15	3.86	4.69	4.12	4.58	5.49	4.60

Table 9. Process results for mill using the large, round casing. All yields are reported on the dry basis.

Run number	:	: L-R-1	: L-R-2	: L-R-3	: L-R-4	: L-R-5	: L-R-6	: L-R-7	: L-R-8	: L-R-9	: L-R-10
Yields of products											
Starch	lb/hr	15.97	24.78	29.57	37.16	32.58	32.24	35.91	52.36	30.47	50.43
	%	29.03	44.70	63.73	60.39	64.69	62.31	71.68	55.05	68.00	58.67
Gluten	lb/hr	5.92	7.00	7.95	8.21	7.68	8.43	8.01	11.01	8.90	11.62
	%	10.78	12.63	17.13	13.34	15.25	16.29	15.99	11.57	19.86	13.52
Bran	lb/hr	4.25	9.06	5.52	11.85	6.44	8.38	3.41	23.52	2.17	19.92
	%	7.74	16.34	11.90	19.26	12.79	16.20	6.80	24.72	4.84	23.17
Total	lb/hr	26.14	40.84	43.04	57.22	46.70	49.05	47.33	86.89	41.54	81.97
	%	47.55	73.67	92.76	92.99	92.73	94.80	94.47	91.34	92.70	95.36
Starch recovery											
Starch extracted	lb/hr	15.97	24.78	29.57	37.16	32.58	32.24	35.91	52.36	30.47	50.43
Starch in feed	lb/hr	46.42	67.78	39.14	51.90	42.49	43.65	42.26	80.24	37.80	71.55
Recovery	%	34.40	36.56	75.55	71.60	76.68	73.86	84.97	65.25	80.61	70.48
Starch accounted for	lb/hr										
In starch		15.88	24.60	29.40	36.99	32.37	32.05	35.68	52.05	30.21	50.05
In gluten		3.55	3.60	4.02	4.01	3.91	4.28	3.49	5.85	4.40	5.75
In bran		2.85	6.42	3.67	8.45	4.08	5.61	1.67	17.03	1.06	13.00
Total		22.28	34.62	37.09	49.45	40.36	41.94	40.84	74.93	35.67	68.80
Total in feed		46.42	67.78	39.14	51.90	42.49	43.65	42.26	80.24	37.80	71.55
Starch accounted for	%	48.00	51.08	94.76	95.28	94.99	96.08	96.64	93.38	94.37	96.16
Protein accounted for	lb/hr										
In starch		0.09	0.18	0.17	0.17	0.21	0.19	0.23	0.31	0.26	0.38
In gluten		1.54	2.27	2.91	3.12	2.81	3.05	3.30	3.69	3.48	4.44
In bran		0.50	1.18	0.84	1.63	0.99	1.40	0.77	3.96	0.48	3.72
Total		2.13	3.63	3.92	4.92	4.01	4.64	4.30	7.96	4.22	8.54
Total in feed		6.51	6.56	4.77	6.32	5.18	5.32	5.15	9.77	4.60	9.47
Protein accounted for	%	32.72	55.34	82.18	77.85	77.41	87.22	83.50	81.47	91.74	90.18
Energy consumption for grinding	KWH/lb										
Per pound of feed		0.0327	0.0222	0.0660	0.0517	0.0517	0.0714	0.1058	0.0476	0.0745	0.0474
Per pound of starch		0.1127	0.0474	0.1038	0.0856	0.0799	0.1143	0.1478	0.0866	0.1092	0.0809
Water consumption	gal/lb										
Process water per pound of feed		0.91	0.99	0.96	0.77	0.89	0.83	1.22	0.45	1.03	0.62
Washing water per pound of feed		1.09	1.08	1.29	0.98	1.19	1.16	1.20	0.63	1.34	0.70
Total per pound of feed		2.00	2.07	2.25	1.75	2.08	1.99	2.42	1.08	2.37	1.32
Process water per pound of starch		3.13	2.21	1.51	1.27	1.37	1.34	1.71	0.82	1.51	1.06
Washing water per pound of starch		3.76	2.42	2.03	1.61	1.84	1.86	1.67	1.15	1.97	1.19
Total per pound of starch		6.89	4.63	3.54	2.88	3.21	3.20	3.38	1.97	3.48	2.25

Table 10. Summary of process conditions for long runs, using the clover-leaf casing with nine pairs of A-blades at zero degree pitch.

Run number		Waxy 1	Waxy 2	Waxy 3	Non-waxy 1	Non-waxy 2	Non-waxy 3
Room temperature	° F	74	72	75	73	72	73
Grinding conditions							
Mill speed	rpm	2,300	2,300	2,300	2,300	2,300	2,300
Mill temperature	° F	87	88	90	85	83	84
Total length of run		6 hr 15 min	7 hr 25 min	2 hr 55 min	5 hr 41 min	6 hr	4 hr
Total feed, wet basis	lbs	135	165	65.0	134.0	135.0	104.0
Total feed, dry basis	lbs	121	148	58.1	118.7	119.6	92
Feed rate, dry basis	lb/hr	19.3	19.95	19.5	20.9	19.95	23
Total power consumption	KW	15.6	18.0	7.1	13.0	12.5	10.5
Power consumption	KW/hr	2.59	2.43	2.44	2.29	2.08	2.62
Specific gravity of starch milk	° Be	2.3	2.2	2.4	2.4	2.3	2.5
Slope of screens							
Coarse screen (single width)	in/ft	1.0	1.0	1.0	1.0	1.0	1.0
Fine screen (single width)	in/ft	0.55	0.55	0.55	0.55	0.55	0.55
Water consumption							
for feeding	gal/hr	8.8	8.8	8.8	8.8	8.8	8.8
for screening	gal/hr	0	0	0	0	0	0
for recycling	gal/hr	7.8	7.8	7.8	7.8	7.2	7.2
for debranning	gal/hr	0	0	0	0	0	0

Table 11. Summary of process results for long runs. All yields are reported on the dry basis.

Run number		Waxy 1	Waxy 2	Waxy 3	Non-waxy 1	Non-waxy 2	Non-waxy 3
Yields of products							
Starch	lbs	40.7	49.8	20.3	52.7	76.9	57.1
	%	33.64	33.69	34.94	44.40	64.30	62.07
Gluten	lbs	13.0	16.4	10.7	10.1	12.8	13.4
	%	10.74	11.08	18.42	8.51	10.70	14.57
Bran	lbs	70.6	86.4	17.7	40.8	12.5	13.0
	%	58.35	58.38	30.46	34.37	10.45	14.13
Total	lbs	124.3	152.6	48.7	103.6	102.2	83.5
	%	102.73	103.1	83.82	87.28	85.45	90.76
Starch recovery							
Starch extracted	lbs	40.7	49.8	20.3	52.7	76.9	57.1
Starch in feed	lbs	103.1	122.60	48.30	105.56	106.35	81.93
Recovery	%	39.48	40.62	42.03	49.92	72.3	69.69
Starch accounted for	lbs						
In starch		40.51	49.5	20.13	52.17	76.48	56.83
In gluten		6.65	7.37	7.15	5.16	7.15	7.34
In bran		54.69	56.78	14.01	34.13	9.37	9.95
Total		101.85	113.65	41.29	91.46	93.0	74.12
Total in feed		103.1	122.60	48.30	105.56	106.35	81.93
Starch accounted for	%	98.79	92.70	85.49	86.64	87.45	90.47
Protein accounted for	lbs						
In starch		0.19	0.30	0.17	0.53	0.42	0.27
In gluten		4.74	6.54	2.53	3.71	4.88	4.92
In bran		8.71	17.77	2.59	4.73	2.01	1.98
Total		13.04	24.61	5.29	8.97	7.31	7.17
Total in feed		15.27	18.66	7.35	11.56	11.65	8.97
Protein accounted for	%	89.33	131.8	71.97	77.59	62.75	79.93
Energy consumption for grinding	KW/lb						
Per pound of feed		0.129	0.122	0.122	0.110	0.105	0.114
Per pound of starch		0.383	0.361	0.350	0.247	0.163	0.184
Water consumption of process	gal/lb						
Process water per pound of feed		0.860	0.832	0.851	0.794	0.802	0.696
Washing water per pound of feed		3.11	3.01	3.08	2.87	3.01	2.61
Total per pound of feed		3.97	3.842	3.931	3.664	3.812	3.306
Process water per pound of starch		2.55	2.47	2.38	1.79	1.25	1.12
Washing water per pound of starch		9.22	8.93	8.60	6.49	4.68	4.20
Total per pound of starch		11.77	11.40	10.98	8.28	5.93	5.32

All of the chemical analyses of the starch, gluten, and bran were determined by the Chemical Service Laboratory of the Chemistry Department at Kansas State College.

DISCUSSION OF RESULTS

The clover-leaf casing was used in the work by Chiang (5) and Chai (4), so that its characteristics were quite well known. In this research the clover-leaf casing was used primarily in experiments with varying blade angles.

The two other casings were used to obtain data for comparison with the clover-leaf shaped casings and to determine some other design variables, such as the effect of blade size and pitch, rate of rotation of the blades and feed rate, on the yield and recovery of starch.

Performance of Different Mill Casings

To compare the effectiveness and power consumption of the three different mill casings, four sets of runs having approximately similar processing conditions were picked from Tables 7, 8, and 9 and listed in Table 12. In this table the hold-up in the mill means the volume of slurry held by the mill at the listed operating speed. It will be observed that the fraction ground per pass for the clover-leaf type casing was slightly less than that for the small, round casing, while the power consumption in KWH per pound of starch produced was three times higher than that for the small, round casing. On the other hand, when the small, round casing and the large, round casing are compared, it is apparent that the large, round casing produced higher mill temperatures and a lower fraction ground per pass, and had a higher power consumption than the other casings. The power consumption when the large, round casing was used was about twice that of the small, round casing. It will be noticed that, although the large, round casing had twice the volume of the small, round casing, the hold-up of the two was approximately the same. The peripheral velocity in the large casing with the B blades is higher than in the small casing when operated at the same mill rpm. It was expected, therefore, that more effective grinding action would be obtained in the larger casing. The results were exactly opposite to this, however. This experience is in agreement with the following statement from Brown, et al. (3), page 503: "Small impellers operating at high speeds with small clearances between the impeller and fixed surroundings are especially suited to produce high shearing stresses."

Effect of Blade Arrangement

None of the blade arrangements used was as good as the regular arrangement of 9 pairs at positions 1 through 9. In run C-9, alternate pairs of A-blades were pitched 45° up and 45° down. With this arrangement excessive mill vibrations occurred, and the power consumption per pound of starch was much higher. In runs C-12 and C-13, 90° blade angles were used. This generated such high temperatures that the grits were cooked in the mill, and the starch was pasted.

In run LR-9 the blades were not arranged in pairs, but in a spiral pattern around the shaft. The power consumption for this arrangement was also higher than for the standard arrangements. When type A blades were used with the large, round casing with pitches of either 90° or 0° (runs LR 1 and LR 2) both the yield and recovery of starch were very low. It appeared doubtful if steady state operation was reached in the total time of 100 minutes of operation in both cases. In hydraulic milling the clearance between the blades and

Table 12. Comparison of the operating characteristics of the clover-leaf casing, small, round casing, and large, round casing. Blade angle = 0° in all cases.

Run No.	Casing	Feed rate lb/hr	Mill speed rpm	Mill temp. ° F.	Fraction ground per pass, %	Hold-up in mill, gal	Power consumption: KWH/lb starch	Power consumption: KW/hr
C- 1	Clover-leaf	22.5	2,400	84	54.7	4.6	0.1644	1.805
S-R-14	Small, round	38	2,450	86	57.5	2.35	0.053	1.2
S-R- 3	Small, round	44.3	1,850	84	47.5	2.65	0.0316	0.842
L-R- 5	Large, round	50.4	1,900	96	43.9	2.60	0.0799	2.6
S-R-17	Small, round	44.4	2,150	84	67.8	2.55	0.047	1.26
L-R- 3	Large, round	46.4	2,150	100	47.1	2.5	0.1038	3.06
S-R-12	Small, round	59.1	2,450	87	40.24	2.35	0.040	1.235
L-R- 6	Large, round	51.7	2,450	105	37.5	2.25	0.1143	3.69

1. Volume of stationary mill: clover-leaf casing, 8.15 gal; small, round casing, 7.7 gal; large, round casing, 15.5 gal.

the casing should be as small as possible. The ineffectiveness of short blades in a large casing is caused by the fact that, in spite of high speeds and resulting high stream velocities, the turbulent zone is concentrated near the center of the casing, and this localized turbulent zone is not desirable for mass transfer in heterogeneous systems (Brown, et al. 3, p. 503).

Effect of Mill Speed

Power consumptions, fractions ground per pass, and starch production rates obtained using the small, round casing, the A blades, and 0° blade pitch, are plotted versus feed rate in Fig. 2 through Fig. 5 at various mill speeds. Since the mill temperature was dependent on the room temperature and the amount of water used, and since these variables could not be completely controlled, an accurate correlation of the mill temperature with mill speed was impossible. However, it appeared that the mill temperatures at 2300 rpm were higher than at 1850 rpm by about 4° F. The temperature difference between 2450 rpm and 2300 rpm was obscure.

Figure 2 shows that the power consumption in KW increased as the mill speed was increased. Power consumption in milling at 2300 rpm was higher than that of 1850 rpm by 0.34 KW. Thus, an increase of 100 rpm in mill speed would increase the power consumption about 0.08 KW. The energy consumption in KWH per pound of starch versus the feed rate are plotted in Fig. 3. A similar tendency for the energy consumption to increase with the mill speed is evident.

Figure 4 shows the effect of feed rate and mill speed on the fraction ground per pass. The curves indicate the mill was more effective at 2300 than at either 2400 rpm or 1800 rpm. The data were not considered sufficient to make this apparent optimum exact. It was expected that the higher the speed of the mill, the more effective the milling would be. The phenomenon of

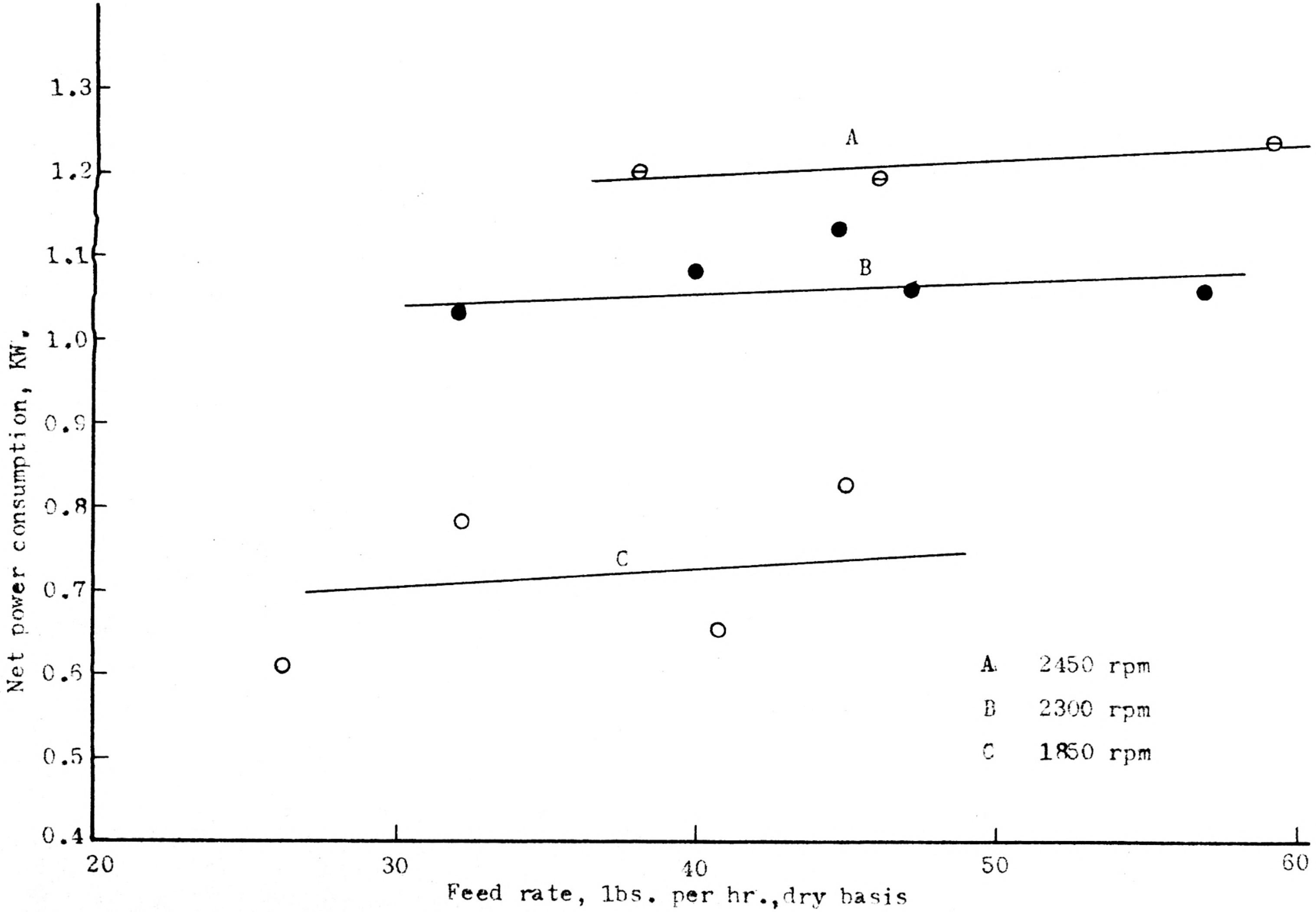


Fig. 2. Effect of feed rate on the net power consumption at various mill speeds for the small round casing.

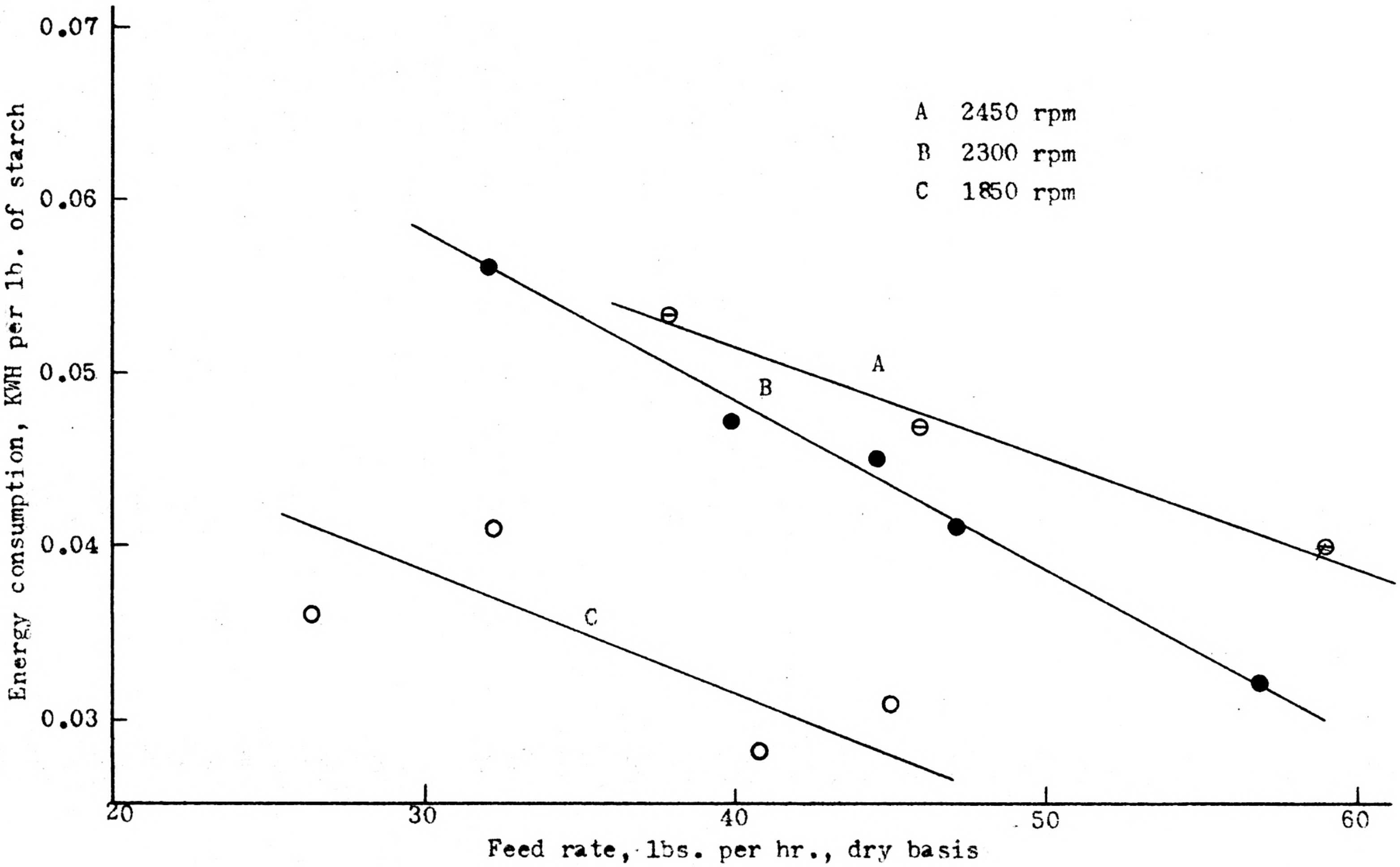


Fig. 3. Effect of feed rate on the net power consumed per lb. of starch produced for various speeds for the small round casing.

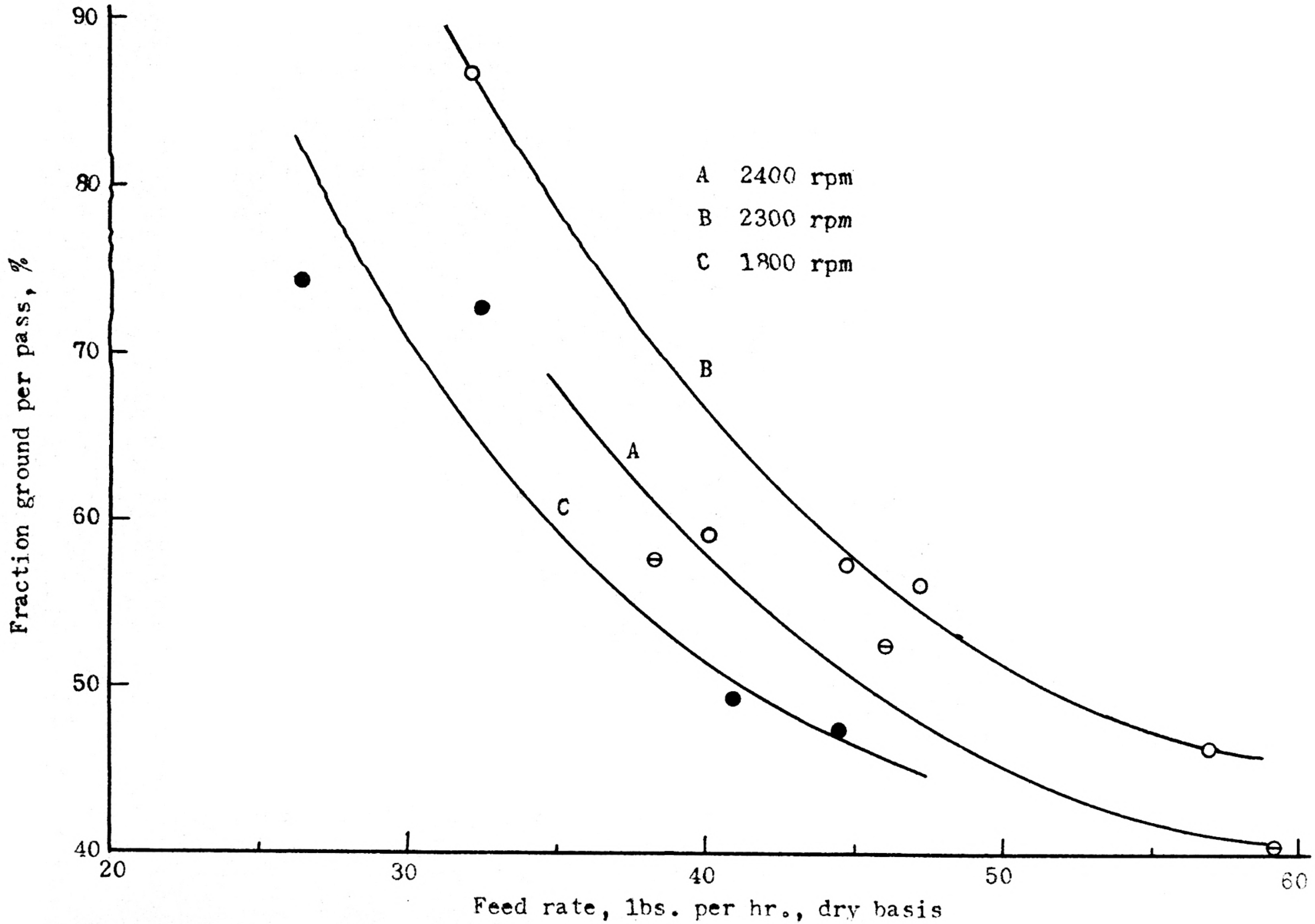


Fig. 4. Effect of feed rate and mill rpm on the grinding efficiency for the small round casing.

an optimum speed may be explained, however, by considering that the decreased hold-up as the speed increased resulted in a shorter residence time and therefore, a lower fraction ground per pass. However, it is not likely that an increase of 100 rpm, from 2300 to 2400, would cause the sharp difference in observed effectiveness.

The effectiveness of grinding in the large, round casing is given in Table 13. It appears that random errors in determining the fraction ground per pass destroyed any trends that might have been present. A similar effect might account for the difference between the 2300 and 2400 rpm curves on Fig. 4.

Table 13. Variation of the fraction ground per pass with mill speed for the large, round casing, equipped with B-blades at zero pitch.

Run No.	rpm	Feed rate	Mill capacity gal	Fraction ground per pass, %
L-R-5	1900	50.4	2.6	43.9
L-R-3	2150	46.4	2.5	47.1
L-R-6	2450	51.7	2.25	37.5
L-R-7	3100	50.0	1.8	47.2

The starch production rates at different feed rates are plotted in Fig. 5 for the runs using the small, round casing. The straight line obtained shows the independence of the effect of mill speed on the production rate. This is another indication that the data were taken after the steady state was reached, since at steady state operation the production rate should be a function of feed rate alone. The change in effectiveness at different mill speeds would change the recycling rate, but the production rate would not be affected. If production rate had varied with the mill speed, it would only indicate that the steady state had not been reached.

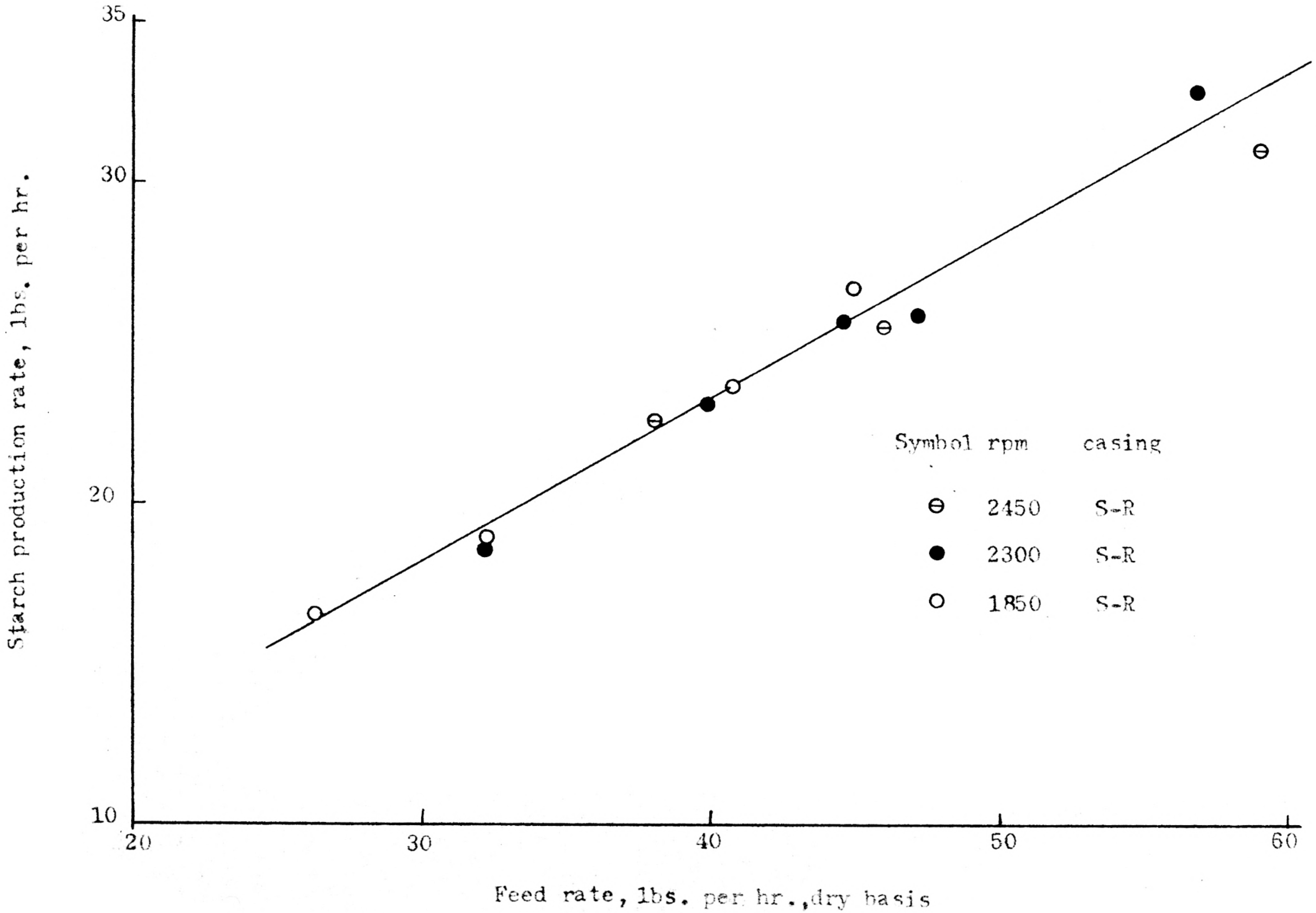


Fig. 5. Effect of feed rate and mill rpm on the starch production rate.

The mill temperature and power consumption in the large, round casing increased with mill speed as shown in Fig. 6, in a similar manner to the effect found with the small, round casing.

Effect of Feed Rate

The mill temperature was almost independent of feed rate. The power consumption in KW increased slightly as the feed rate was increased, as shown in Fig. 2, while the energy consumption in KWH/lb starch produced decreased remarkably as feed rate was increased, as shown in Fig. 3. These facts indicate that the higher feed rates had a lower energy cost per lb of starch. The most economical feed rate, however, would depend upon the amount of partly-ground material to be recycled, since, as is shown in Fig. 5, the fraction ground per pass decreased when the feed rate was increased. This implies that the higher the feed rate, the higher the recycle rate. It was expected that the production rate would increase with increasing feed rate, and Fig. 5 shows this to be true.

Effect of Blade Pitch

The mill temperature and the fraction ground per pass obtained by using the clover-leaf casing and the small, round casing were plotted against blade pitch in Fig. 7. It is evident that the temperature increased with increase of blade pitch while the effectiveness of grinding decreased. The power consumption in KW were also plotted against blade pitch in Fig. 8, which shows the increase of power consumption when the blade pitch was increased. The increase was much more rapid when the pitch was between 45 and 90 degrees. The two figures indicate that much of the energy was consumed as heat rather than for grinding.

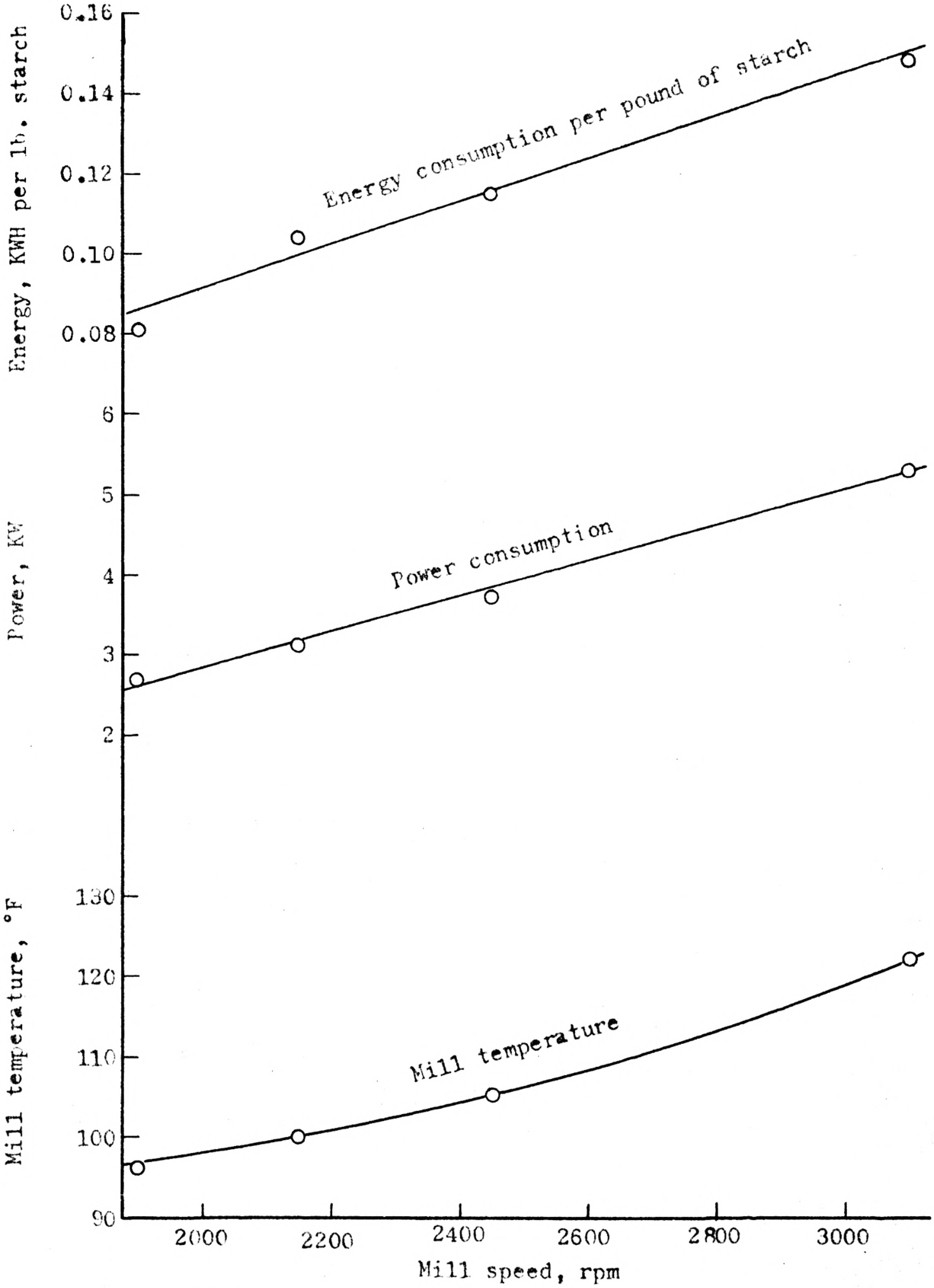


Fig.6. Effect of mill speed on the mill temperature and power consumption for the large, round casing with B blades at zero degree pitch.

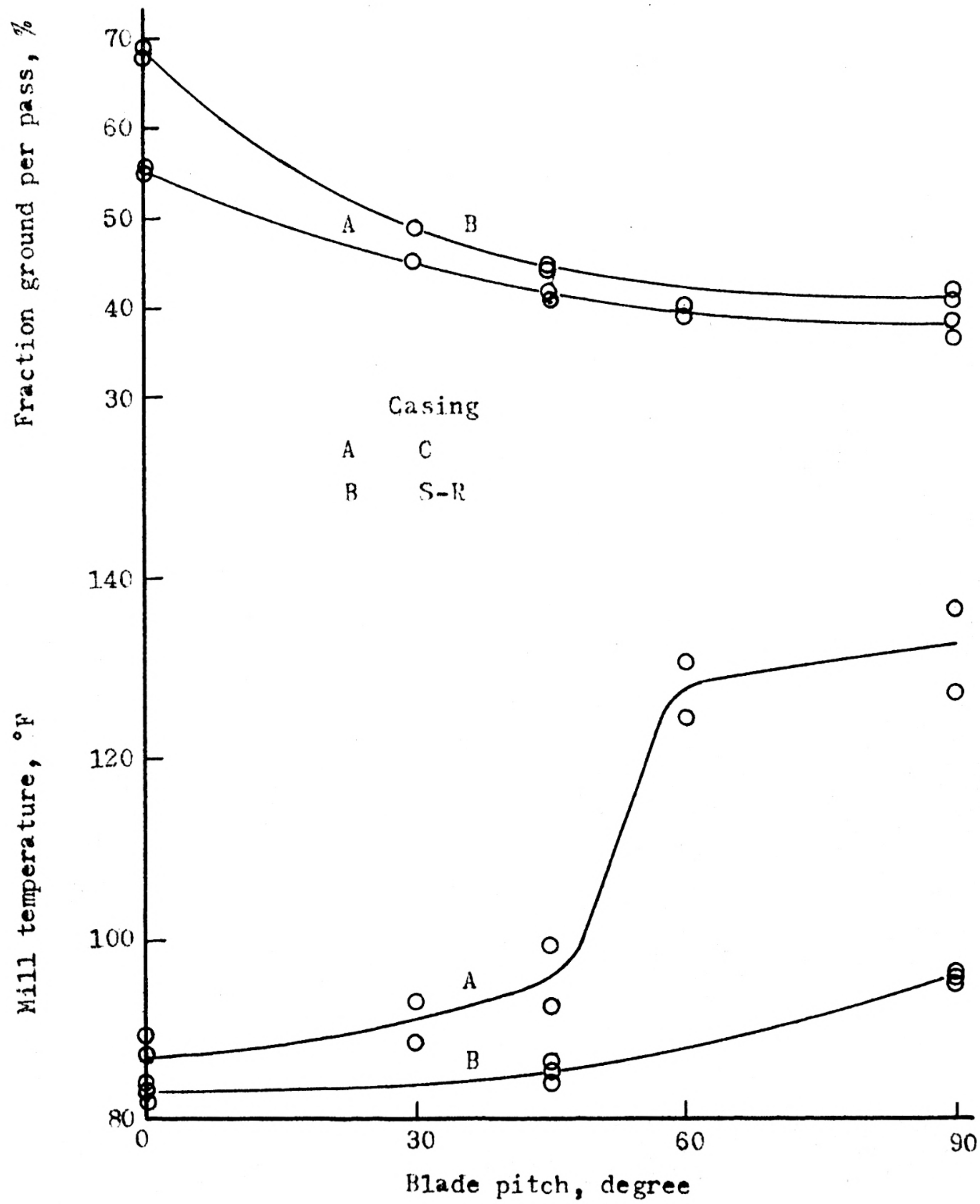


Fig. 7. Effect of blade pitch on the mill temperature and grinding efficiency.

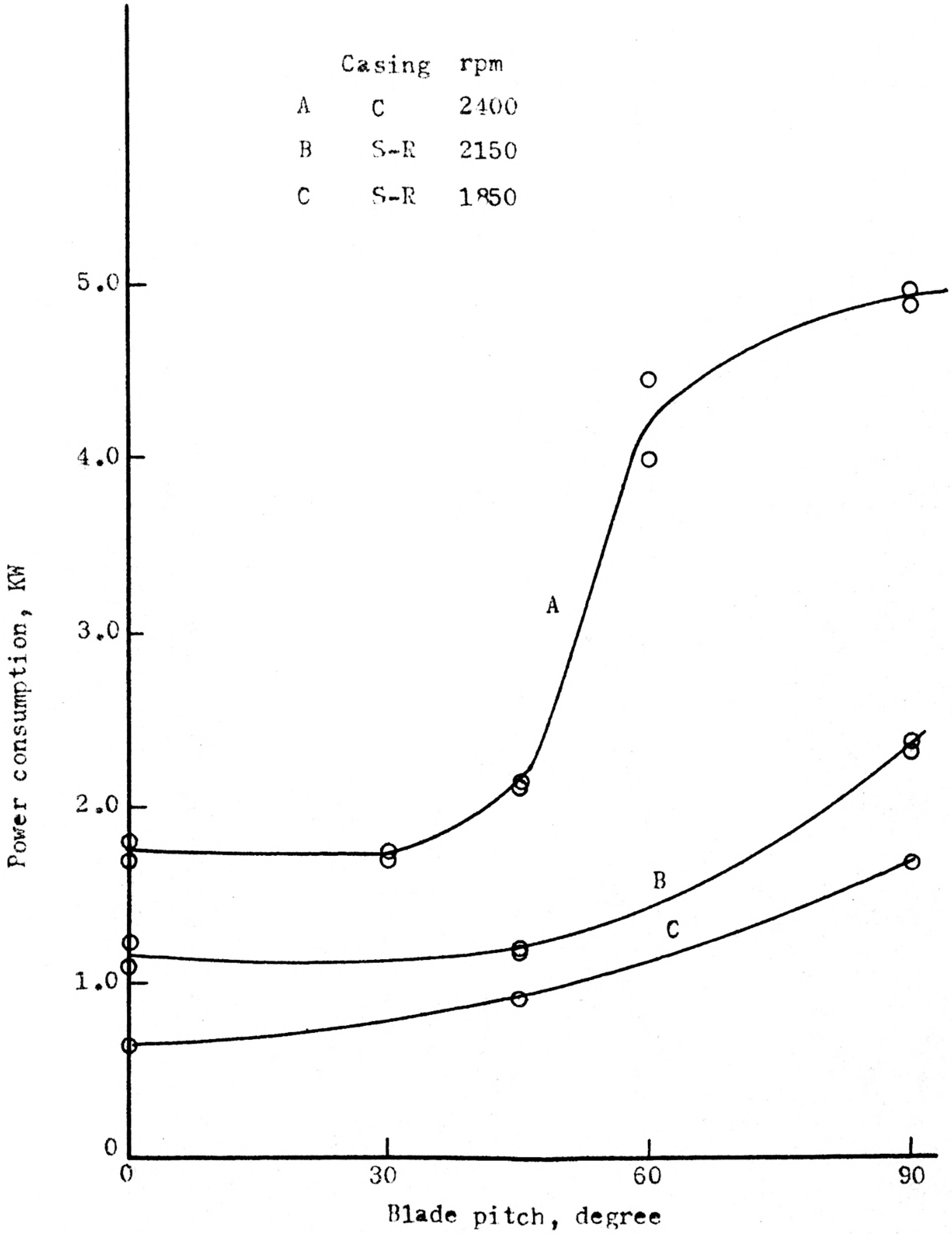


Fig. 8. Effect of blade pitch on the power consumption.

The mill hold-up decreased appreciably when the blade pitch was increased as shown in Table 14.

Table 14. Hold-up in the clover-leaf casing at 2400 rpm for various blade pitches.

Run No.	Blade pitch degrees	Mill hold-up gal
1 & 2	0	4.6
3 & 4	30	2.4
5 & 6	45	1.95
7 & 8	60	1.85
10 & 11	90	1.8

The actual mill speed decreased up to 200 rpm when the blades were pitched at between 60° and 90°, due to the greater belt slippage as a result of the higher resistance to the blades.

Effect of Variations in the Screening Operation on the Recovery of Starch

The material loss in steeping was determined to be 4.4 per cent of the grits charged on the dry basis. In addition, starch was lost in the gluten, in the bran, and, to some extent, through leakage in the bran filter cloth. The loss in the gluten could not be overcome, but the loss in the bran was decreased by pumping the bran from the debranner to an auxiliary 200-mesh screen where it was washed with a spray of water. The underflow was combined with the starch milk, while the overflow was sent directly to the dryer. This recovery process was used for runs L-R-7, L-R-8, L-R-9, and L-R-10. From Table 9 it will be seen that a starch yield of 72 per cent, corresponding to a starch recovery of 85 per cent, was obtained for run L-R-7, even at the high feed rate of 57 pounds per hour. The yield and recovery of starch in run L-R-7 were the highest of all runs, and those of run L-R-9 were only a little lower than those of L-R-7. The lower yields and recoveries in runs L-R-8 and L-R-10 were due to the very high feed rates of 108 and 97 pounds per hour, respectively, and the resulting overloading of the coarse screen and the debranner. It was observed that particles finer than 40-mesh passed over the end of the coarse screen and out of the debranner with the bran, from which they could not be recovered by the subsequent operations. This is borne out by the higher starch content of the bran for these two runs. In run L-R-10 a coarse screen of double area was used. As a result, the recovery of starch was somewhat higher than for run L-R-8. A larger settling area for the debranner probably would further reduce the loss of starch with the bran.

The screen area used in the process must be balanced with the capacity of the mill in order to obtain maximum recoveries of starch. Unless sufficiently large screens were used, high yields and recoveries of starch could not be obtained, no matter how effective the mill was. The screen capacity, therefore, is a controlling factor in the grinding process. The effectiveness of the mill determines the recycling rate and accordingly, the time required to reach the steady state, and the power consumption. Starch recovery is primarily determined by the screening operations. The data in Tables 3 through 5 bear out this statement. A single, coarse screen and a single, fine screen were used for runs C-1 through C-11, and a single, coarse screen and a double-area, fine screen were used for all S-R runs and L-R-1 through L-R-9. Both the yield and the recovery were lower in runs C-1 through C-11, despite the lower feed rates used. Larger screens with more efficient washing on the screens might increase the starch recovery even more.

Protein Content of the Starch

The protein content of starch is an important factor in controlling its properties. The protein contents of the starch obtained in this work, except for a few cases, were well within the specification for corn starch which is 0.5 per cent protein.

The tabling rate and the rate and time of washing the starch on the tables are the most important factors affecting the protein content of the starch. Other factors include the type of grinding operation used, the steeping process, and the concentration of the starch milk pumped to the tables. The latter factors may account for the fact that the protein content of the starch obtained in this work was somewhat less than that obtained by Chai, even though the tabling and washing rates were the same.

Long Runs

During the first of the six long runs, the fine screen broke. It was repaired by soldering, but its effective area was decreased appreciably. This screen was used for the long runs Waxy 1, Waxy 2, Waxy 3, and Non-waxy 1, and the yield and recovery of starch were both very low. The energy consumption per pound of starch was almost twice that of runs such as C-1 and C-2, which had the same processing conditions. When the repaired screen was replaced by a new one for runs Non-waxy 2 and Non-waxy 3, the starch recovery and yield were about normal. The importance of screen capacity is, therefore, very great. When the fine screen was too small in area, part of the starch ran off over the end of the screen and was returned to the mill with the fine recycle. This, in turn, overloaded the coarse screen so that some ground material passed over the coarse screen into the debranner, and was collected with the bran. Thus, large amounts of starch were lost in the bran. Once an overload on the fine screen occurred, a "snow ball effect" followed with resulting starch loss. From Table 11 it is apparent that the bran in the first four long runs contained a higher fraction of the starch than in any of the other runs.

In Table 11 it will be noticed also that the per cent yields of all products for Waxy 1 and Waxy 2 exceeded 100 per cent. This probably was caused by poor sampling techniques.

CONCLUSIONS

The casing constructed from 8-inch standard pipe was the most effective of the three casings studied. The energy consumptions for this casing were the lowest of the three and ranged from 0.031 to 0.053 KWH per pound of starch produced, depending on the feed rate used. The power consumptions for this casing were about half of those for the mill constructed from 12-inch standard pipe, and only one-third of those for the clover-leaf type casing, when operating under similar processing conditions.

The effect of increasing mill speed on the effectiveness of milling could not be completely described from the data taken. However, the mill temperature and the power consumption increased with increasing mill speed. Milling speeds of 2100 to 2400 rpm were satisfactory.

Increased pitch of the blades increased the power consumption and mill temperature markedly, while decreasing the effectiveness of milling. Flat blades with zero degree pitch were found to be most effective, and to give the lowest rise in mill temperature and the lowest power consumption.

The regular arrangement of the blades, i.e., nine pairs at positions 1 through 9, was the most effective of several arrangements studied. The smaller the clearance between the blades and the casing, the higher the effectiveness of grinding.

The screen capacity and debranner size were found to be critical in obtaining high yields and high starch recoveries.

An additional washing of the bran on a screen greatly reduced the loss of starch in the bran fraction. When such a step was added, a starch recovery of 85 per cent of the starch fed was obtained.

The production rate of starch was directly proportional to the feed rate and independent of mill speed over the range studied. An increase in feed rate reduced the energy consumption per pound of starch, while the mill temperature was independent of the feed rate, but varied with mill speed.

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VARIABLES IN THE DESIGN OF A HYDRAULIC MILL FOR THE PRODUCTION OF STARCH FROM SORGHUM GRITS

by

YAO-TONG HSIEH

B. S., National Taiwan University, China, 1950

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The so-called "hydraulic milling" utilizes the principle of physical disruption in the presence of water to remove the starch from the grit structure. This thesis is a systematic investigation of the effect of several variables in the design of a hydraulic mill in the production of starch from sorghum grits.

Three different sizes and shapes of mill casings were used. The first was a clover-leaf shape, the second was a small, round casing made of 8-inch standard pipe, and the third was a large casing made of 12-inch standard pipe; two different size blades were used. One was 2 13/16 inches by 1 inch by 1/8 inch, and the other was 4 15/16 inches by 1 inch by 1/8 inch. Different pitches and arrangements of blades were used at various shaft speeds ranging from 1800 to 3100 rpm and at various feeding rates, ranging from 20 to 107 pounds per hour on dry grits.

The sorghum grits were first steeped in hot water at 125 ± 5° F. for one hour with plain water. The steeped grits were continuously fed into the hydraulic mill through a V-shaped feed hopper for grinding. The ground grits were separated by two screens, one of 40-mesh and the other of 200-mesh. Fine particles which passed through a 200-mesh screen were stored as starch milk and subsequently pumped to four starch tables where the gluten was separated, and the final starch product was collected on the tables. The particles coarser than 40-mesh ran into a debranner where bran was separated by floatation, and the partially-ground material was recycled by a flight conveyer for regrinding. The fraction which overflowed from the 200-mesh screen was recycled to the mill also.

In addition to 42 runs of relatively short duration, six runs of periods of several hours were carried out using two varieties of grits, waxy and non-waxy.

The results showed that the small casing constructed from 8-inch standard pipe was the most effective in grinding and its energy consumption, which was the lowest of the three, ranged from 0.031 to 0.053 KWH per pound of starch produced. The energy consumed per pound of starch for this casing was about half of that for the mill constructed from 12-inch standard pipe and only one-third of that for the clover-leaf type casing when similar processing conditions were compared.

Milling speeds of 2100 to 2400 rpm were satisfactory. The mill temperature and the power consumption increased with increasing mill speed, while the grinding effectiveness was not improved by increasing mill speed.

Flat blades with zero degree pitch were found to be most effective and gave the lowest rise in mill temperature and the lowest energy consumption.

Small clearances between the blades and the casing are desirable for highly effective grinding.

An increase in feed rate reduced the energy consumption per pound of starch, while the mill temperature was independent of the feed rate.

The capacity of the screens and the debranner was an important variable in obtaining high starch recovery. An additional washing screen for the bran greatly reduced the loss of starch in the bran fraction. A starch recovery of 85 per cent of the starch fed was the maximum for all runs.