A STUDY OF THE THRESHING OF WHEAT BY CENTRIFUGAL FORCE

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Benson J. Lamp, Jr.

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This is to certify that the

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Wesley F. Buchele
Major professor

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A STUDY OF THE THRESHING OF WHEAT

BY CENTRIFUGAL FORCE

By

Benson J. Lamp, Jr.

AN ABSTRACT

Submitted to the College of Agriculture,

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Wheat (five varieties), rye, corn and soybeans were completely threshed by the application of centrifugal force. Wheat was threshed at all mature moisture conditions. Only exploratory research was accomplished with the other grains.

An experimental batch-type centrifugal thresher which was capable of holding 25 to 50 head samples was designed. This machine developed peripheral speeds up to 250 miles per hour which was sufficient for complete threshing. The experimental technique and equipment permitted the determination of the total weight of grain threshed at any selected speed. These data were used to establish threshing forces required to achieve various percentages of threshing.

Centrifugally threshed grain could be readily cleaned by air, since only chaff remained with the grain. When threshed without air resistance, the grain did not require cleaning, since the chaff remained attached to the straw.

Quality of centrifugally threshed wheat was superior to hand threshed wheat as measured by germination tests. At higher peripheral speeds, high moisture grain required additional rubber matting to prevent kernel damage during the dissipation of kernel kinetic energy at the thresher housing.

Performance comparisons were obtained between centrifugal and conventional threshing. These comparisons established cylinder adjustments equivalent to the centrifugal force required to achieve various percentages of threshing. Conventionally threshed grain had twice as much chaff to be removed as centrifugally threshed grain. The last to be threshed kernels, when centrifugally threshed, weighed up to 28 percent less per kernel than

the average kernel weight. There were no differences in kernel weights of combined grain separated at any of eight zones under the cylinder and rack or of unthreshed grain. Germination of centrifugally threshed grain was superior to combined grain.

Theoretical threshing equations were developed for impulsive and non-impulsive acceleration. Values of the threshing force for use with the formulas were established. Other factors occurring in the equations need to be determined.

Concepts and equations of motion were derived for possible use in the development of continuous-flow centrifugal threshers.

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Outline of Studies:

Major Subject: Agricultural Engineering
Minor Subjects: Mechanical Engineering
Applied Mechanics

Biographical Items:

Born: October 7, 1925, Cardington, Ohio.

Undergraduate Studies: Ohio State University, 1943; continued 1946-1949.

Graduate Studies: Ohio State University, 1950-1952; continued 1954-1958; Michigan State University, 1958-1959.

Experience: Student Assistant, Ohio State University, 1949; Junior Engineer, Soil Conservation Service, 1949; Instructor, Ohio State University, 1949-1952; Assistant Professor, Ohio State University, 1952-1959; Assistant Professor, Ohio Agricultural Experiment Station, 1956-1959; Research Assistant, Michigan State University, 1958-1959; Associate Professor, Ohio State University and Ohio Agricultural Experiment Station, 1959; Agricultural Engineer and Consultant, several companies from 1950 to present.

Member of Tau Beta Pi, Gamma Sigma Delta, Sigma Xi, American Society of Agricultural Engineers, American Society of Engineering Education, Professional Engineer.

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INTRODUCTION

Threshing, the process of freeing the seed from its attachment and covering (husk), is a necessary process in harvesting of practically all seed, feed and food crops. This process has been called the most important of all grain harvesting processes because it influences the functioning of the subsequent separating and cleaning processes.

The history of threshing dates back to the beginning of grain crops. Numerous references to grain and threshing are found in the Bible. It would be natural to expect, therefore, a rather complete understanding of the basic nature of threshing. Such is not the case, however, although the present state of the art of threshing and threshing design has been developed to the point where it is generally conceded to be satisfactory.

Existing machines, however, are sensitive to many crop and operational variables. They are large and bulky, often causing traction and storage problems. With their principles of operation, they are not adaptable to hillside operation. Particularly the present state of design is questioned when one realizes the harvesting machine weighs 300 to 400 times the sample being threshed at any time.

As research directed toward increasing basic knowledge about the threshing process unfolds, new threshing methods may evolve with design, operational and functional advantages that completely obsolete conventional threshing techniques.

Objective

The objective of this research was to contribute to the fundamental knowledge of the basic nature and requirements of the threshing process, with special emphasis upon the development of new concepts of threshing.

REVIEW OF LITERATURE

Evolution of the Threshing Processes

Conjecture would lead one to state that man first threshed grain rubbing his hands together on individual heads. This method, while very efficient and damage free, was very slow and laborious. Means to increase the rate of threshing and reduce the labor requirement were obviously sought (Church 1939, 1947).

One means for increasing the threshing output per unit of labor was by bunching the grain and striking the bunch (or bundle) on a stationary object numerous times. Another approach was to lay the unthreshed material on a solid, stationary object over which animals trod until the beating and rubbing of the animal hooves threshed the grain. One of these methods was used by Gideon of Biblical account. Indeed in certain relatively non-mechanized countries of the world the latter method is still in use today (Nag 1957).

The previous methods did not separate the straw or clean the chaff from the grain. The processes of separating and cleaning required time equal to that required for threshing. Man next wondered how these processes could be made easier. The concept of unthreshed grain moving into a stationary threshing device and the threshed material passing on into elements achieving separation and cleaning was efficiently developed in the historical stationary separator-thresher so common in America the first third of the 20th century.

But still much time and effort was required for gathering the unthreshed grain and moving it to the stationary thresher. Reduction of time and effort was made possible by the conventional and contemporary combine-harvesters.

This brief history is given only to emphasize the evolutionary nature of threshing development. From it, however, one conceives that the basic principles of threshing the grain have not changed during the evolution to date (Church, 1939). The evolution essentially has seen only a change in the method of handling the unthreshed and threshed materials--from a stationary batch during the early stages of development to a continuous flow during later development. The threshing elements have been common--a moving object forcing the material to be threshed against a stationary object. The means of achieving the relative motion between the two threshing members has been obviously different. Changes in power source, configuration and materials of construction of the threshing members and operating speeds have been but a few of the evolutionary developments.

History shows that the vacuum engine development arrested the development of the internal combustion engine (Lichty, 1939). Perhaps the contemporary moving-stationary threshing method has likewise slowed, hindered or perhaps even prevented the development of improved threshing processes.

Results of Research with Contemporary, Cylinder-Concave Threshers

Many research results are to be found in the literature relative to the performance of the contemporary threshing method. Little is available, however, concerning design variables.

To summarize these research findings, it appears desirable to suggest criteria for good threshing and then to report findings in light of these criteria. The following criteria are suggested for acceptable threshing:

(1) Complete threshing

(2) Maintenance of grain quality

(3) Enhancement of the subsequent processes of separation and cleaning

(4) Minimum power requirement with ample capacity

(5) Functional under a wide variety of field and crop conditions

Completeness of threshing

McCuen (1943) in a study of 58 farmer-operated machines stated "practically all operators were very careful about getting all the kernels out of the heads." The cylinder losses averaged 10 to 14 percent of total machine losses. All machines analyzed were operating in wheat or oats.

Johnson (1959) and Mitchell (1955) have shown that completeness of threshing is possible at moistures well above 20 percent kernel moisture in wheat. Arnold (1958 and 1959) did similar work in barley and oats with the same result. Likewise corn and soybeans have been completely threshed at moistures above 40 and 20 percent respectively (Lamp, 1956, 1957).

Small legume and grass seeds, however, are much more difficult to thresh. Even though the cylinder be adjusted to give maximum aggressiveness, threshing losses may be 20 to 45 percent (Bainer, 1955). Booker (1952) had losses up to 50 percent in clover. Reports have been received of farmers who run the clover straw through the combine the second time, apparently obtaining sufficient seed to make the operation profitable. It is particularly important to have low seed moistures when harvesting the small seeds, if completeness of threshing is to be achieved.

Bainer (1955) states "Under certain conditions the type of cylinder may have some effect, although there is no conclusive evidence that any one type is consistently superior to the others." Johnson (1953) found that for the same cylinder speed and concave clearance, the rasp cylinder had somewhat higher threshing loss than a flail cylinder. His work was with four wheat varieties.

From the literature and farmer experience one would conclude that the present designs for threshing are able to achieve complete threshing when properly adjusted for most crops. The small seeded legumes offer the greatest threshing challenge.

Maintenance of grain quality

Losses in grain quality resulting from the threshing process have been measured by test weight, percent visible damage, percent loss in germination, percent loss in germination energy, and percent loss in dry matter by different investigators. The relative importance of these measures depends upon the use of the grain. Germination tests are important when the ultimate use is as seed, while percent loss in dry matter is the most important measure of feed grain. All of the measures frequently have importance for market grain.

The extent of quality loss depends upon the grain physical characteristics, the kernel moisture content at threshing and the severity of the threshing effort. Since most operators adjust the threshing effort to levels resulting in complete threshing and the grain physical characteristics are fixed for any crop and variety, the kernel moisture content becomes the only independent variable influencing grain quality losses.

Berg (1949) investigated damages from threshing in winter and spring wheat, rye, barley and oats at moistures up to 38 percent. Damaged kernels were found in all immediately threshed samples with kernel moisture above 20 percent. The damage was found to be independent of whether the moisture was from unripeness or rainy weather. Grain cut at moisture above 20 percent and permitted to dry prior to threshing showed no decrease in germinative and shooting ability. The decrease in germinative and shooting ability appeared to depend upon kernel damage resulting from threshing.

Johnson (1959) reported losses in test weight of soft winter wheat caused by both delay in harvest and harvesting at high kernel moistures. The test weight reduction was 0.23 pound per bushel per day after the grain had ripened to 27 percent. Germination reduction ranges and visual kernel damage were reported at various moistures. Attempts were made to minimize damages by selecting favorable combinations of cylinder and concave coverings. Rubber angle bar cylinders, steel concave bars, and grated and solid concaves were evaluated. No combination significantly reduced kernel damage. He concludes "it would appear from the standpoint of resulting grain condition, wheat threshing must be limited to grain moistures below 20 percent."

Delong (1942) conducted field studies in barley. He varied the threshing effort of spike toothed, rasp, and angled bar cylinders. The grain moisture varied in the 12 to 15 percent range. The rasp and angle bar cylinders gave greater visual damage than the spike tooth design, with the rasp having slightly greater damage than the angle bar.

British research showing the effect of threshing effort and crop moisture contents upon the germination ability of oats, barley and wheat was reported by Arnold (1958, 1959) and Mitchell (1955). They concluded that a rapid deterioration of germination occurred when kernel moisture was above 19 percent and that the overall effect of the drum speed was greater than the concave setting.

Large seeds, particularly those of dicotyledonous plants, are extremely susceptible to damage as reported by Bainer (1955). His work suggests that complete threshing will cause excessive damage with spike tooth cylinders (16.4 percent moisture). The amount of damage for a given threshing effort increases rapidly as the moisture content of the beans is reduced. He indicates that special bean threshers have been built with two spike-tooth cylinders in series in order to reduce damage. The first cylinder was operated at a lower speed than the second.

The Russian, Kolganov (1958), attempted to reduce grain damages and has reported the research results of a two cylinder machine threshing wheat. The first stage cylinder had a peripheral speed of 7 to 20 meters per second (1400 to 4000 feet per minute) while the second stage cylinder ran at 30 meters per second (6000 feet per minute). The kernel weight obtained from the first stage was greater than that of the second in all tests. Also, mechanical damage was 2-1/2 times less in the first stage.

"Research institites should pay the most serious attention to the question of mechanical damage to seed and its effect on germination", wrote another Russian, Usenko (1952). The germination on the collective farms was as follows: 16 percent of the total quantity had germination from 95-100 percent; 34.1 percent, 90-94 percent; 36.5 percent, 85-89 percent; and 13.4 percent, less than 85 percent. The principal cause for the decreased viability was mechanical damage during harvesting and threshing. The growth vigor of undamaged seed was much better than of mechanically damaged seed. Russian data show the yield from mechanically damaged seed is appreciably reduced.

Grass and small hard seeds like crimson clover and the lespedezas were generally not seriously damaged by the necessary aggressive threshing effort required, reported Park (1956). He found that while hand threshed clover had often 100 percent hard seed, the percent was seldom over 25 percent for combined threshed seed. Bainer reported 10 to 20 percent germination damage when harvesting alfalfa seed with a 5.2 to 6.8 percent moisture. Park did not indicate seed moistures in his report, although it surely was much greater than that of Bainer's work.

The removing of kernels of corn from the cob (a process commonly called shelling but which can properly be called threshing) frequently results in damage as reported by Burroughs (1953), Pickard (1955), Morrison (1955), Barkstrom (1955), and Lamp (1957). Visual damage increased with cylinder speed particularly over 2500 feet per minute. Damage was relatively independent of concave clearance. The extent to which the visual damage results in a dry matter loss has not been adequately researched, although some preliminary work suggests 5 to 10 percent loss (Miles, 1956 and Lamp, 1958).

Heitshu (1928) reported the germination of soybeans collected from farmer operated combines varied from 56 to 98 percent. In an effort to reduce harvesting losses, Lamp (1956) combined soybeans at 18 percent moisture. Although visual damage was minor, germination damage was very severe. He concluded that for oil use, the germination loss would not be important.

In summary, careful attention must be given during threshing to prevent grain damage. The moisture limit seems to be 19 percent for many of the crops. The practical limit of threshing for feed corn depends upon the extent to which kernel damage is a dry matter loss.

<u>Effect of threshing upon separation and cleaning</u>

Ideal threshing would integrally achieve separation of the grain from the straw and chaff. Threshing that does not perform partial separation places severe demands upon the rack. Likewise, threshing that breaks the straw badly and strips all the glumes from the head is undesirable because it increases the cleaning load.

McCuen (1932) recorded 60 to 70 percent separation at the cylinder in stationary threshing separators. This percentage range was obtained for several different concave arrangements. Johnson (1953) conducted extensive laboratory tests with four wheat varieties and two cylinder types, determining the amount of separation at the cylinder. Holding constant cylinder speeds, the percent of separation did not change significantly as the concave clearance was decreased, although the weight of chaff and short straw increased as the clearance was reduced. He found average percentages of separation for the rasp cylinder of 69, 66, 62 and 68 for Vigo, Thorne, Butler and Trumbull varieties respectively. Similar respective data for the flail cylinder were 54, 54, 46 and 51. Moisture ranges were in the range from 12 to 15 percent, and the feeding rate was 35 pounds per foot of cylinder width.

Under California conditions, Goss (1958) found that the percent separation of barley at the cylinder was 85, 71 and 57 for feed rates of 80, 120 and 160 pounds per minute respectively. These data are an average of concave clearance and cylinder speed of 5700. The combine was equipped with a 30-inch in length rasp bar cylinder and the barley moisture was 7 to 9 percent. At a feed rate of 80 pounds per minute, separation was 92, 86 and 78 percent at clearances of 1/4, 1/2 and 3/4 inches respectively. The shoe chaff-load decreased from 20 to 5 percent of total feed rate in going from 1/4 to 3/4 inch clearances. Goss also shows the effect of cylinder speed upon separation. With a clearance of 1/4 inch and feed rate of 120 pounds per minute, 80, 75 and 59 percent of the grain was separated at 5700, 4800 and 3800 feet per minute cylinder speed. The overall range of separation was 40 to 92 percent.

McCuen (1943) showed that increasing the threshing effort by increasing cylinder speeds increased total combining losses. Goss (1958) suggests that increasing the threshing effort reduces total losses, since greater separation is obtaining during the threshing function. Further, Johnson's work (1953) does not agree with that of Goss relative to the effect of cylinder clearance upon separation at the cylinder. Perhaps the crop, machine and operating variables account for the difference.

Under the most favorable condition, Goss (1958) achieved 92 percent separation. If this could be increased another 6 or 7 percent, perhaps the separate separating mechanism of conventional combines could be eliminated. This possibility has challenged Russian and German designers to place 2, 3 and 4 cylinders in series (Segler 1957). See Figure 1. Performance results of these threshing mechanisms are not available.

Power requirements for threshing

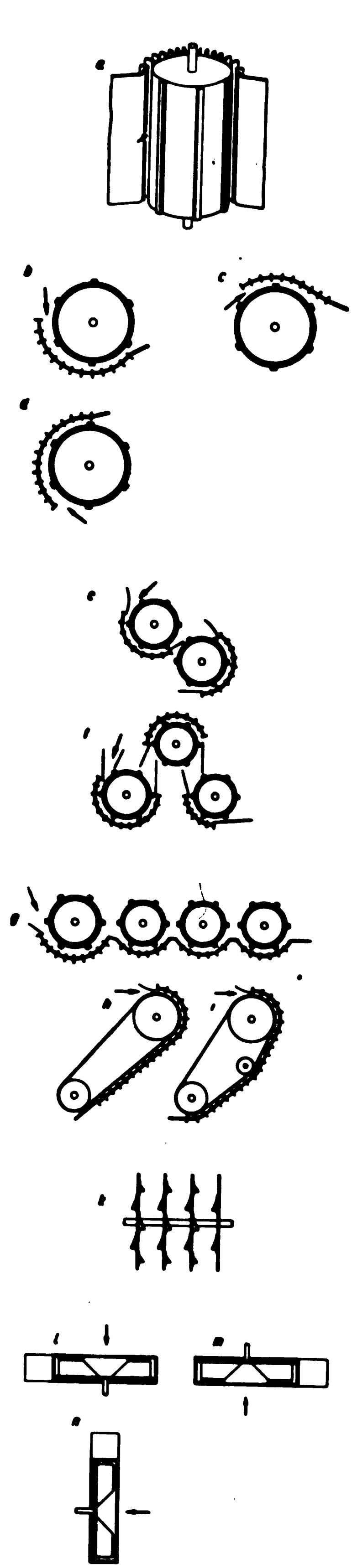
McCuen (1932) determined the effect of rate of feeding upon power requirements of separator cylinders. He found nearly straight line relationships between feed rate and power requirements. The concave arrangement had a noticeable effect upon power. A typical relationship can be expressed by equation 1:

$$P = .05C - 1.6 \qquad (1)$$

in which P = horsepower

C = feed rate in pounds per minute.

Burroughs (1954) gave power requirements of 1.0, 1.8, 2.2 and 3.8 horsepower at feed rates of 32, 44, 52 and 68 pounds per minute respectively. His work was with a 5-foot rasp bar cylinder.



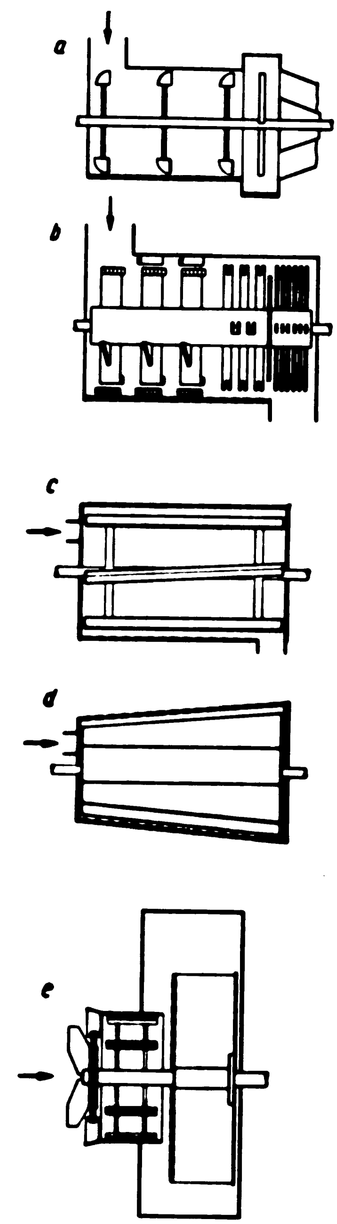


Figure 1. Systems for threshing grains which are in use or have been used experimentally (Segler 1957)

Bigsby (1959) found that solid stemmed wheat required more power for threshing than hollow stemmed. The power equations were

$$P \text{ (horsepower)} = 1.59 + .0439\ C \qquad (2)$$

for solid stemmed wheat and

$$P = 1.35 + .0368\ C \qquad (3)$$

for hollow stemmed wheat. The units for the feed rate C were reported as bushels per hour of grain. Straw-grain ratios approached 1, so that the grain feed rate is approximately equal to the straw feed rate.

Dolling (1955) determined that over a 5-second period the power varied from a minus 2 to 9 horsepower. He reported also a power balance for an empty machine wherein 2.6 horsepower or 20 percent of total power was required for the threshing mechanism.

Results of Research with Experimental Threshers

The Germans have researched considerably with the chop-threshing method. A forage or field harvester chops the straw and grain and blows it into a wagon. The wagon carries the chopped material to a stationary separator.

Harris (1956) reviewed the method, citing certain advantages and disadvantages. From this review and research reports by Segler (1952 and 1955) and Völzki (1954) an indication of the performance efficiency was determined. With cutting lengths of 110, 56 and 22 millimeters (4.3, 2.2, and 0.9 inches respectively) and a peripheral speed of 28.2 meters per second (5600 feet per minute) 80-96, 71-83 and 51-68 percent of rye, oats and wheat were threshed out respectively. This method did not increase the amount of mechanical damage. When the length of cut was over 40 millimeters (1.6 inches), the damage was lower than that of the conventional thresher. The minimum length of cut for cereals was about 22 millimeters (0.9 inches); beans, 55 millimeters (2.2 inches). Most damage was due to cutting. The germination capacity of chop-threshed wheat was 3.5 percent higher than that harvested by conventional methods. Direct harvesting losses were reported somewhat lower than direct combining.

Segler (1953) indicates that the chop-thresh method is limited because straw moisture is too high for immediate storage. Air blowing over the heads at 60 percent relative humidity would have 70-80 percent relative humidity near the grass level. The grain and the straw at the top would have 15 percent moisture, whereas the lower straw might have 35 percent and any green material would have 75 percent moisture.

The chop-threshing method has been used some in the primarily dairy state of Wisconsin. No performance data are available. Clingerman (1956) and Lamp (1956) have used a field harvester at different cutter speeds and knife arrangements to thresh corn, soybeans and wheat. Satisfactory threshing of corn was achieved, although damage was high. Complete threshing of soybeans was achieved, but the minimum crackage was slightly less than 5 percent. In 16.1 percent moisture wheat, 1.9-2.5 and 7.1-8.2 percent losses occurred with 0 and 3 knives respectively. In 13 percent moisture wheat, threshing losses varied in the range 1.7-2.9 percent and was independent of cutter speed. Separation was difficult.

An endless belt threshing mechanism was built and tested by Hamblin (1952). Although built as a cereal plot harvester because of its easy-to-clean design, the author concluded numerous advantages over the conventional cylinder thresher mechanism. Among these were as follows:

(1) Neither concave adjustment nor speed was at all critical.

(2) Will not wrap under conditions causing this trouble in conventional cylinder.

(3) The operator can choose the state in which to leave the straw - either beat up or nearly whole.

(4) The high speed parts run at only 60-65 percent of the speed of conventional cylinders.

(5) Tractor mounted combine feasible.

The latter advantage seemed possible because the conventional rack was completely eliminated and cleaning was done by a separate machine. Four acres of wheat, barley, oats, mustard and linseed were harvested at moisture ranges from 17 to 21 percent. Machine losses varied from 1.8 to 6 percent.

Booker (1952) reported an experimental endless belt thresher for clover harvesting. Two endless belts rotating in opposite direction gave fair feeding and excellent threshing. When the upper belt turned 300 feet per minute backward and the lower belt 500 feet per minute forward, 95 percent of the seed was threshed. The machine tended to roll the straw and clog when higher moisture seed was threshed. Belt life was too short also.

Buchele (1953) developed an experimental thresher for small, hard to thresh seeds. This machine achieved threshing action similar to the belt machines by continuously rubbing the seed against a perforated screen formed into a cone. Belt strips rotating on a shaft held the material against the screen and gave motion to the material. All of this action took place in the perforated rotating cone where the seed was separated as it was threshed from the straw. The cones and the rubber blade impeller although rotating in the same direction, had different peripheral speeds. A device somewhat similar to this was used for separation in Germany also (Segler, 1957).

The Wild Model 50 Harvest Thresher (1950) was of simplified design and sold in England for some time. See Figure 2. The principal unique feature was the method of threshing. The straw was not cut but rather a threshing rotor beat the grain from the head. The rotor consisted of a series of discs mounted on a shaft, each disc carrying radial vanes staggered on adjacent discs. It was claimed that the staggering of the vanes causes the grain to be beaten rapidly from side to side. The rotor also acts as a fan, blowing the grain and chaff into a swirl chamber. The chamber was designed to permit the chaff to be blown out, leaving clean grain and unthreshed heads. Another rotor with blades was located at the bottom of the swirl chamber. This rotor passed through a fixed comb finalizing threshing. The success of this harvester is not known and performance data are not available.

Zink (1958) gave a progress report on the development of "new principles in combining". Threshing was accomplished by feeding the material into a fan. Subsequently, the threshed grain was separated in a rotating cone device similar in concept to that described previously. One of the claims for the machine was its unusual capacity, up to 400 bushels of wheat per hour. Also it was claimed that the new principles could work on the hillside. None have been sold commercially to date (1959).

Emirli (1956) placed individual heads of wheat into a commercial centrifuge and found that complete threshing was possible. The limited work suggested the need for exploration of this method of threshing.

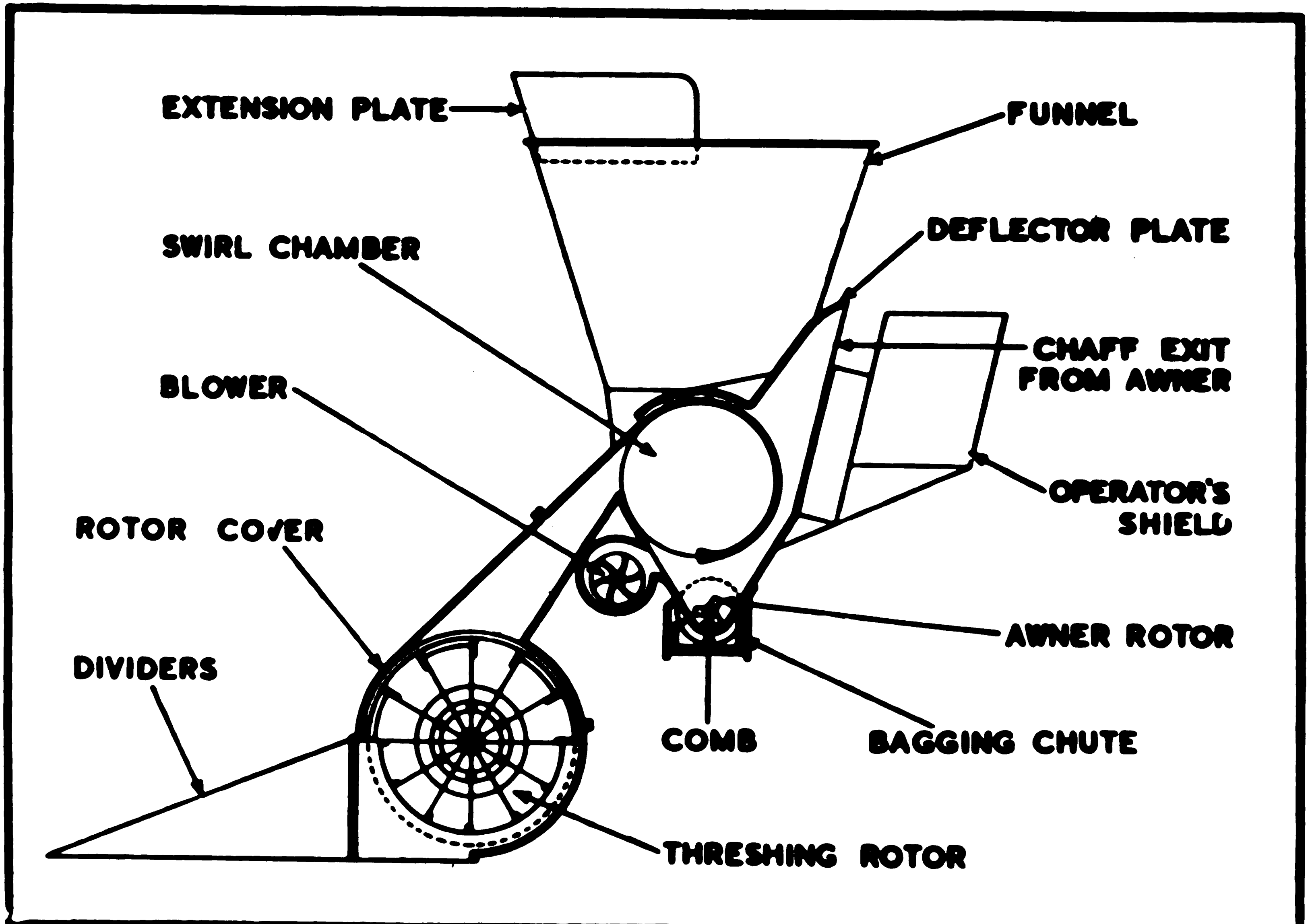


Figure 2. Schematic of the Wilde Harvester, which was commonly used in England for harvesting of small grains

Crop Characteristics Significant to Threshing

Germane to threshing is the time of maturity of the crop. There is usually no reason to harvest the grain crops prior to the maximum dry matter yield. Scott (1957) determined that wheat yields increased regularly until the kernel moisture ranged from 38 to 44 percent. The moisture decreased quite regularly until it reached a point slightly less than 40 percent, after which it decreased very rapidly. After a 4 to 6 day desiccation period, the moisture fluctuated under the influence of the environment. Scott's work was in agreement with that of other researchers.

Miles (1959) found that corn harvested as shelled corn at 28 percent kernel moisture gave the highest dry matter yield. His work reports a lower value than most researchers, but he felt this was partly caused by the small samples used by other investigators.

The Russian Kolganov (1958) reports that the work of separating the kernel from the stem was 60 centimeter grams (0.052 foot pounds) for heavy grains and 120 centimeter grams (0.104 foot pounds) for light grains. Seventy-five percent of large heavy grains were ruptured at an impact speed of 36 meters per second (7100 feet per minute). The cylinder peripheral speed for threshing was determined by equation 4:

$$V = \frac{1}{(1 + E)\ \mathrm{Cos}\,\alpha} \sqrt{\frac{2\,A_k}{m}} \qquad (4)$$

V : peripheral speed of cylinder, centimeters per second

A_k : work of separation in centimeter grams

α : angle between the direction of peg movement and the axis of the grain

E : coefficient of recovery on impact of the grain on the cylinder peg

m : grain mass in grams per second squared per centimeter

Values of m were from 20 to 40 x 10^{-6} grams per second squared per centimeter for wheat. E was taken as 0.2 for 15 percent wheat moisture and 0.1 for 10-12 percent wheat moisture. An average value of Cos α was 0.64.

Zoerb (1959) determined the impact energy for rupture of wheat. In the moisture range from 13 to 20 percent, 15 to 25 inch pounds of energy were required. He reported the modulus of elasticity of the wheat kernel to vary from 63,000 pounds per square inch at 13 percent to 24,000 pounds per square inch at 20 percent.

SPECIFIC OBJECTIVES OF RESEARCH

The literature review presents some challenging possibilities for functional performance of threshing mechanisms. Can a threshing method be developed that integrates the threshing and separation functions and minimizes the cleaning requirements? Can a threshing mechanism be developed that will remove grain without damage as soon as the grain is physically mature? How can the thresher mechanism take advantage of the physical seed variation, perhaps giving seed sizing integrally with threshing? Can the threshing, separation and cleaning functions be independent of the earth's gravity, thereby eliminating the need for special hillside combines? Achievement of any of these possibilities in an economically feasible manner would offer excellent potential benefits to agriculture.

The experimental work in which centrifugal force was used for threshing is the only completely new concept reviewed. Further, if achievable, it could meet several of the challenges stated in the previous paragraph. It would appear worthy of exhaustive research to determine its capabilities.

The review indicated that the literature was practically void of theories concerning threshing. Threshing theories could serve an important function in challenging future researchers and should be developed.

Finally more should be known about conventional threshing, with any new approaches correlated to the conventional methods.

Therefore, the specific objectives of this research were:

(1) Develop theories of threshing

(2) Explore the concept of centrifugal threshing

(3) Correlate the conventional threshing methods with results of

centrifugal threshing.

The research was confined principally to wheat harvesting, in order that the research could be intensified.

THEORY OF THRESHING

Definition and Force Required

The process of detaching and freeing the seed from its natural binder is defined as threshing. This process requires the breaking of the seed attachment and overcoming the resistance of adjacent coverings until the seed is free.

Figure 3 shows side and edge views of three heads of Genesee variety wheat. Figure 4 presents the names of the various parts of a wheat head.

Threshing in the case of wheat is breaking the rachilla and freeing the kernel of glume and lemma frictional resistance. If either the pedicel or the rachis breaks with chaff-like material attached to the kernel, threshing is not complete.

The force required to break the rachilla and overcome the glume and lemma friction is defined as the threshing force F and can be expressed in equation form as follows:

$$F = C A \sigma \tag{5}$$

in which F is threshing force in pounds

C is a constant relating to method of applying the force

A is the cross sectional area of the rachilla and

σ is the stress required to break the rachilla in pounds per square inch.

The constant C considers also the direction of applying the threshing force as shown in Figure 5. Figure 5-A shows the threshing force exerted so that the rachilla is in direct tension. There is no separation of the glumes with this loading until the kernel begins motion relative to the pedicel. The threshing force will be maximum with this manner of loading.

Side View

Edge View

Figure 3. Side and edge view of three heads of Genesee wheat

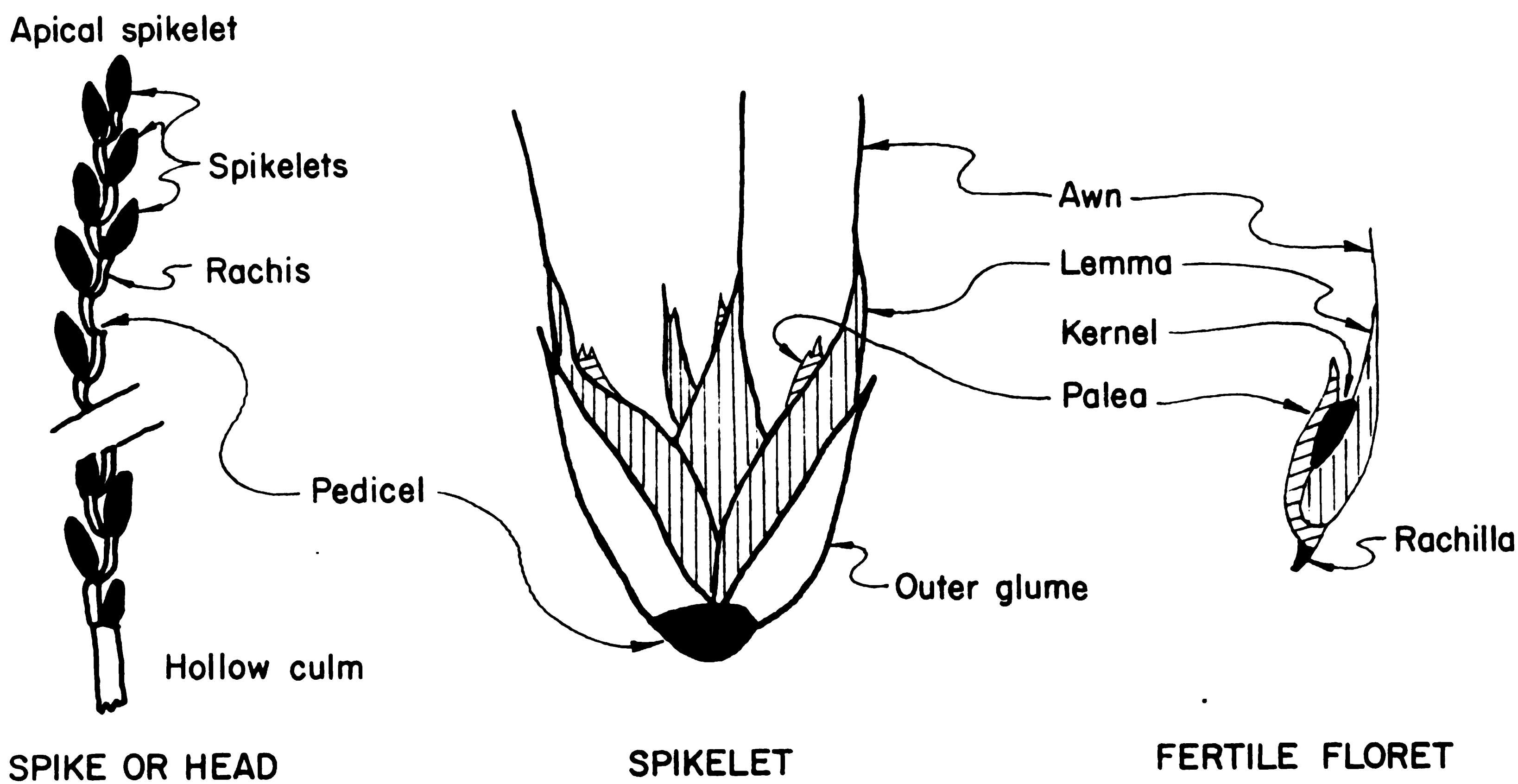


Figure 4. Schematic diagram of a head, spikelet and fertile floret of wheat, showing the names of parts

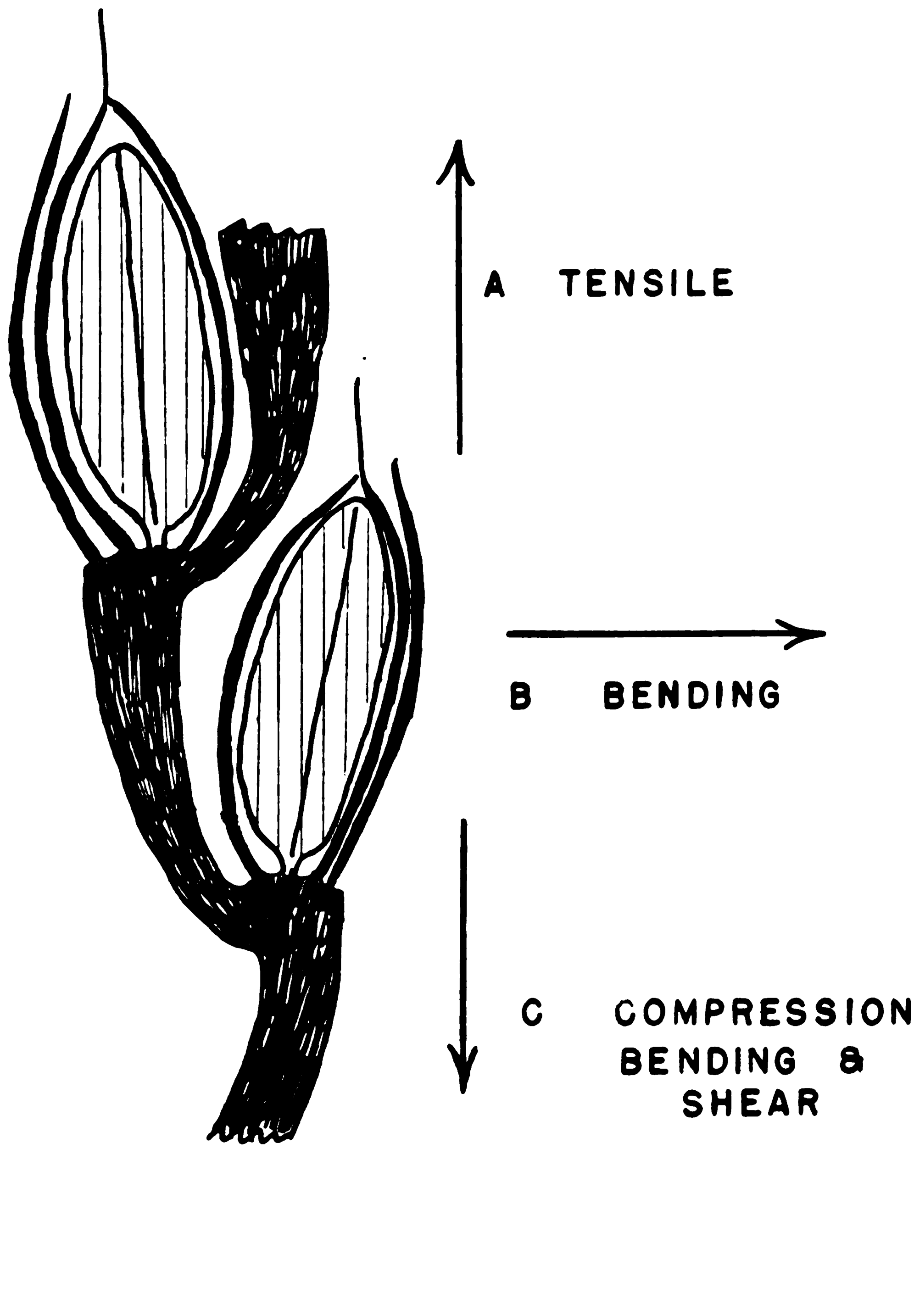


Figure 5. Schematic diagram of kernel, chaff and attachment, showing direction of force application

The force bends the kernel about the point of attachment when applied in the direction shown in Figure 5-B. It separates the glumes and causes the rachilla to be stressed through bending. The condition of loading shown in Figure 5-C would shear the rachilla and should require the minimum threshing force. C values for the loading of Figure 5-A shall arbitrarily be assigned a numerical value of 1. Values for the other positions will need to be determined experimentally.

Determining finite values for the area of the rachilla would be a time consuming and difficult task. It would vary with seed physical characteristics, not only among varieties but also within a given variety. Even within a given head of wheat, considerable variation would exist.

The unit stress for breaking the rachilla would appear principally dependent upon its moisture content. The stress would depend also upon the time interval between maturity and harvesting.

From the standpoint of using equation 5, the product of the area and the unit stress would be usable and much easier to obtain. This product is defined as the breaking force f. Equation 5 then takes the form:

$$F = C f \qquad (6)$$

Methods for Obtaining the Threshing Force

Mechanical processes

The mechanical processes of rubbing, stripping and compression either singularly or in combination cause relative motion between kernels and their attachments, resulting in threshing. No effort will be made to develop theories of threshing for these processes, since the physical concepts are relatively elementary.

Impulsive acceleration

Newton's rule states the relative velocity after collision is equal and opposite to the coefficient of restitution (or impact) times the relative velocities before the collision (Becker, 1954). In symbols this expression becomes for a conventional threshing mechanism:

$$- E_g (V_{ci} - V_{gi}) = V_{cf} - V_{gf} \tag{7}$$

$$- E_s (V_{ci} - V_{si}) = V_{cf} - V_{sf} \tag{8}$$

The symbols have the meanings indicated below.

E_g is the coefficient of restitution of the grain.

E_s is the coefficient of restitution of the straw.

V_{ci} is the velocity of the cylinder initially or before impact, feet per second (fps).

V_{gi} is the initial grain velocity (fps).

V_{cf} is the final cylinder velocity (fps).

V_{gf} is the final or after impact velocity of grain (fps).

V_{si} is the initial straw velocity (fps).

V_{sf} is the straw velocity after impact (fps).

V_c is the cylinder velocity (fps).

For a powered cylinder with even feed, $V_{gi} = V_{si}$ and $V_{ci} = V_{cf} = V_c$. Also V_{gi} is very small compared to V_c and can be neglected. Equations 7 and 8 simplify, after these substitutions, to:

$$V_{gf} = V_c (1 + E_g) \tag{9}$$

$$V_{sf} = V_c (1 + E_s) \tag{10}$$

The grain and straw velocities can also be obtained from the laws of acceleration and are equal to:

$$V_{gf} = V_{gi} + (at)_g \tag{11}$$

$$V_{sf} = V_{gi} + (at)_s \tag{12}$$

The products of the acceleration and time for grain and straw are represented by $(at)_g$ and $(at)_s$ respectively.

Equating equations 9 and 10 with 11 and 12 respectively and neglecting the small term V_{gi}, the equations of the acceleration can be obtained.

$$a_g = \frac{V_c\ (1 + E_g)}{t_g} \tag{13}$$

$$a_s = \frac{V_c\ (1 + E_s)}{t_s} \tag{14}$$

Newton's law of motion states

$$F = \frac{Wa}{G} \tag{15}$$

in which F is the accelerating force in pounds, W is the weight of the mass being accelerated in pounds, a is the acceleration of the mass in feet per second squared, and G is the gravitational constant.

If the straw and the grain had different rates of acceleration, a threshing force would evolve as:

$$F = \frac{W_g}{G}(a_g - a_s) = \frac{W_g}{G}\left[\frac{V_c\ (1 + E_g)}{t_g} - \frac{V_c\ (1 - E_s)}{t_g}\right] \tag{16}$$

To visualize equation 16, consider that the straw is fixed in space. If there is relative acceleration between the straw and the grain, the mass being accelerated becomes that of the kernel $\frac{Wg}{G}$. The accelerating kernel in turn pulls on the rachilla with a force F until the attachment is broken. If the time of acceleration for both the grain and straw is t (seconds), equation 16 reduces to:

$$F = \frac{W_g\ V_c}{G\ t}(E_g - E_s) \tag{17}$$

Clearly, the time can be expressed as occurring in a finite distance of cylinder travel, X feet. Thus:

$$t = \frac{X}{V_c} \tag{18}$$

Substituting equation 18 into equation 17 and eliminating the time gives after rearranging and solving for the cylinder velocity

$$V_c = \sqrt{\frac{F\,G\,X}{W_g\,(E_g - E_s)}} = 5.67\sqrt{\frac{F\,X}{W_g\,(E_g - E_s)}} \tag{19}$$

Equation 19 gives the cylinder velocity required for threshing in terms of the kernel weight, grain and straw coefficients of restitution, and the threshing force-all of which are experimentally determinable physical characteristics of the crop and X-a factor largely dependent upon machine design and adjustment. The equation assumes that the grain enters into contact with the cylinder at the tangent and that the contact is complete.

<u>Non-impulsive acceleration</u>

Suppose that a stem with head attached were suddenly accelerated. All parts would be accelerated simultaneously, provided that breakage did not occur someplace. Now consider each individual rachilla which must exert the force to accelerate its kernel. This force would be:

$$F = \frac{W_g\,(V_f - V_i)}{G\,t} \tag{20}$$

Let two mating cylinders, turning on each other at the same speed V_c, be the mechanism that accelerates the stem. Using equation 18 and neglecting V_i, equation 20 reduces to:

$$V_c = \sqrt{\frac{F\,G\,X}{W_g}} = 5.67\sqrt{\frac{F\,X}{W_g}} \tag{21}$$

Comparing this equation to equation 19, it is readily seen that the coefficient of restitution does not enter. Since the numerical value of the quantity (E_g - E_s) is always greater than zero but less than 1, a mechanism following equation 21 would require only $\sqrt{E_g - E_s}$ as much cylinder speed as the conventional cylinder (assuming the value of X in equation 19 and 21).

The last equation, however, still has the quantity X, the distance through which acceleration occurs. This can be eliminated by accelerating the mass non-rectilinearly. For such acceleration, the acceleration is:

$$a = \frac{V^2}{R} \tag{22}$$

In this formula V is the absolute speed of the accelerated mass in feet per second and R is the radius of rotation in feet. Substituting this value for the acceleration into Newton's motion equation, equation 15, the equation for centrifugal force is obtained.

$$F = \frac{W_g \, V_c^{\,2}}{G \;\; R} \tag{23}$$

Rearranging and solving for the velocity, the following is obtained:

$$V_c = \sqrt{\frac{F \; G \; R}{W_g}} = 5.67 \sqrt{\frac{F \; R}{W_g}} \tag{24}$$

Since R is a definite quantity and W_g and V_c are easily measured, the force required for threshing can be obtained. Equation 25 perhaps is more convenient to use, since N_c is the threshing head speed in rps.

$$N_c = 0.903 \sqrt{\frac{F}{W_g \; R}} \tag{25}$$

Energy Relationships

Impulsive acceleration

The energy absorbed by a kernel can influence germination. It is therefore important to have energy relationships for threshing processes. In addition the relationships can be used to establish power required for threshing.

The kinetic energy for the grain mixture immediately after impact from the cylinder is:

$$T = \frac{\Sigma W_s V_c^2 (1+E_s)^2 + \Sigma W_g V_c^2 (1+E_g)^2}{2G} \tag{26}$$

For most wheat varieties, the mixture ratio of grain to straw approaches 1. Using this fact and calling the total mixture weight W, equation 26 becomes:

$$T = \frac{W V_c^2}{4G} \left[(1+E_s)^2 + (1+E_g)^2 \right] \tag{27}$$

It should be noted that W refers to total quantity of mixture accelerated per second and W_g refers to the total quantity of grain. Horsepower can be obtained entering time into equation 27.

Upon striking a concave bar, the grain and straw rebound velocities become:

$$-V_{gb} = E_g \left[V_c (1+E_g) \right] = V_c (E_g + E_g^2) \tag{28}$$

$$-V_{sb} = E_s \left[V_c (1+E_s) \right] = V_c (E_s + E_s^2) \tag{29}$$

The rebound kinetic energy becomes:

$$T_b = \frac{W_{gb}}{2G} \left[V_c^2 (E_g + E_g^2)^2 \right] + \frac{W_{sb}}{2G} \left[V_c^2 (E_s + E_s^2)^2 \right] \tag{30}$$

Assume that W_{gb} and W_g are equal as are W_{sb} and W_s. Further assume that W_g equals W_s and their sum is W. The rebound energy equation then becomes:

$$T_b = \frac{W V_c^2}{4G} \left[(E_g + E_g^2)^2 + (E_s + E_s^2)^2 \right] \tag{31}$$

The work done on the straw and grain becomes:

$$Q = T - T_b = \frac{W V_c^2}{2 G} \left[1 + E_s + E_g - (E_g^3 + E_s^3 + \frac{E_g^4 + E_s^4}{2})\right] \quad (32)$$

Assuming that E_g and E_s are much smaller than one, the third and fourth powers can be neglected and the work is approximately:

$$Q = \frac{W V_c^2}{2 G} (1 + E_s + E_g) \quad (33)$$

Unfortunately, the division of this work done on the grain and straw needs to be experimentally determined.

<u>Non-impulsive energy</u>

The energy for non-impulsive acceleration is again more simply stated, since the kernel will be leaving the straw at the velocity existing at threshing. This velocity previously was referred to as V_c. Thus, the kinetic energy becomes:

$$T = \frac{W_g V_c^2}{2 G} \quad (34)$$

This is an expression for the energy of threshing and the energy which must be dissipated before the kernel becomes static. When a stationary kernel arrester is installed, the energy of rebound becomes:

$$T = \frac{W_g}{2 G} E_g^2 V_c^2 \quad (35)$$

and the work by the kernel becomes:

$$Q = \frac{W_g V_c^2}{2 G} (1 - E_g^2) \quad (36)$$

Ideally, it would be desirable to have an arrester that would make E_g zero and that absorbs all the kernel kinetic energy. This is true from the standpoint of kernel damage.

RESEARCH EQUIPMENT AND TECHNIQUES

Laboratory Research

Theoretical analyses indicated that the threshing force could best be determined by applying centrifugal force until the desired level of threshing had occurred. The threshing force would then be equal to the value of the applied centrifugal force. To determine this force, measurement of (1) rotational speed, (2) radius of rotation of the kernel mass, and (3) the kernel weight was necessary.

Threshing in commercial centrifuge

Exploratory threshing was accomplished in a commercial centrifuge. Individual heads of wheat were held in standard 1-1/2 by 6-inch test cups by two piece, tapered wood plugs. See Figures 6 and 7. As the centrifugal force increased, the plugs wedged tighter into the cup, securely holding the straw and head at a fixed radius. Wood plugs were selected because they could be easily removed.

After the samples were prepared and placed in the trunnions, the centrifuge was accelerated to the lowest rpm of the sequence. The power to the centrifuge was then turned off, the cap opened, and free or threshed kernels removed. The plugs holding the straw and head were next carefully replaced and the centrifuge accelerated to the next higher speed. This technique was continued for five or six speeds, after which the straw residue was searched for unthreshed grain.

The kernels threshed at each speed were counted and weighed on analytical balances with four place decimal gram accuracy. The grain and straw were later dried at 200° F. for 48 hours in order to obtain moisture contents.

Figure 6. Tapered wood plugs and metal test cups used to mount wheat heads in a commercial centrifuge

Figure 7. Commercial centrifuge used for exploratory centrifugal threshing

This equipment and procedure was not completely satisfactory for the following reasons:

(1) The force obtained was marginal. Many times complete threshing could not be achieved. This was true even after the input voltage to the centrifuge was increased by means of a variable voltage transformer to 140 volts. This voltage gave a maximum speed of 3200 revolutions per minute.

(2) Only two or four heads could be threshed at a time, one in each cup.

(3) A test sequence required considerable time, since the centrifuge had to be stopped after each speed increment to remove threshed grain.

(4) The protective cup eliminated all air resistance, a condition which would be practically impossible to achieve in any conceivable application.

Experimental batch thresher

It was decided to design and construct a centrifugal thresher with the following functional requirements:

(1) Speeds variable from 1000 to 5000 revolutions per minute at radii greater than 6 inches.

(2) Capable of handling large samples, 50 to 100 heads or more at one time.

(3) Continuous collection of threshed grain.

(4) Threshing head flexible for holding the grain so that the effect of direction of force application relative to the kernel could be determined.

(5) Permit subjecting heads to combined effects of centrifugal force and air resistance.

A circular mounting clamp was positioned horizontally at the end of a vertical shaft which was held firmly in position by two flange-type bearings. The shaft was powered by an electric motor driving through a variable-speed mercury clutch and a V-belt-driven counter shaft. The direction of the power was turned 90° by twisting the V-belt between the mercury clutch and the countershaft. The countershaft was parallel to the main threshing shaft (Figure 8).

The mounting clamp consisted of a flat 1/4 inch steel base plate, 12 inches in diameter and a flat steel top ring with outside diameter 12 inches and inside diameter of 9 inches. A hub was welded to the base plate, which permitted attaching the mounting clamp to the drive shaft (Figure 9). The ring was bolted to the base plate with four 1/4 inch stove bolts. The mounting clamp was carefully balanced statically.

The clamp was completely enclosed by a housing which de-accelerated the threshed kernels and delivered them to a sloping metal drain. The discharged grain was collected and delivered by means of spouts on either side of the threshing frame to paper containers. The areas on the housing which made contact with the threshed kernels were lined with a 1/4 inch rubber pad in order to reduce grain damage. See Figure 10. The housing top was made of plexiglass to permit strobotrac observations.

The sample to be threshed was hand arranged between the base plate and the ring (Figures 10 and 11). The straw was usually inserted with the heads pointing radially outward. Each head was adjusted to a fixed radius. Generally 24 head samples were used, 12 heads on each side. The clamp was

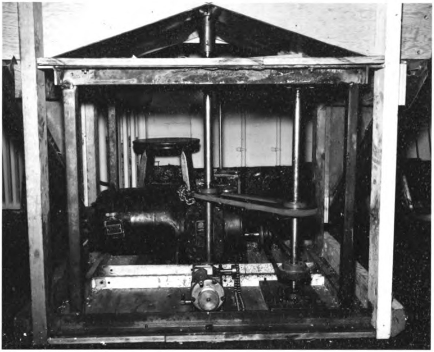


Figure 8. Drive parts of experimental centrifugal thresher

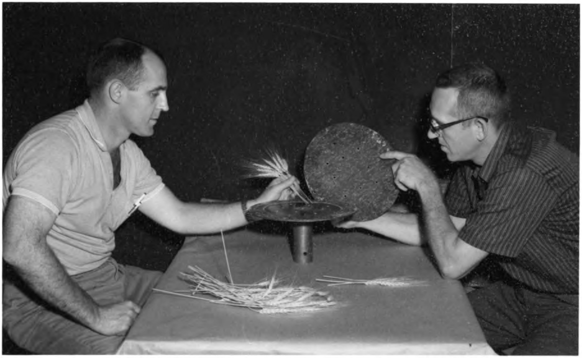


Figure 9. Threshing head, showing method of attaching the grain

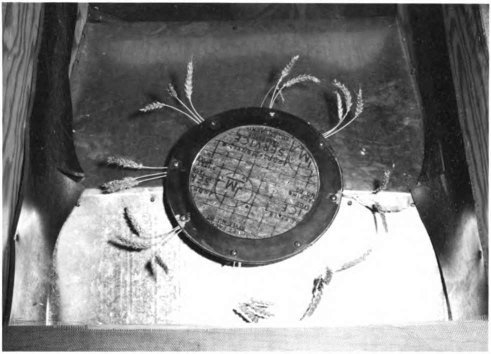


Figure 10. Unthreshed grain mounted in threshing head. The outher housing was lined with a rubber pad to protect the threshed grain from damage.

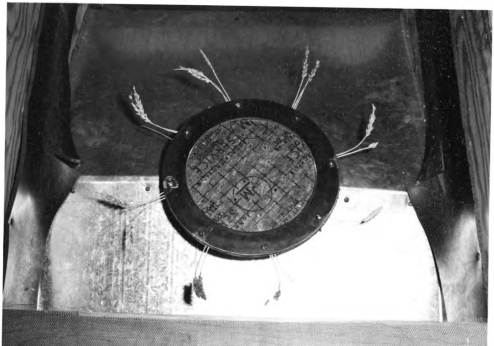


Figure 11. Straw condition after complete threshing

tightened securely after final positioning of the heads. The base plate and ring were each coated with asbestos gasket material to prevent cutting of the straw.

The orientation of the heads could be varied to achieve three types of loading. Most of the tests were conducted with the apical spikelet at the greatest radius as described in the previous paragraph. This mounting was previously stated to be the condition giving the most difficult threshing and was referred to as regular holding. Some tests were conducted by clamping the stem portion exposed by removing the apical and adjacent spikelets. This holding was called reversed holding. Intermediate holding was obtained by placing the heads in hollow cylinders made of perforated galvanized sheet metal. These cylinders were bolted to the base plate.

The method of holding corn was considerably different. One-fourth inch steel rods were formed with a hook on one end and were threaded on the other. These rods were keyed to the base plate. Specimens were prepared by cutting an ear of corn into 1-1/2 inch transverse sections. These were drilled through the cob center with a 1/4 inch bit. The specimens were inserted on the steel rod, washered flush with the cob, and then locked in position.

It was found that a test sequence of the following speeds would generally include the complete range of threshing: 1000, 1500, 2000, 2500, 3000, 3500 and 4000 revolutions per minute. A strobotrac was used to calibrate the speed. The radius of the tip kernel was kept at 11 inches when regular holding was used. The test technique involved increasing the threshing speed from the lowest to the maximum speed in succession. After the machine had stabilized at each speed, the containers were removed and new ones inserted on the collection spouts. The straw was removed and analyzed for unthreshed kernels after the last speed was attained.

The discharge obtained at each speed increment was processed according to the following procedure:

(1) Net weight of grain, chaff and straw determined.

(2) Sample blown to remove chaff. Straw, if any, was picked out by hand.

(3) Net weight of kernels was determined.

(4) Net weight of straw, if any, was determined.

(5) Kernels were counted, noting visual kernel damage, if any.

(6) Grain and straw samples were desiccated in an oven at 200° F. for 48 hours.

The weighings were made in grams with accuracy to two decimal places. Several grain samples were saved for germination tests.

Grain for the original experimentation was cut by binder during the 1958 growing season and stored. Greenhouse wheat of Genesee variety was used for pre-season threshing. Seneca wheat samples were obtained directly from the field during the Ohio testing (June 28 through July 13). Moistures varied from 40 to 10 percent. One hundred head samples of several wheat varieties were collected every other day and freezer stored in plastic bags during the early pre-combining period in Michigan. The threshing unit was returned to Michigan July 15, after which samples were collected directly from the field during the normal combining period. The freezer stored samples were later threshed.

It was considered desirable to photograph the threshing action. The original approach was to construct a rotating mirror arrangement which would project the images of the grain samples to center mirrors. A high speed camera was to be located over the center mirrors, taking 4000 to 5000 frames per second. Four silvered mirrors were placed in a rotating housing so that the line of sight of the camera was split and moved horizontally outward four inches on each side. The device was bolted to the mounting clamp and rotated with it. Two factors forced abandonment of this approach. First, the unit could not be satisfactorily balanced. Second, the fan action of the assembly increased the power requirements necessary for complete threshing beyond that available with the electric motor and transmission.

A set of high speed breaker points were installed on the main drive shaft and set to open once each revolution of the mounting clamp. The points triggered a strobotrac-strobolume arrangement that flashed once each revolution. This combination gave satisfactory light for motion pictures at 16 frames per second. Three hundred feet of movie film recorded the threshing action.

This photographic technique at best was a compromise arrangement. First, the range of view was only 4 inches of a total threshing range of 23 inches, so that the probability of photographing discharging kernels immediately becomes only 17 percent. This probability was further reduced if the movie camera shutter was closed at the time of the flash. This occurred at certain speeds. The technique permitted visual determinations of head condition at various speeds and therefore was useful.

<u>Grain physical characteristics</u>

Accurate centrifugal force calculations depended upon kernel weight and kernel radius, in addition to the speed of rotation. It was therefore necessary to determine kernel weights by location within the wheat head.

Individual heads had spikelets removed in order from the apical spikelet. The kernels in each spikelet were individually weighed in grams to four decimal place accuracy. The position of the kernel within the spikelet was also recorded. The distance between adjacent spikelets was obtained by dividing the total head length by the number of spikelets.

The above determinations were made on both immature and mature heads to establish differences in kernel moistures within a head.

Straw physical characteristics

The method of obtaining the threshing force depended upon the culm and stem not breaking before the kernels were removed. This fact prompted establishment of straw breaking forces at different stages of maturity and moisture.

A Schopper tensile testing machine, commonly used in the packaging industry, was available for these determinations. Straw specimens six inches in length were prepared from the culm immediately under the head. These specimens were clamped into the machine and stressed, using the slow speed loading drive. (See Figure 12). Breaking forces were recorded for at least eight specimens at each moisture condition. After fracture, the broken pieces were flattened by using a straight edge and the area of the fractured point obtained with measurements made with micrometer.

Static and dynamic coefficients of straw friction were determined prior to the tensile tests. A tilting board arrangement as seen in Figure 13 was available for these tests. The surface material was galvanized metal. The static coefficient of friction was considered to be the angle the surface made with the base when the straw would start to slide from rest. The dynamic coefficient of friction was recorded as the angle the surface made to

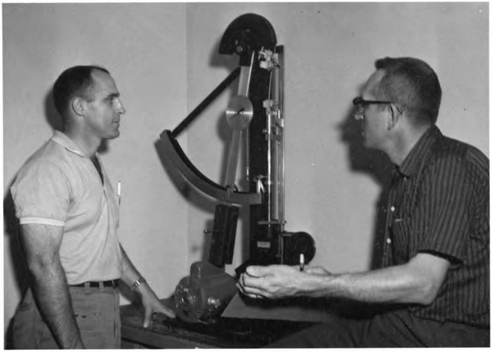


Figure 12. Straw tensile strength was determined by use of Schopper testing machine.

Figure 13. Straw frictional data were obtained with a tilting board device, surfaced with galvanized metal.

the base when the straw would continue to slide after being initially accelerated.

Straw, chaff and grain proportions of heads were established by threshing and separating by hand heads with seven inches of straw attached. These proportions were used to establish percentage of chaff removed during threshing.

Field Research

Simultaneous conventional and centrifugal threshing

Seneca wheat was threshed with a conventional rasp bar cylinder and grated concave and with the centrifugal thresher simultaneously two afternoons. A John Deere model 30 combine powered by a Farmall 460 diesel tractor was used for the field studies. The combine was conventionally equipped for these tests.

Straw feeding rates were maintained practically constant by using first gear speed and a constant depth of cut. A strip of uniform wheat 62.2 feet long and 300 feet wide was established. When driving with full width of cut, one-hundredth acre test plots were harvested. At the beginning of each test, the combine was cleared. It likewise was cleared at the end of each test plot.

The total discharge from the rack was collected in canvasses (Figure 14). Grain threshed and separated was gathered at the tank. These collections were weighed, samples for moisture taken, and then stored for subsequent evaluations.

Twenty tests were conducted at five cylinder speeds and four concave clearances the first afternoon in grain of 14 to 15 percent moisture. Fifteen

Figure 14. Canvasses were used to collect total discharge from the rack during field combine tests.

Figure 15. Straw discharged over the rack was analyzed to determine rack and cylinder losses by use of a rethresher.

tests with five cylinder speeds and three concave clearances were conducted in grain 12 to 13 percent moisture the second afternoon. During the time of the field tests, at least six samples of 24 heads each were centrifugally threshed each day. (Moisture of combined grain was determined by use of an electric Steinlite Moisture Tester.)

The straw samples were analyzed in a specially constructed rethresher built by McCuen (1943) for his research (Figure 15). The straw passed over a rack designed to remove any threshed but unseparated grain. Grain thus collected was referred to as rack loss. The straw next entered a double cylinder of spike tooth design which finalized threshing. The grain removed by this mechanism was called cylinder (or threshing) loss.

The collected grain samples were first recleaned in a Clipper seed cleaner. Test weight determinations were made. Next 100 gram samples were divided several times on a Cuthbert sampler until two lots of approximately 150 kernels remained. Visual kernel damage was determined after which duplicate germination analyses were made. Dormancy was broken by refrigerating the samples. After seven days in the germinator, the number of dead and weak sprouts were counted. Hand threshed grain samples were germinated as checks.

<u>Conventional threshing and zones of separation</u>

The combine was altered by removing the shoe assembly, the fan assembly and the slat conveyor which returned grain separated by the rack to the front of the shoe. A collector housing with two compartments was rigidly attached to the concave (Figure 16). Grain sacks attached to this housing collected all grain, chaff and short straws separated at the concave during the threshing process. A wood pan with five compartments (zones) was inserted under the rack and moved forward until it mated the rear cylinder compartment. The pan was removed after each test (Figure 17).

This arrangement gave seven separating zones, two at the cylinder, one for the cylinder after beater, and four on the rack. The eighth zone (or the grain going over the rack) was collected in a canvas and analyzed as previously indicated. See Figure 18.

Twelve tests of 1/100 acre each were conducted with threshing effort the only variable. Five cylinder speeds and three concave clearances were used in 12 percent moisture grain. Seven tests were run with feed rate the only variable.

The material collected at the different zones was carefully sacked, marked and stored for subsequent analysis. The stages of the analyses were:

(1) Total weight of collected material was determined.

(2) The material was subjected to the blower of a Clipper cleaner which removed chaff and light straws. Net weight was again determined.

(3) The remaining material was separated by the Clipper cleaner in the conventional manner, removing all foreign materials.

(4) One hundred kernel weights were taken to establish size differences by zones.

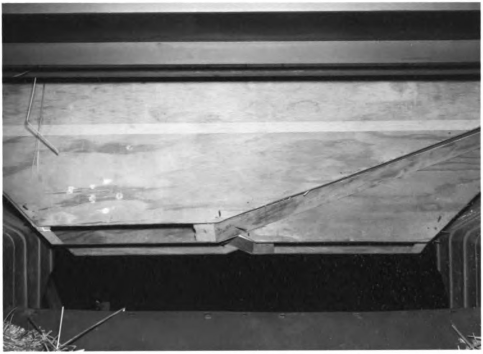


Figure 16. Housing which was attached to the combine concave to collect grain, chaff and straw separated by the cylinder at the concave

Figure 17. Grain and straw passing through the rack was collected by a wooden tray with five zones inserted under the rack.

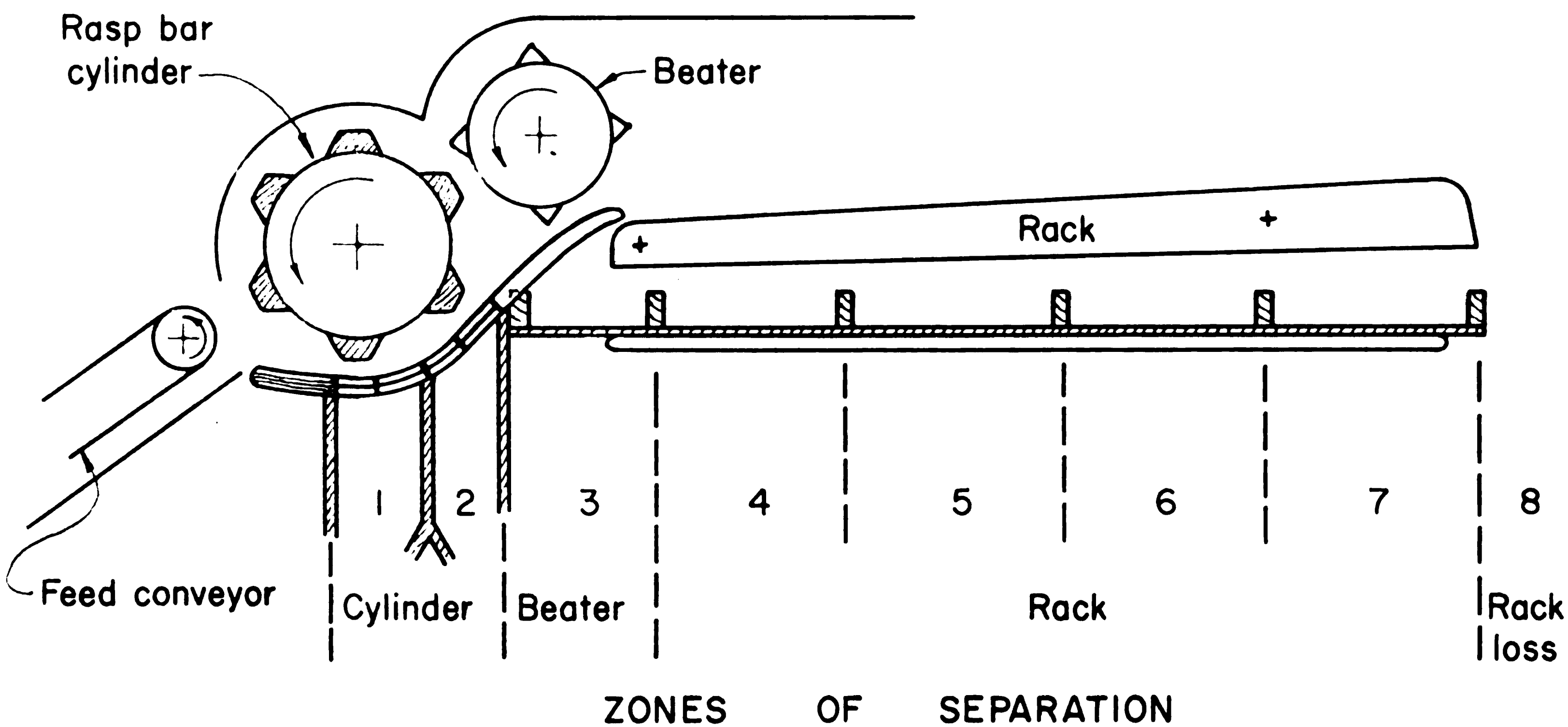


Figure 18. Schematic diagram of combine as adapted for determining the location of separation

RESULTS AND DISCUSSION OF RESULTS

Laboratory Research

<u>Centrifugal threshing</u>

Centrifugal force was used to thresh completely five wheat varieties, rye, soybeans, and corn. The threshing properties of wheat were established under many moisture conditions. Exploratory tests only were conducted on the other crops.

At kernel moisture contents above 35 percent, some of the kernels would break from the straw with chaff attached. The chaff could not be removed from these kernels by air blast until drying had occurred. Figure 19 pictures wheat kernels threshed at 44.8 percent and indicates the relative amount of kernels which threshed with glumes attached.

Straw breakage generally was not a problem. The kernels would break (thresh) free of their attachments before the breaking force of the straw was attained. As grain threshed from the head, the centrifugal force tending to cause straw breakage reduced. The club head type of wheat, however, was an exception in that the kernels would not thresh prior to straw breakage (Figure 20). An occasional straw would break with the other wheat varieties, particularly when the straw was extremely dry or very immature and green.

It was noted that the high moisture heads which broke from the straw and hit the housing had very few kernels threshed. This indicated that impact alone was not sufficient for removing kernels with 35 percent moisture and over.

Figure 19. Grain centrifugally threshed at 44.8 percent kernel moisture, showing some chaff attached

A B C D

Figure 20. Samples of grain centrifugally threshed (A, rye; B, Genesee wheat; C, Blackhead wheat; D, Clubhead wheat)

Effect of moisture upon threshing force

The relationship between threshing force and percent of threshing for Genesee wheat at various kernel moistures is presented in Figure 21. The relationship between peripheral velocities and percent of threshing for the same wheat is shown in Figure 22. In all of these tests the straw was free of surface moisture. At 98 percent of threshing, wheat at 29 percent kernel moisture required nearly twice the threshing force as oven dry wheat.

Similar threshing relationships are presented in Figures 23 and 24 for Seneca wheat at two moistures and in Figure 25 for Blackhawk wheat. It should be noted that the same peripheral speed achieved almost identical degrees of threshing in Seneca wheat at the two moistures.

The effects of surface moisture upon threshing of Genesee wheat are shown in Figure 26. The forces required for 98 percent threshing are similar to those of grain free of surface moisture. Even after a heavy rain with straw moisture over 35 percent, a threshing force of 0.30 pounds was sufficient.

The forces required to achieve 98 percent threshing of Seneca wheat under all test conditions are plotted against kernel and straw moistures in Figures 27 and 28. Regression line equations were calculated for each by the method of least squares and are shown on the figures. Although the threshing force increased with the higher moistures, the relationship was not absolute under all conditions for centrifugal threshing. The large variability was probably caused by the extremes in surface straw moistures and kernel weight differences. The variability was dampened at the higher percents of threshing as is presented in Figure 29.

A complete record of all tests is found in the Appendix, Table 18.

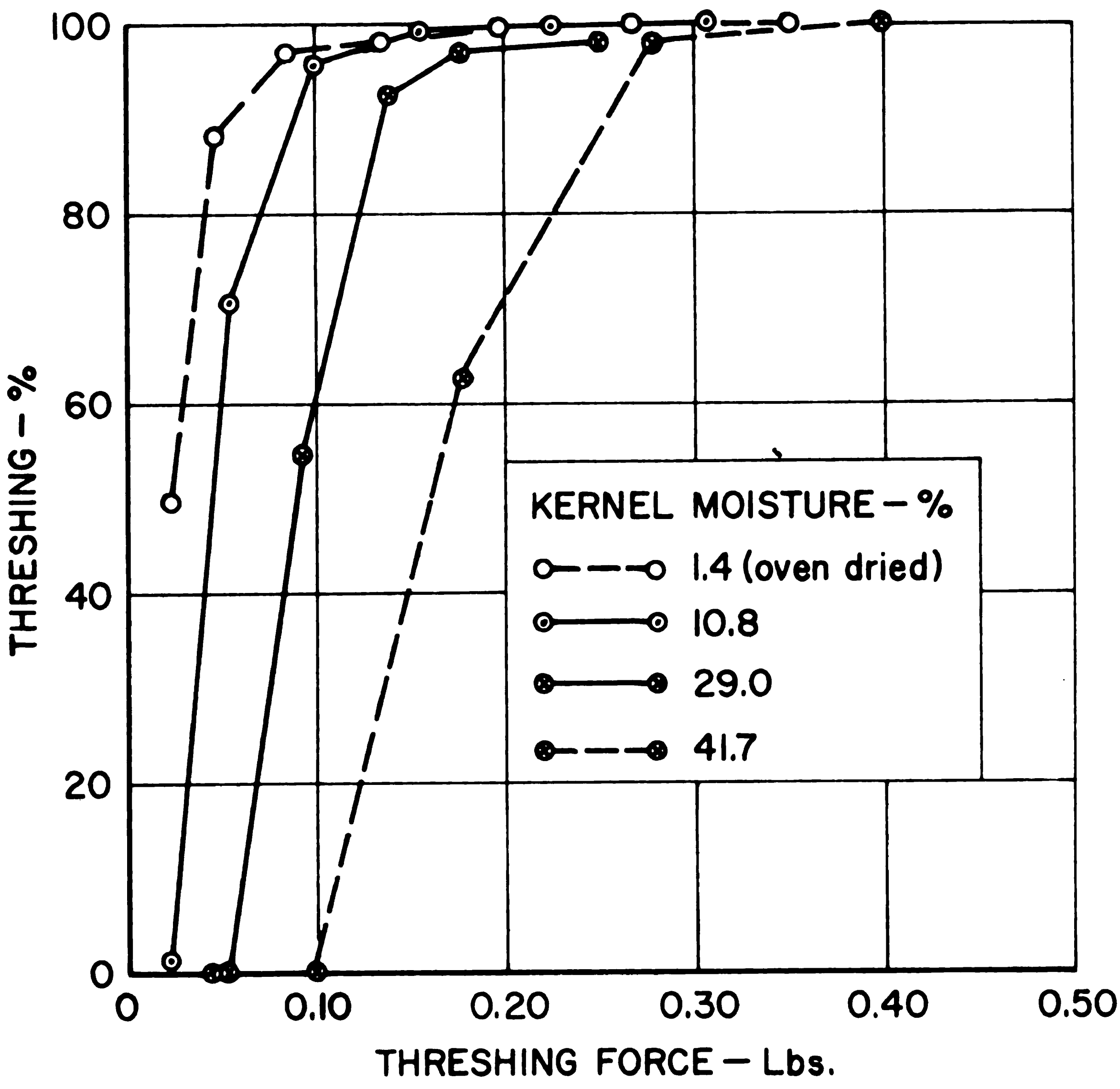


Figure 21. Relationship of threshing force to percent of threshing for Genesee wheat

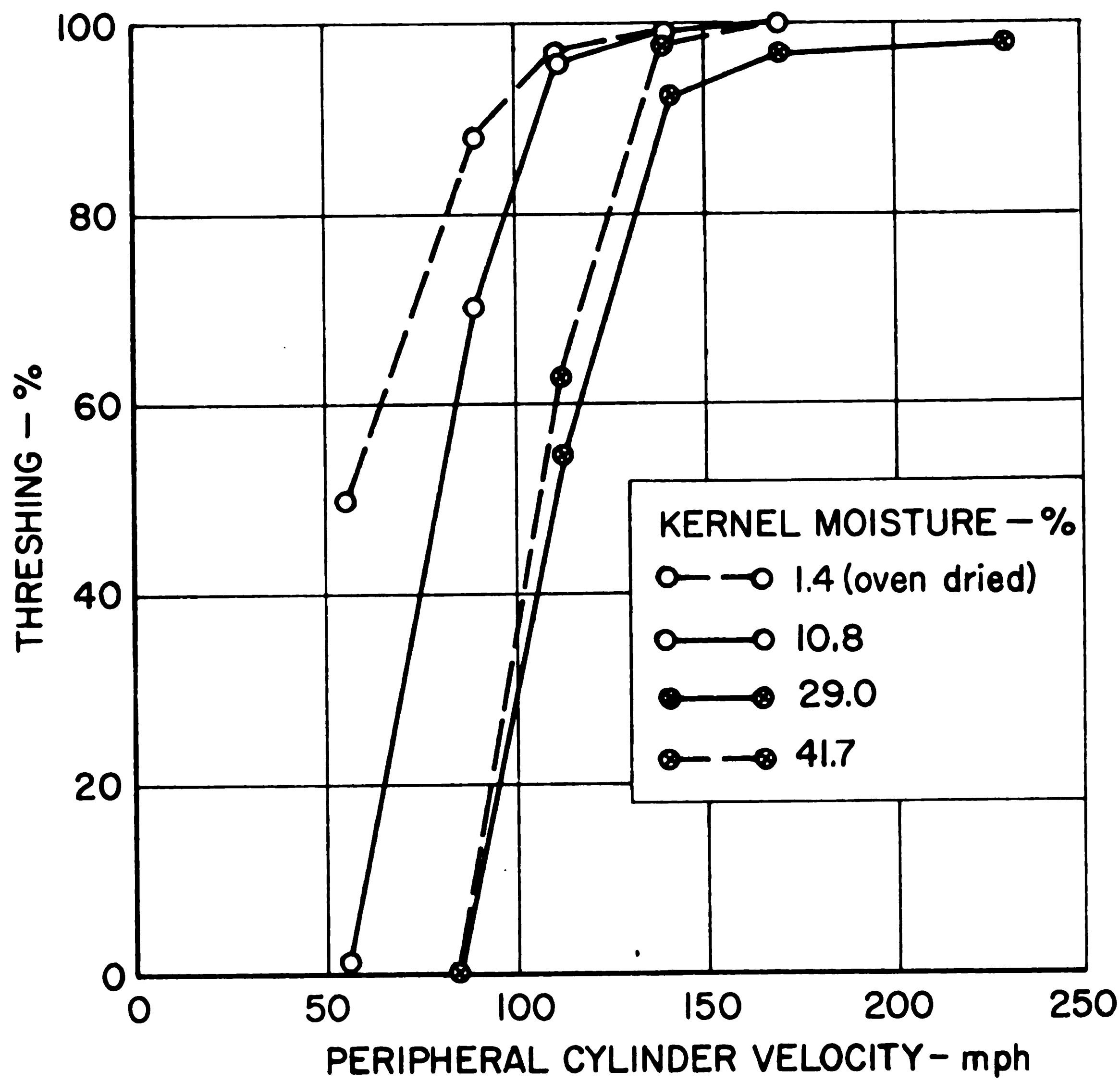


Figure 22. Relationship of peripheral cylinder velocity to percent of threshing for Genesee wheat

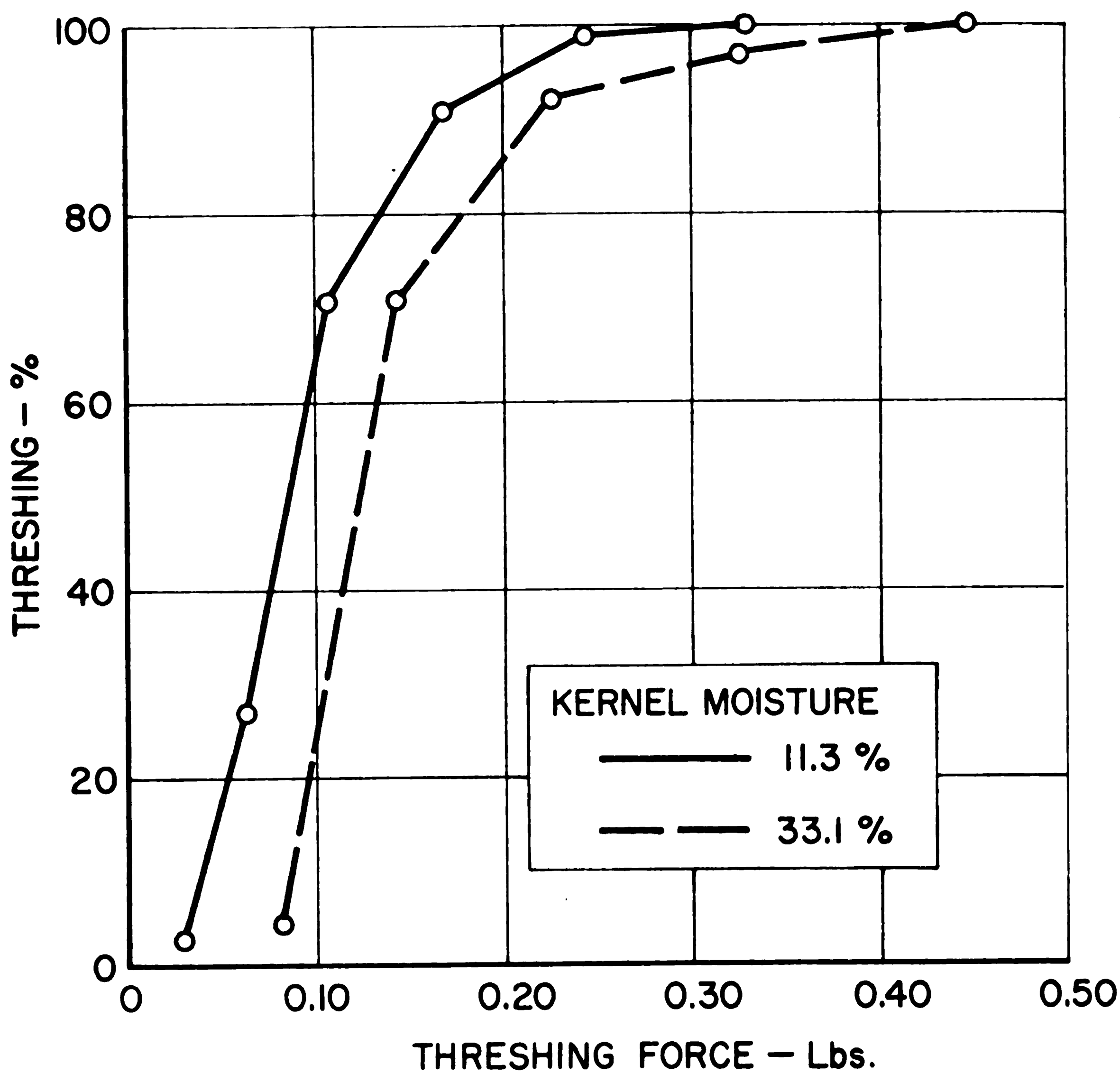


Figure 23. Relationship of threshing force to percent of threshing for Seneca wheat

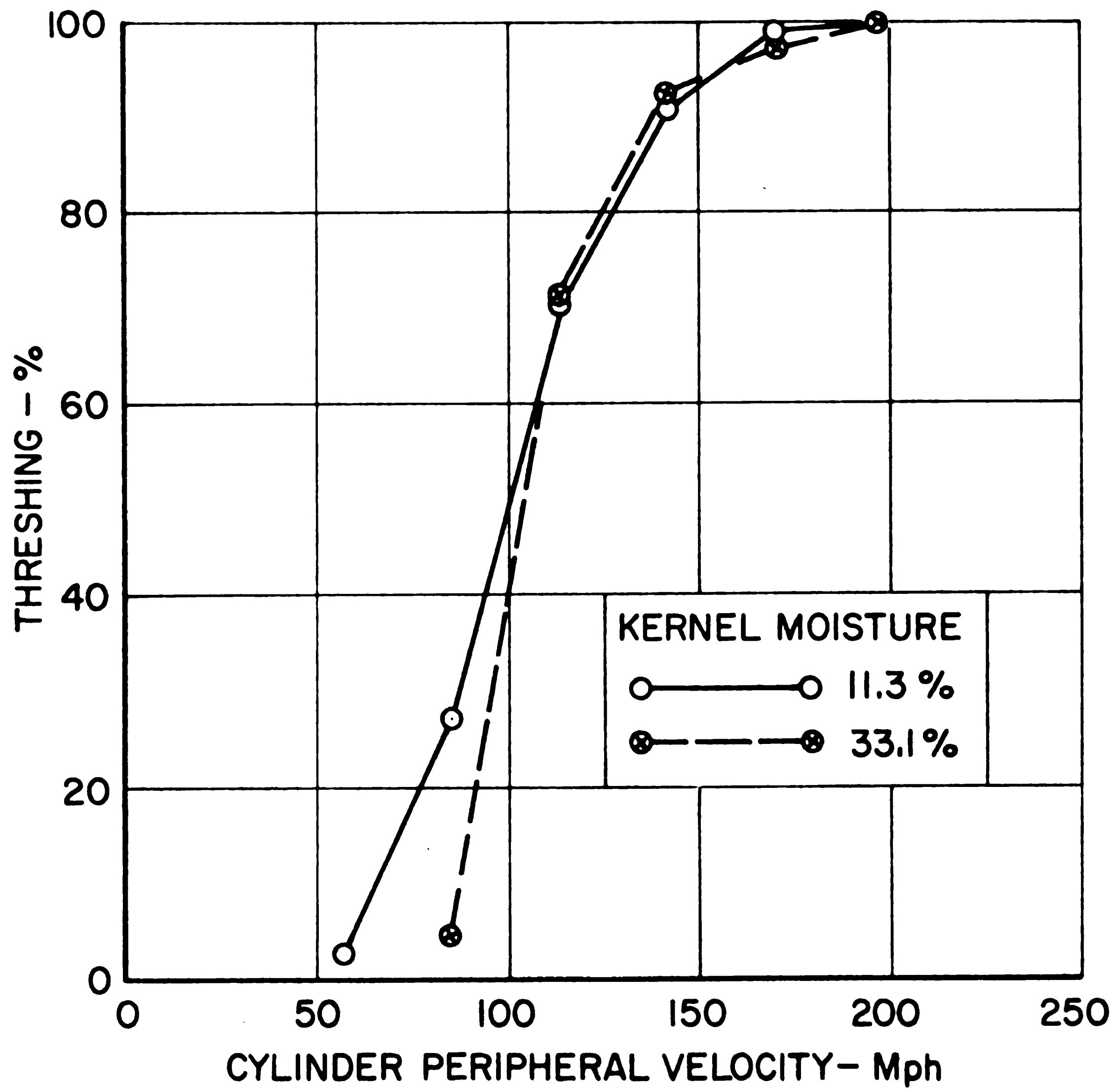


Figure 24. Relationship of cylinder peripheral velocity to percent of threshing for Seneca wheat

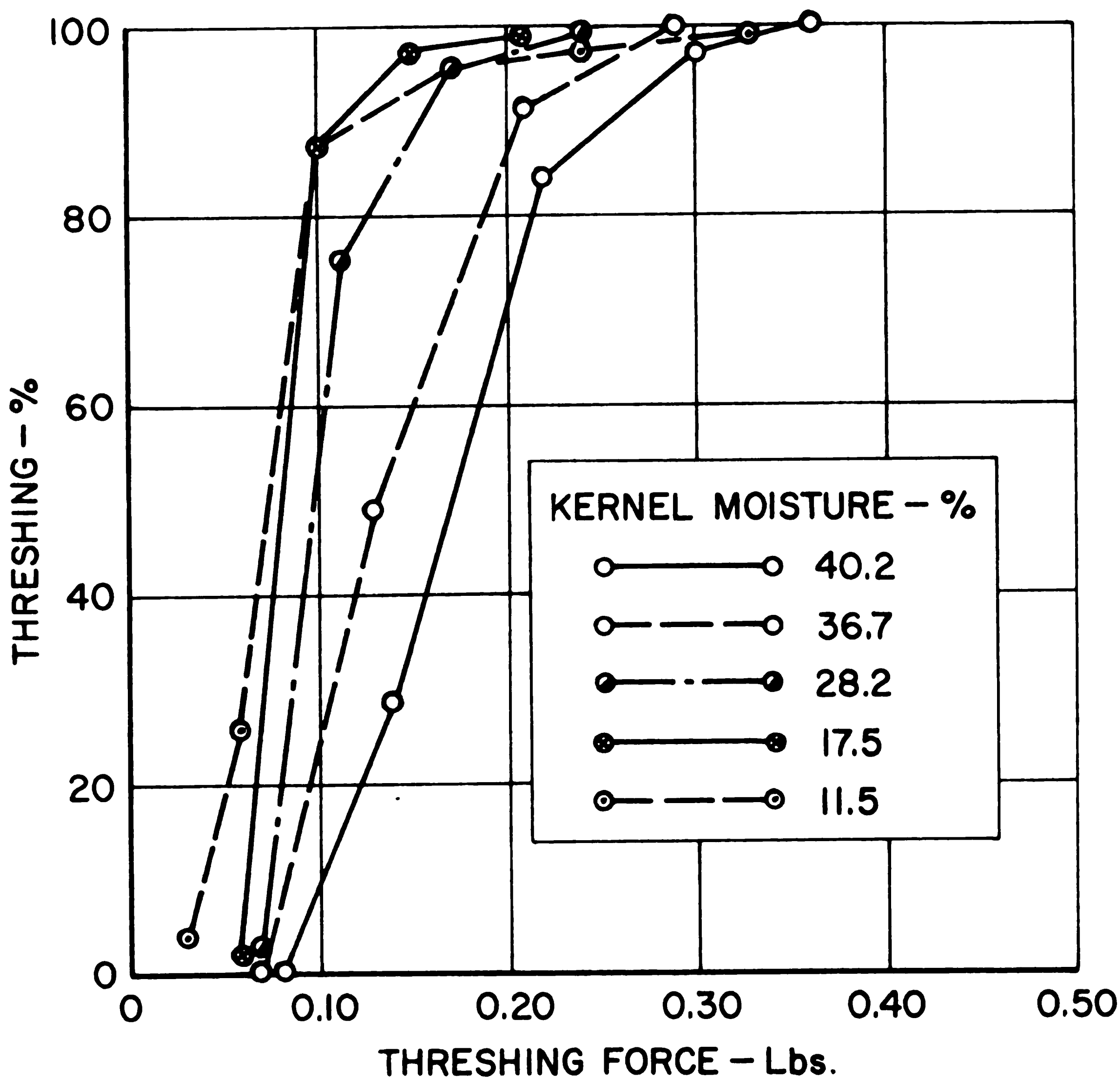


Figure 25. Relationship of threshing force to percent of threshing for Blackhawh wheat

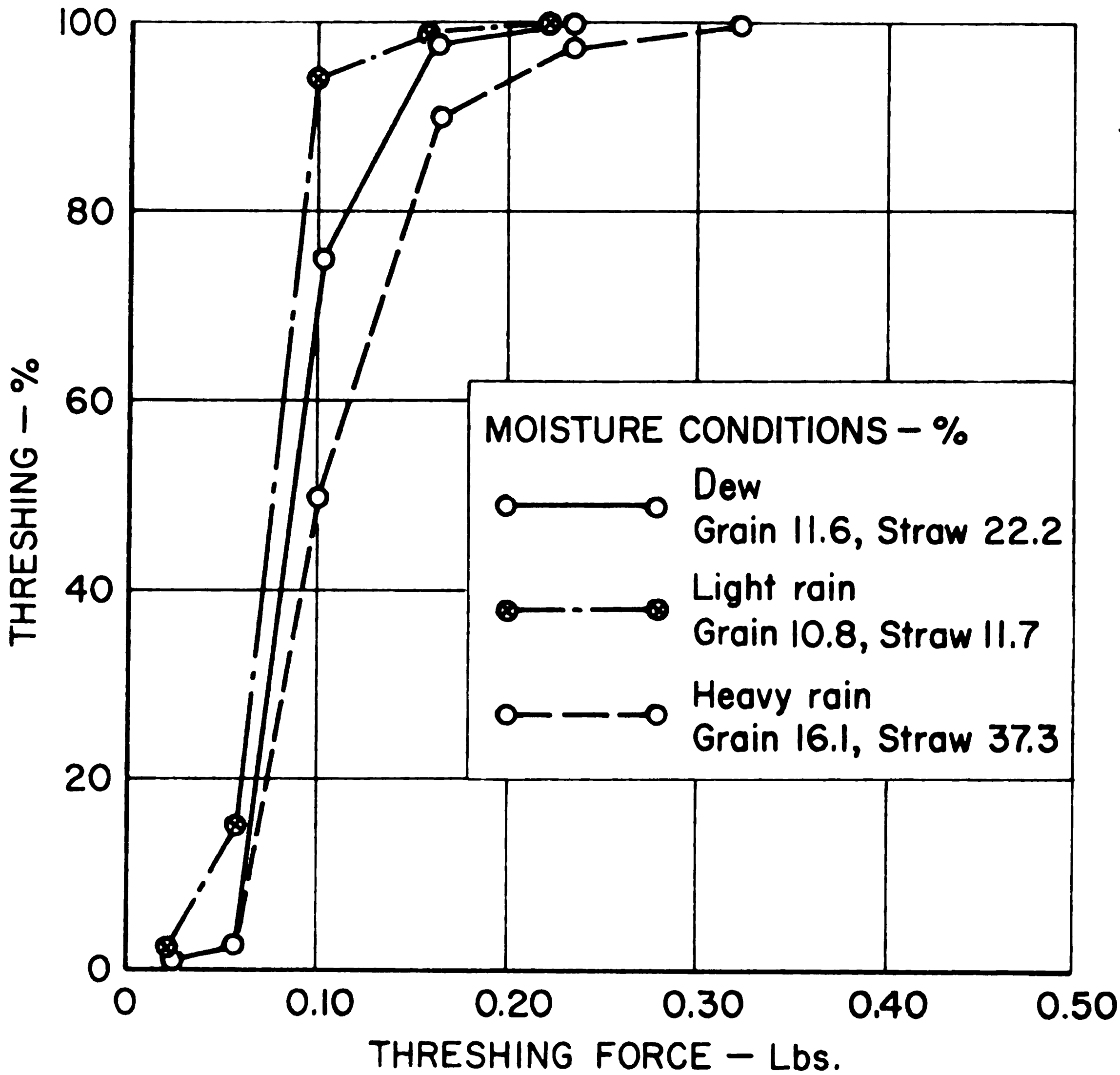


Figure 26. Relationship of threshing force to percent threshing for three conditions of survace moisture (Genesee wheat)

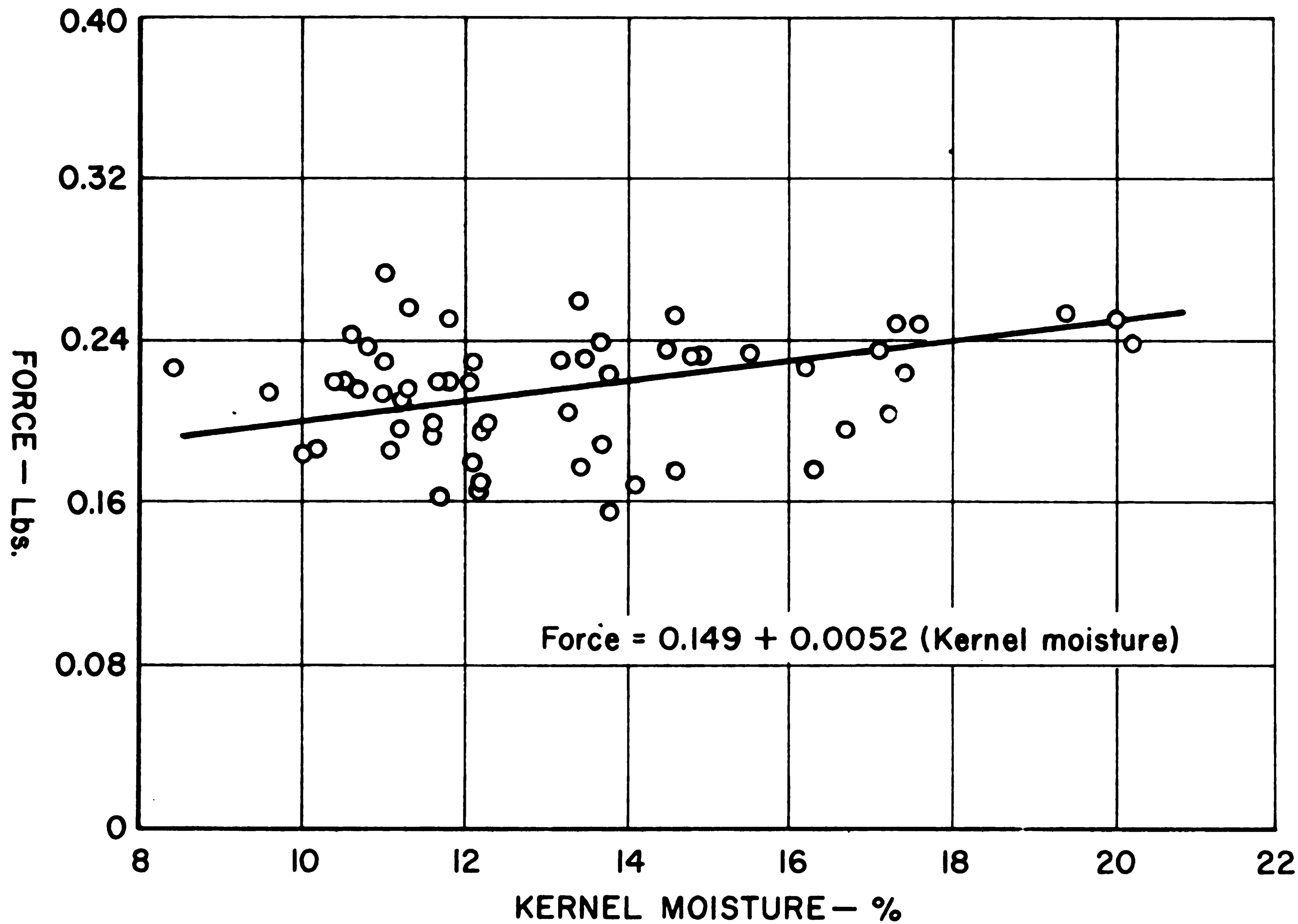


Figure 27. Relationship of kernel moisture to threshing force required for 98 percent threshing (Seneca wheat)

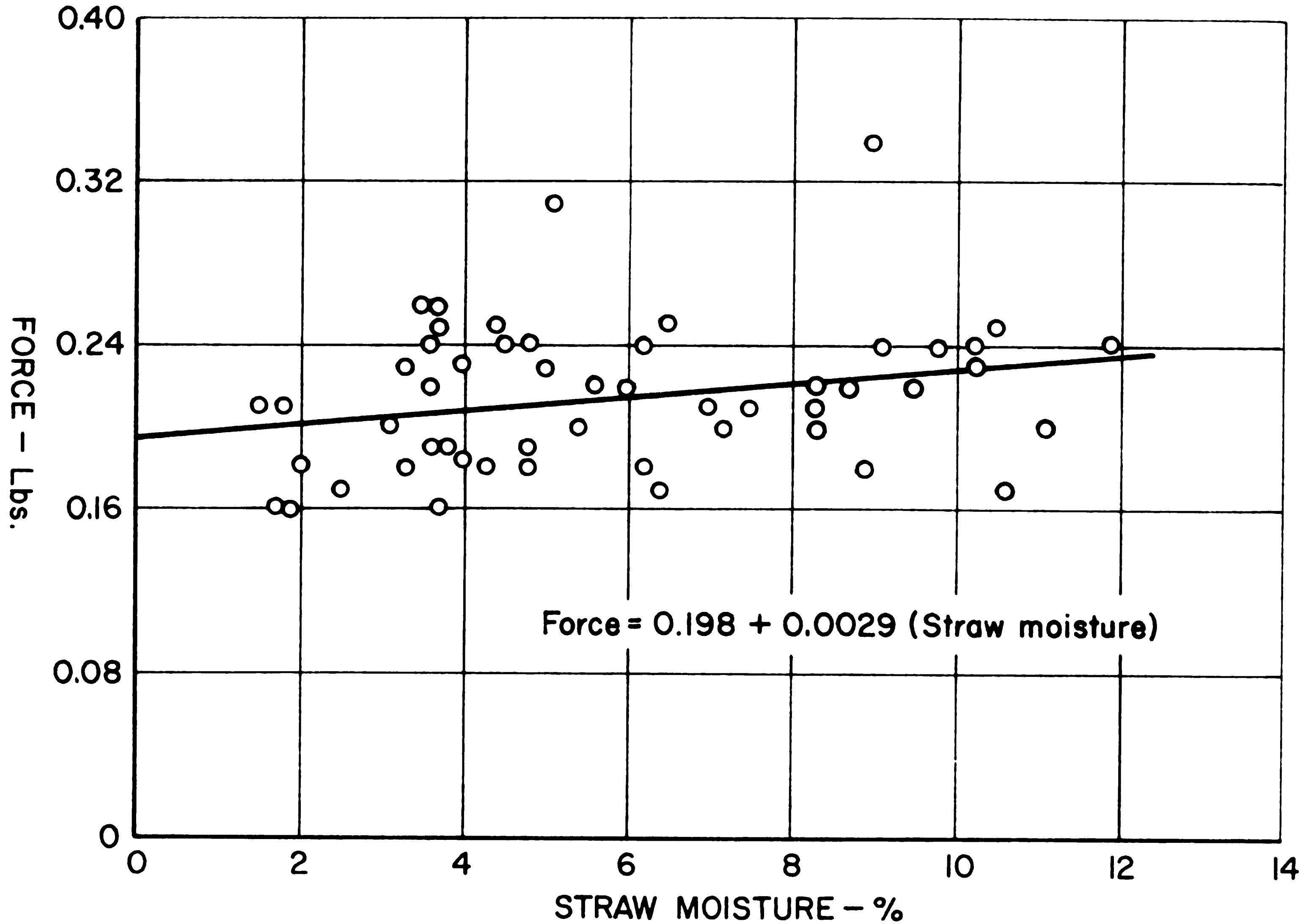


Figure 28. Relationship of straw moisture to threshing force required for 98 percent threshing (Seneca wheat)

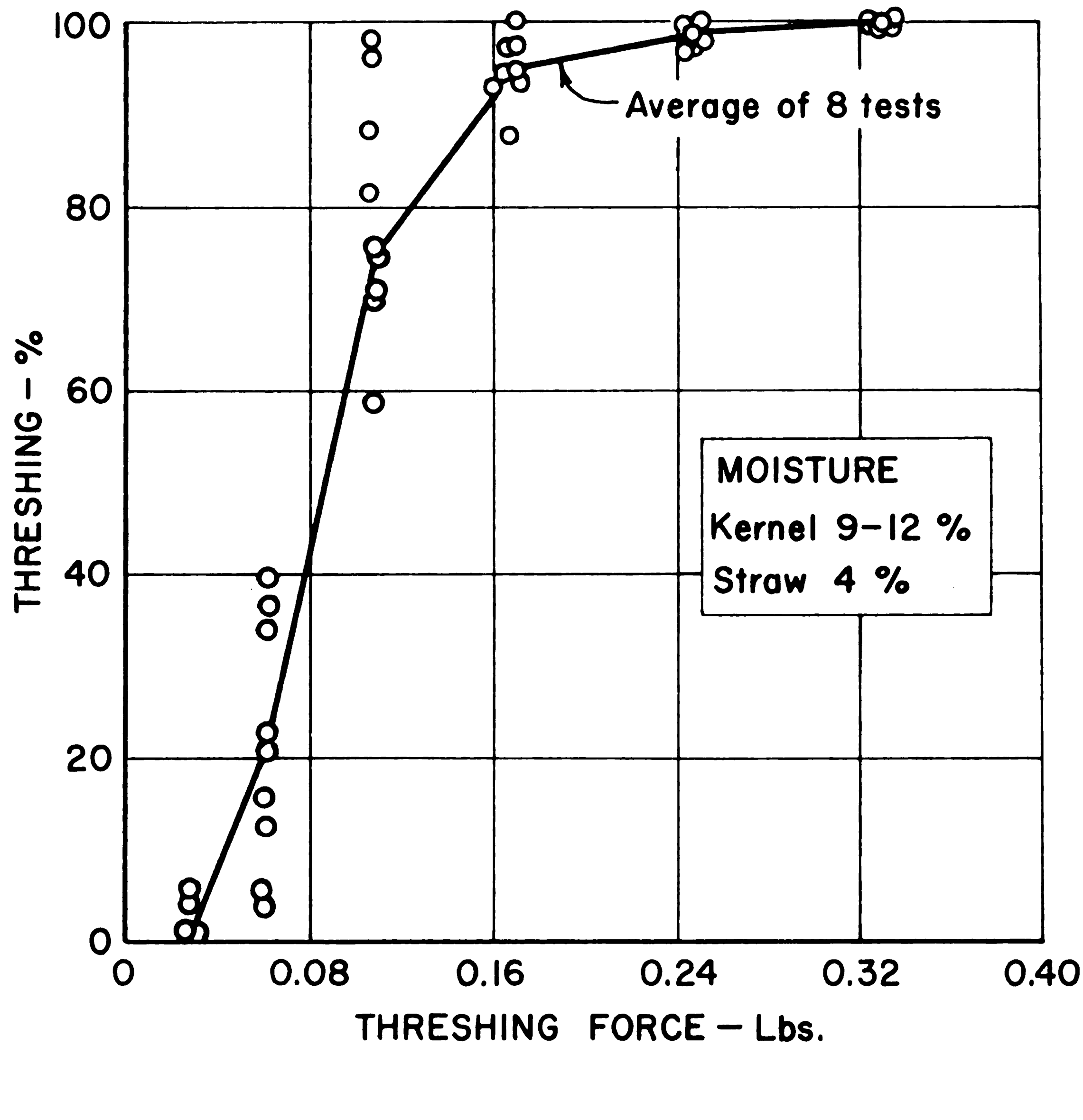


Figure 29. Variations existing in the relationship of threshing force to percent threshing (Seneca wheat)

Effect of variety upon threshing force

It is generally accepted that certain wheat varieties thresh easier than others. At least, certain varieties are subject to more pre-harvest losses through shattering than others. Figure 30 shows a threshing comparison among five wheat varieties and rye.

The CI-13170 variety is considered to be an easy thresher because of excessive field shattering tendencies. It shows low forces for initial threshing but relative to the others, it was the most difficult of all to thresh. Blackhawk, a bearded variety of wheat, was not particularly difficult to thresh. Rye, also bearded, was an easy thresher. The threshing differences presented could have been caused by the slight moisture variations.

Awns did not cause any problem in threshing; with the awns attached, however, the chaff was more difficult to separate from the grain. See Figure 31.

Effect of method of force application

Regular mounting (heads extending on radial lines from center and constrained by holding the straw) required approximately twice the force of that with reversed mounting as presented in Figure 32 for high moisture grain. This difference was not as great for low moistures (see Figure 33). With the reversed holding the kernels bent back, opening the glumes during the process, and sheared the attachment. This holding would be the best method for minimum threshing force.

Tests, conducted with intermediate holding, did not achieve more than 50 percent threshing. Retaining cylinders with 3/8 and 1/2" holes were used

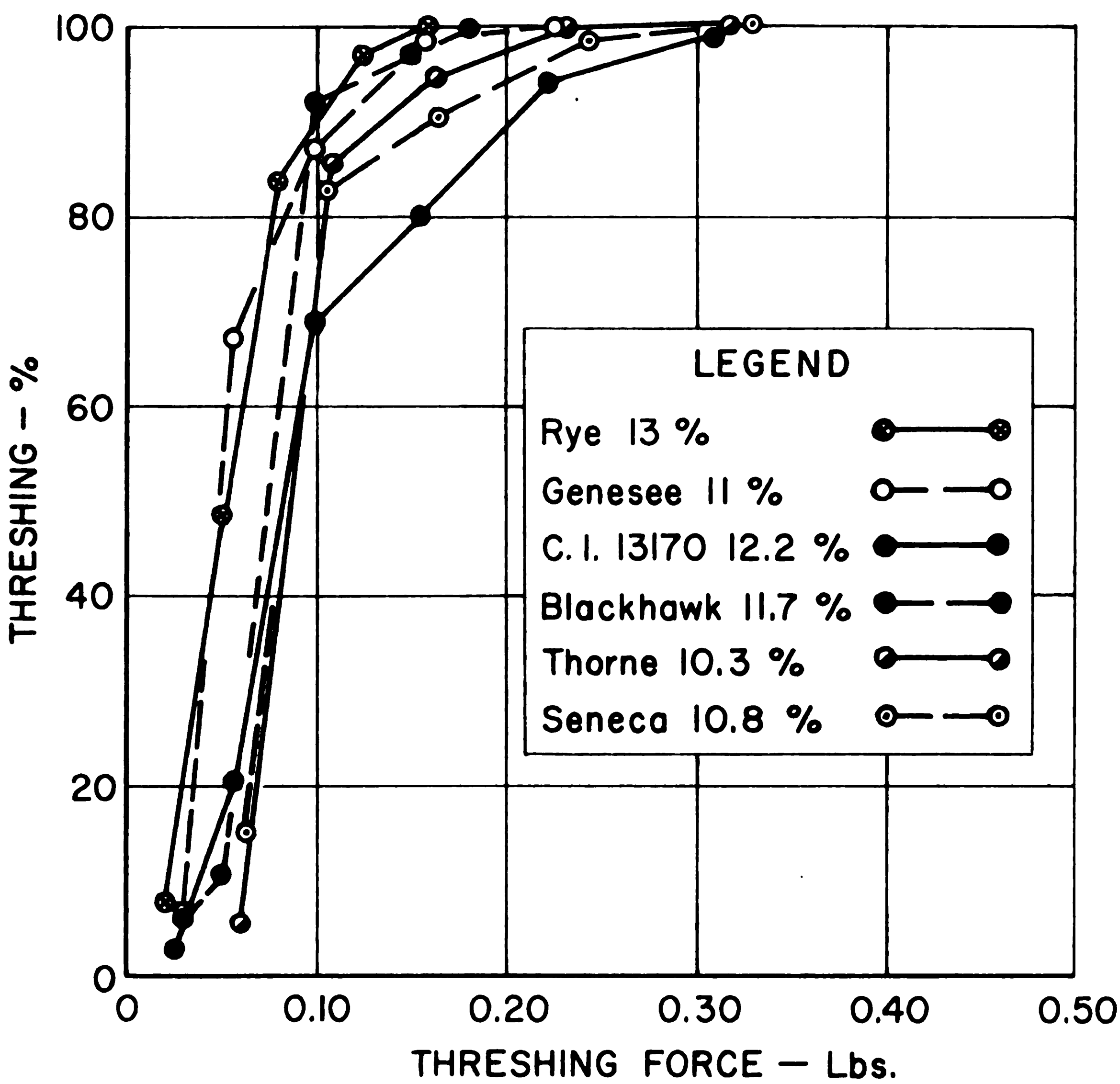
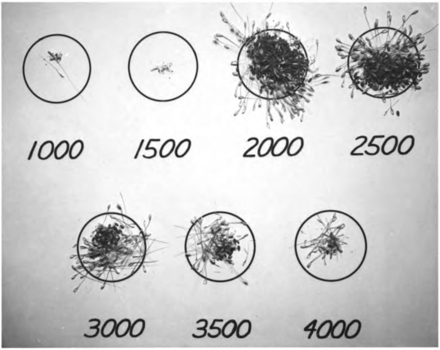
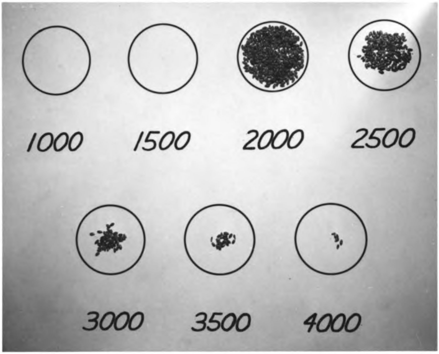


Figure 30. Effect of grain and variety upon the relationship of threshing force to percent of threshing



As threshed



After cleaning

Figure 31. Relative quantities of a bearded wheat threshed at various speeds of rotation (rpm)

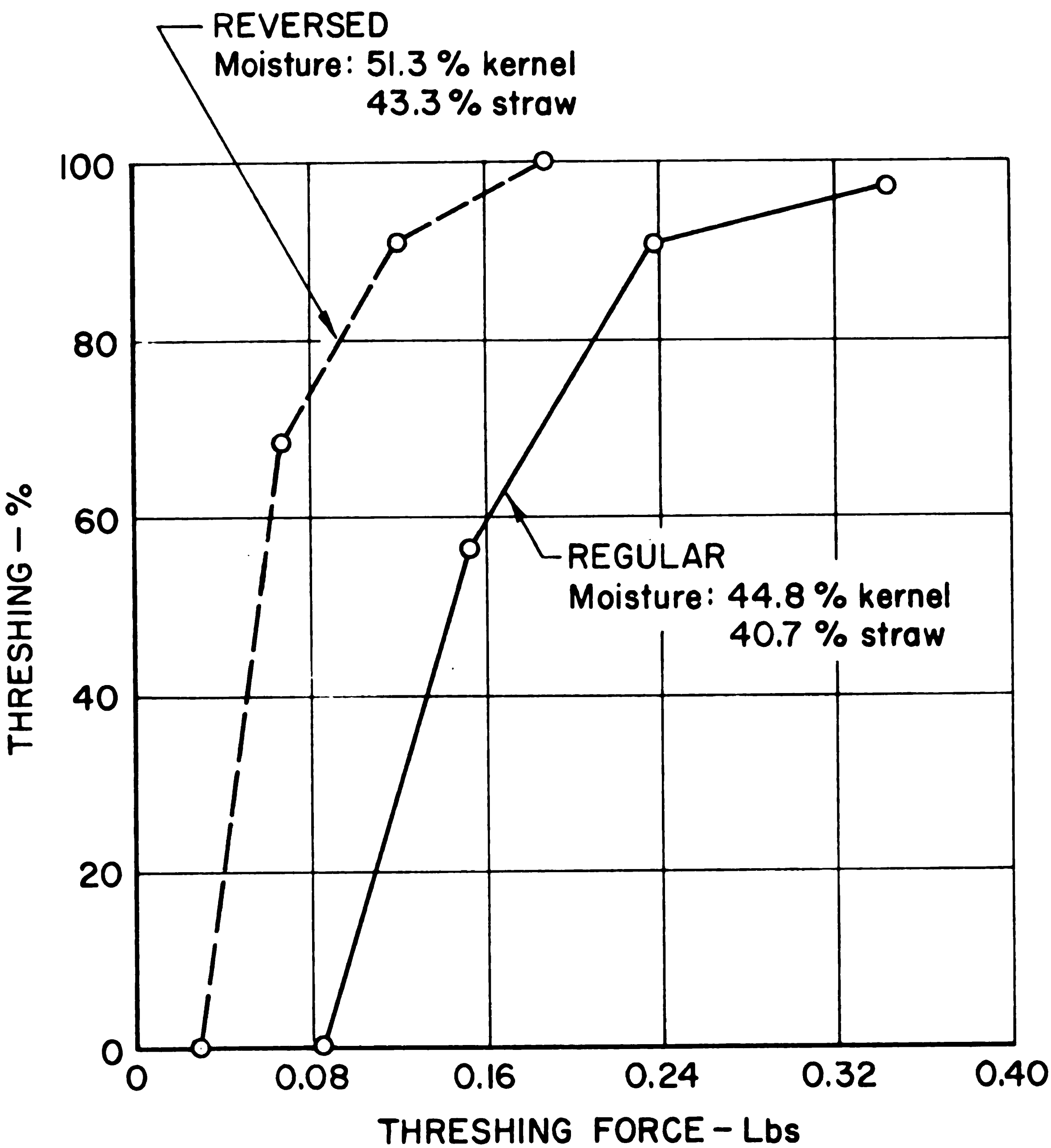


Figure 32. Effect of method of holding upon the relationship of threshing force to percent of threshing for high moisture Genesee wheat

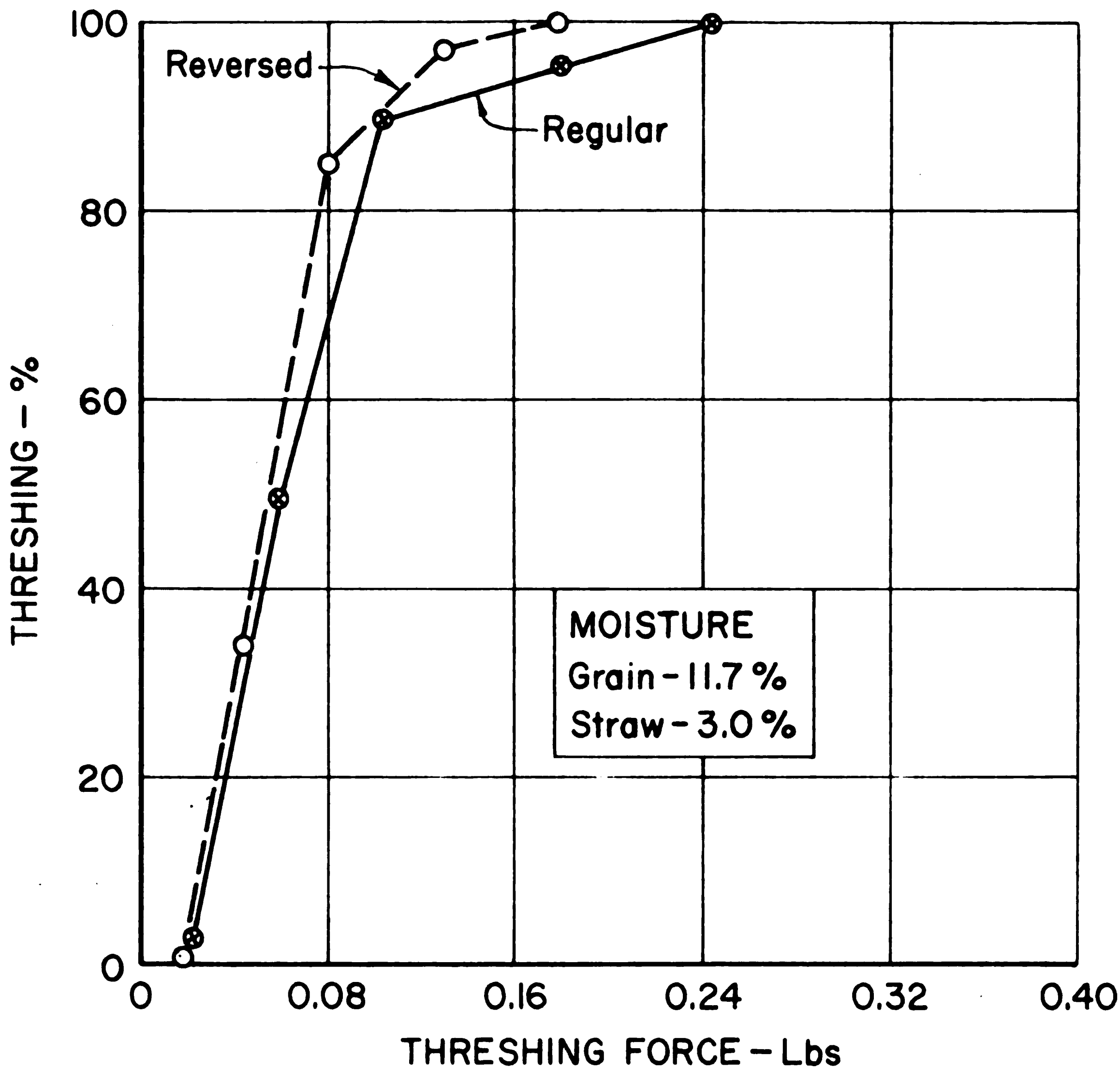


Figure 33. Effect of method of holding upon the relationship of threshing force to percent of threshing for dry Seneca wheat

with the straw stationary relative to the cylinders. For complete threshing relative motion between the straw and the cylinder must be obtained. It was also observed that visual kernel damage would be a problem if the perforated holes had sharp edges.

Figure 34 presents the difference when centrifugal force was applied with and without air resistance. The data shown were obtained simultaneously from the same crop sample. Each datum point on the centrifugal curve represents one head whereas each point on the other curve is the average of 24 heads. The heads which were completely enclosed in a centrifuge cup had to be subjected to higher forces for threshing to occur. The air resistance helps to open the chaff and lessen the threshing forces required.

<u>Chaff removal</u>

The amount of chaff removed during threshing varied according to crop maturity, moisture of chaff and straw, variety and method of holding. Quantitative measurements of comparative amounts of chaff removed under the various conditions were not obtained, although chaff-grain ratios were calculated on the wet basis. This ratio was not satisfactory for comparative use because chaff moistures were not obtained.

Grain threshed in the centrifugal cup was completely clean of chaff. See Figure 35. Head appearance after threshing was identical to unthreshed heads under this air resistance-free condition (Figure 36). Results of this nature would completely eliminate subsequent separation and cleaning operations.

The other extreme, where the stems were completely stripped of chaff, was frequently obtained when threshing in the experimental thresher with a dry, mature crop. The stems on the leading side of clamped group were always

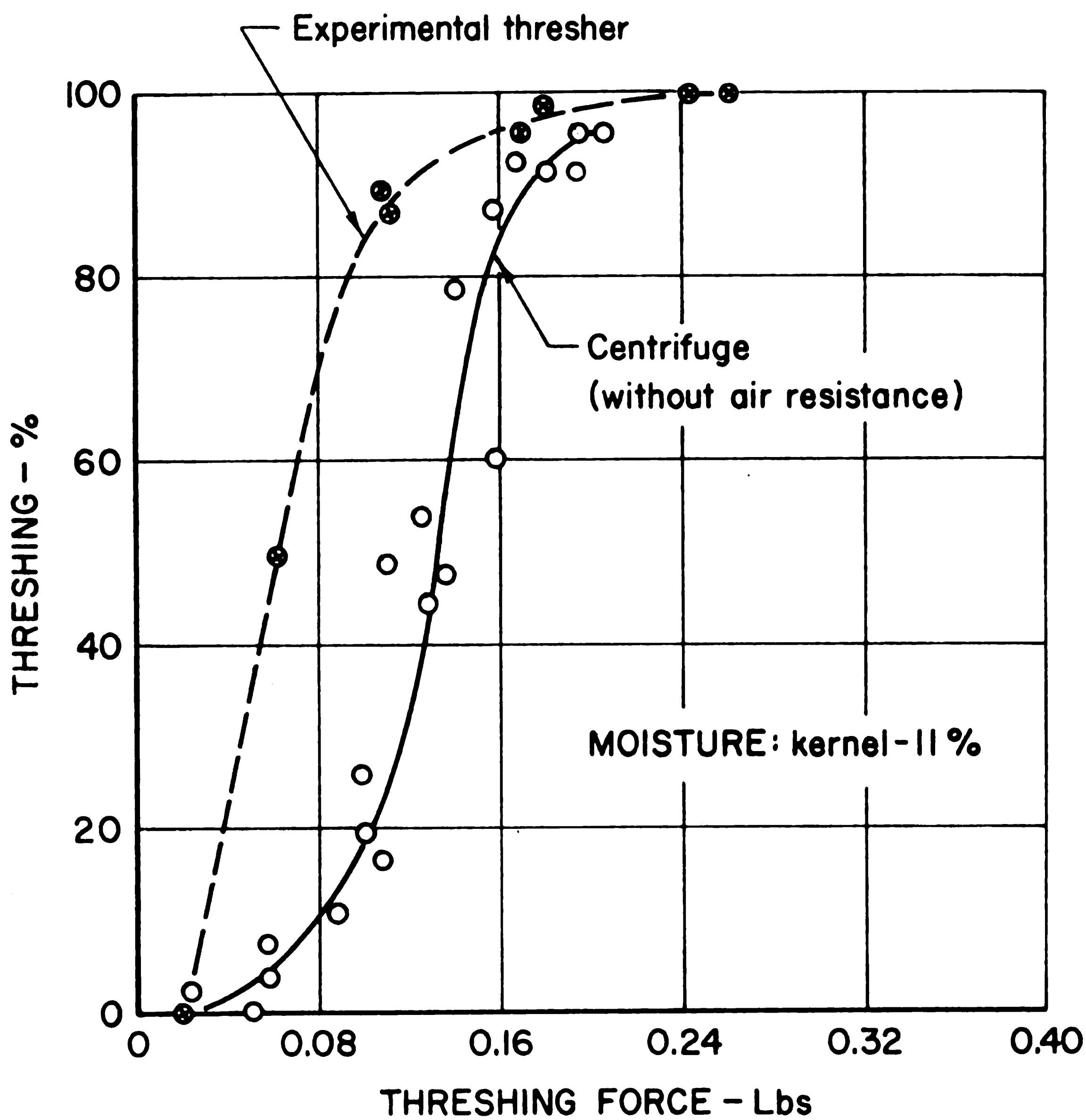


Figure 34. Effect of air resistance upon the relationship of threshing force to percent of threshing

Figure 35. Resultant straw and grain condition after threshing without air resistance

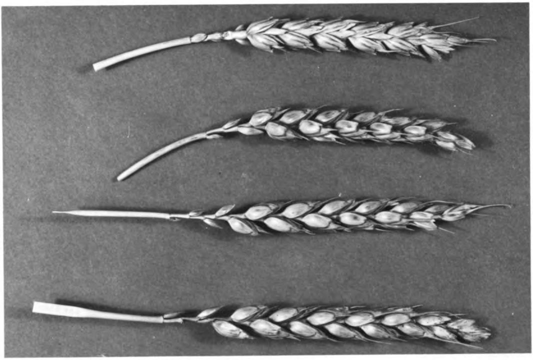


Figure 36. The two threshed heads at the bottom appear similar to the unthreshed heads at the top when threshed without air resistance.

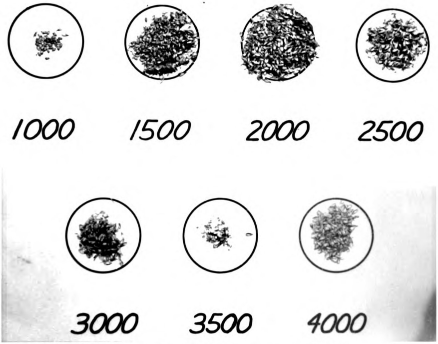
more free of chaff than those on the trailing side. (Leading side refers to that which would first contact air or other resistance.)

Two samples were hand stripped to obtain chaff-grain ratios under complete threshing conditions. A sample of Genesee taken from the greenhouse and permitted to air dry to a kernel moisture of 13.4 percent had a chaff-grain ratio of 0.182. A field sample obtained immediately after a rain gave ratios of 0.138 and 0.132 for the wet and oven dry conditions respectively. The grain, chaff and straw moisture contents under the wet condition were 15.5, 35.0 and 21.3 respectively. The chaff-grain ratio varied during threshing with the experimental thresher from 0.088 to 0.185.

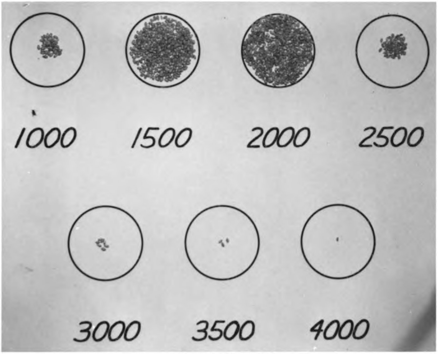
In general, a high percentage of chaff remained on the stem when the chaff was high in moisture, regardless of the source. The bearded wheat and rye during threshing lost a smaller percent of the chaff than the other varieties. Reversed holding resulted in more chaff being removed from the stem. Figures 31 and 37 give an indication of the quantities of chaff removed at the various speeds.

The effect of surface moisture upon the speed at which the chaff was separated is shown in Figures 38, 39 and 40 for dry, dew-laden and wet-by-rain samples of Genesee wheat. All curves are based upon total chaff removed and do not indicate comparative amount of chaff removed under the three conditions. The relative amount of grain threshing in percent is also shown for each condition.

Moisture, it is noted, reduced the peak percentages of chaff removed and shifted chaff removal to higher speeds. Accepting speeds necessary to remove 98 percent of the grain would reduce the chaff loads by substantial percentages. (Note also that the speed at which the greatest amount of grain



Before cleaning to remove chaff



After cleaning

Figure 37. Total and clean grain threshed at various speeds of rotation (rpm), Genesee wheat

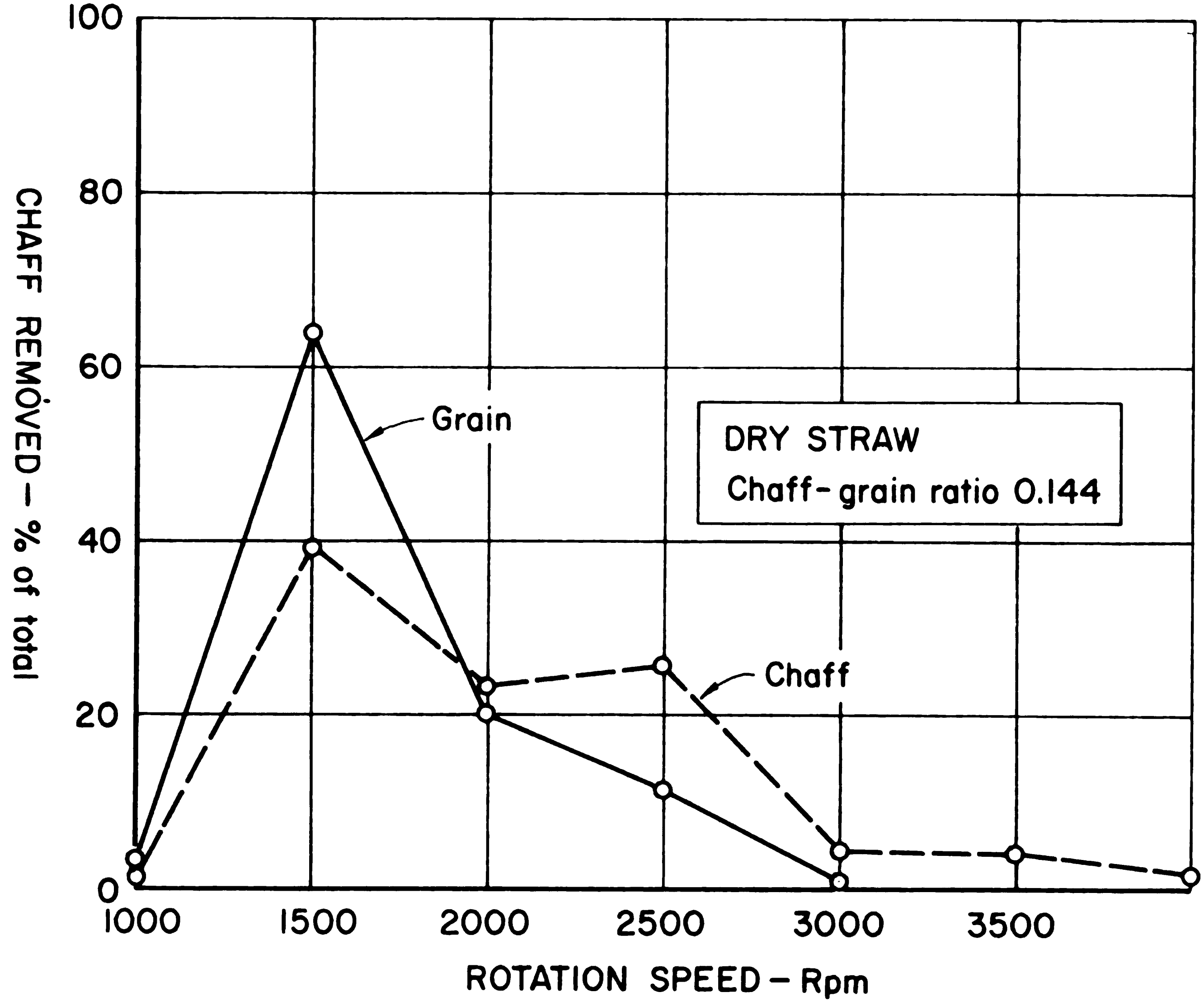


Figure 38. Relationship of speed to quantity of chaff and grain removed from dry straw

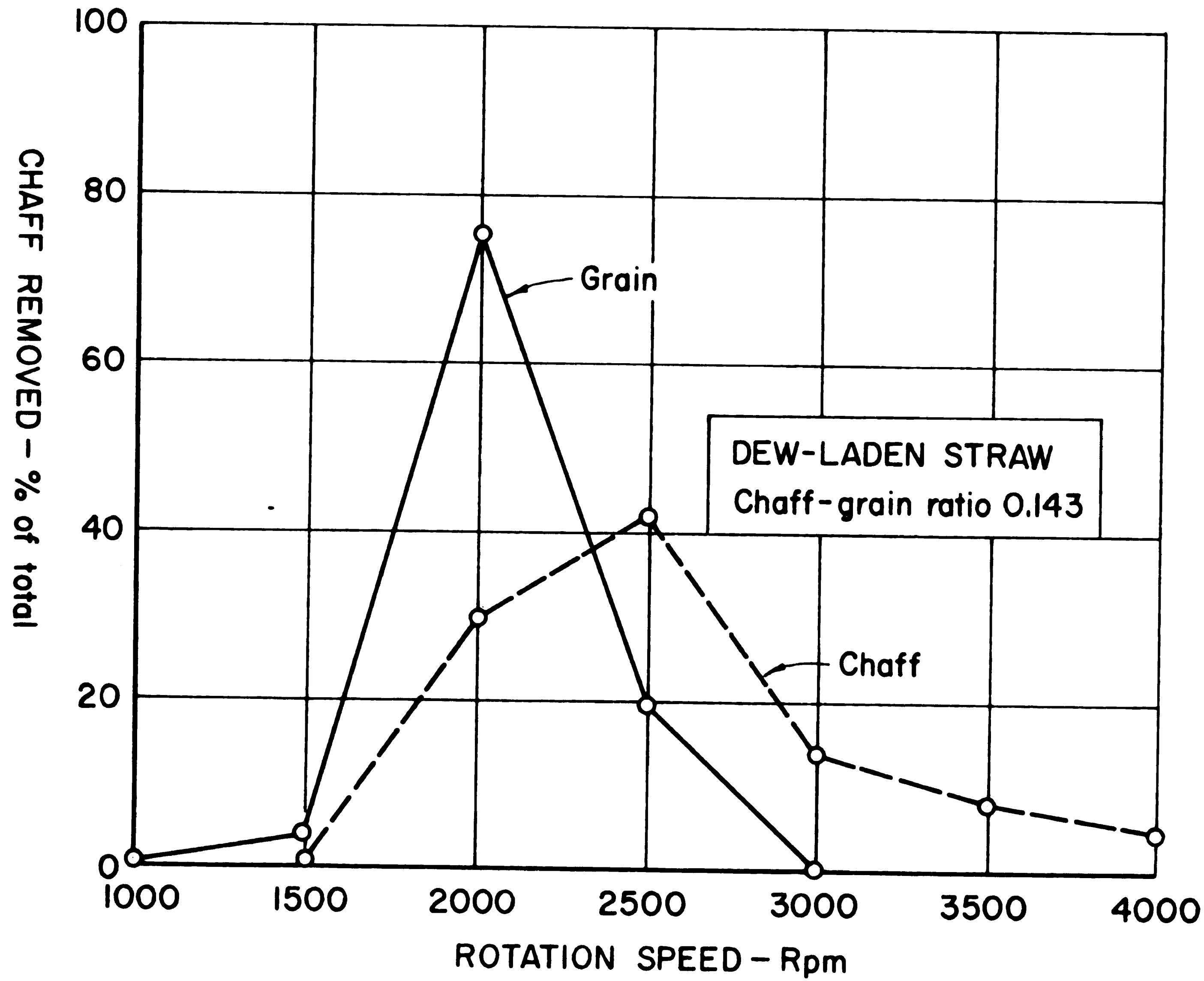


Figure 39. Relationship of speed to quantity of chaff and grain removed for dew-laden straw

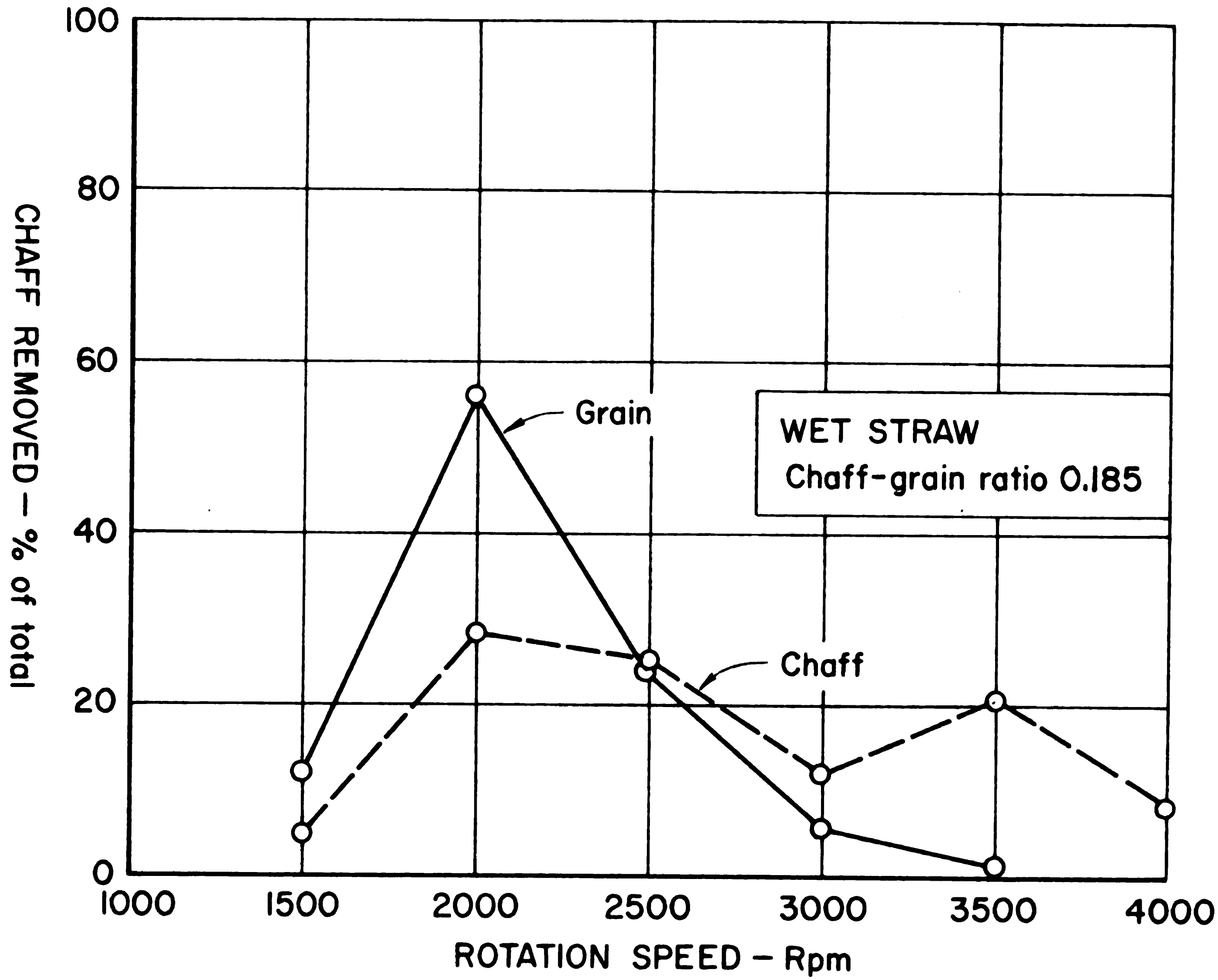


Figure 40. Relationship of speed to quantity of chaff and grain removed fro wet straw

was threshed was increased by the moisture. Maximum speed for complete threshing, however, was not materially influenced by the dew.)

Kernel separation by size

Table 1 shows the average kernel weights of grain threshed and removed at the various speeds of rotation in the experimental thresher and the commercial centrifuge.

The last to be threshed kernels were 21 to 28 percent lighter than those removed in the middle speed ranges. There was probably little significance in weight between those removed at the lower speeds and those removed at the middle speeds.

Kernel germination

The percent germination of Seneca wheat threshed centrifugally and by hand under various moisture conditions is shown in Table 2. The hand threshed samples were air dried in the head until threshed.

At kernel moisture above 36 percent, there was definite evidence of kernel deformation, since the hand threshed samples were much higher in germination. The highest percent of germination was obtained for the hand threshed grain at these moistures, ranging 93 to 98 percent. The germination for the centrifugally threshed samples varied from 2 to 86 percent with most samples under 50 percent. A softer coating on the outer housing of the centrifugal thresher would be required at these moistures.

The germination of the centrifugally threshed grain removed at the lower speeds was consistently higher than the check-hand threshed sample. It was frequently lower at the higher speeds, however, indicating that internal kernel damage can readily occur. The drier grain did not experience

Table 1. Relationship between cylinder speed and average weight of kernels removed when threshed by experimental thresher and centrifuge

Experimental thresher

Speed of rotation up to	Winter stored Genesee	Maximum Weight	Field picked Genesee	Maximum Weight
rpm	grams	%	grams	%
1000	.048	96	.041	98
1500	.050	100	.042	100
2000	.049	98	.041	98
2500	.049	98	.041	98
3000	.045	90	.037	88
3500			.030	72
4000	.038	76		
unthreshed kernels	none		none	

Commercial centrifuge

Speed of rotation up to	Winter stored Genesee	Maximum Weight
rpm	grams	%
1650	.049	93
2000	.053	100
2400	.053	100
2850	.048	90
unthreshed kernels	.042	79

Table 2. Germination of Seneca wheat when threshed by different methods and at various kernel moistures

Kernel Moisture	Hand Threshed	Centrifugally threshed: rpm of threshing 1500	2000	2500	3000	3500
Percent	Percent			Percent		
39.4	93		2	54		
39.0	96			47	49	
38.6	98			21	44	
38.1	96		65	32		
36.4	95			86		2
33.1	77		63	61		
23.0	76		92	82		
20.2	83		7	88		
19.4	68		73	60		
19.0	70		96	87		
17.3	71		85	92		
17.2	78		83	80		
16.7	89	99	94			
15.5	63	96	82			
14.8	62		94	90		
14.6	90	96	71			
14.6	73		94	62		
14.5			96	71		
14.4			93	87		
13.8	71		93	43		
13.7	85	99	82			
13.4	89	100		91		
13.2	76		97	60		
12.2	87	98	85			
12.2	76		93	88		
12.1	89	100	84			
12.1	76	94	86			
11.8	83		90	59		
11.8			98	93		
11.6	88	100	89			
11.4			100		99	
11.3	90	99	84			
11.2			98	68		
11.1	69		90	70		
11.0	60	69	87			
11.0	89	93	96			
10.9	74	88	60			
10.8	96		98	90		
10.7	93		99		82	
10.5	73	82				
11.4	87	89	82			
10.2	82	98	71			
9.6	95		97	82		

a severe germination loss, however.

The superior germination of the centrifugally threshed grain at the lower speeds over the hand threshed samples could be caused by kernel selection in harvesting. The healthier, better kernels (as measured by the germination criterion) were perhaps removed first. The extent to which kernel selection affected germination cannot be pinpointed from this study, although the fact that the check germination generally falls between the higher and lower values of the centrifugally threshed wheat strongly suggests kernel selection.

Grain threshed centrifugally had better germination than combine harvested grain as indicated in Table 3. The maximum germination obtained from centrifugal threshing was 98 percent compared to 91 percent for the combine.

Table 3. Comparative germination of Seneca wheat when threshed by combine, centrifugal thresher and hand

Kernel moisture	Hand threshed	Combine threshed	Centrifugally threshed, rpm of threshing: 1000	1500	2000	2500
Percent	Percent	Percent	Percent			
11.3					96	
11.3		80	98			97
11.1		to			93	86
10.0		91			98	98
9.2				96	96	
11.4	87	70		89	82	
10.2	82	to		98	71	
9.6	95	85			97	82

Exploratory threshing of corn

Figure 41 presents the forces required to thresh high moisture wheat and 17 percent corn. The corn was placed so that the kernels had to bend through an angle of 90°. The kernels broke clean, apparently using the cob as a partial fulcrum.

Although the force required for corn threshing was much greater than that required for wheat, the drum speeds required were similar. This can be explained by the fact that individual corn kernels weigh approximately four times as much as wheat kernels.

There was evidence of corn kernel damage at the higher speeds, indicating that a thicker padding would be required on the housing. Occasionally the cob would shear from the restraining bolt before shelling was complete.

Physical Characteristics of Grain

Kernel weight analysis

Kernel weight-frequency histograms for five wheat varieties and rye are presented in Figure 42. Rye approaches a normal distribution curve. All the wheat varieties are skewed heavily to the larger kernel side of the histogram.

A complete grouping by weight for a 250 kernel random sample of Genesee wheat is presented in Table 4. The percent of total weight is also shown in this table. The range in kernel weight (0.039 grams) exceeds the average kernel weight.

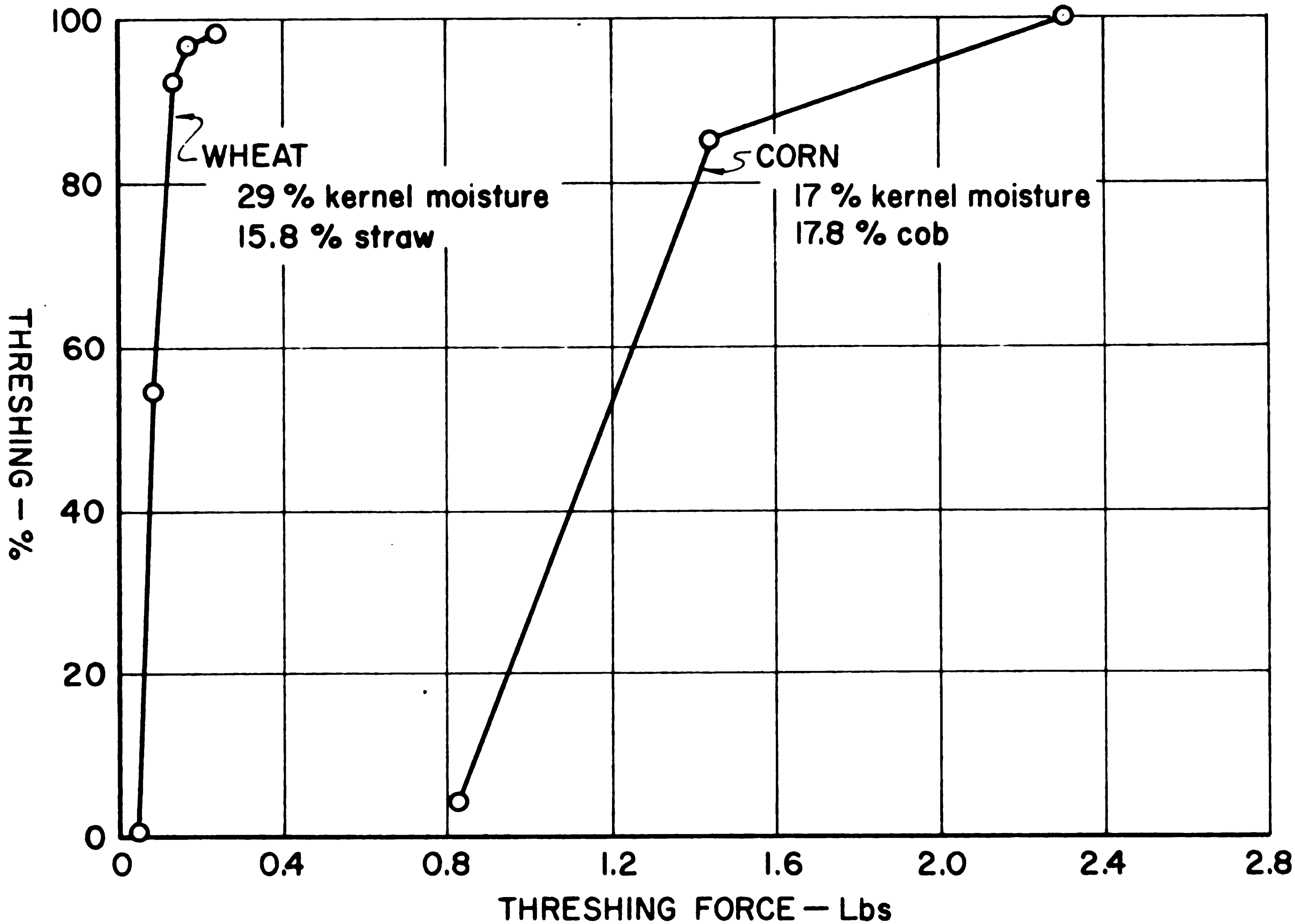


Figure 41. Comparative forces required to thresh high moisture wheat and corn centrifugally

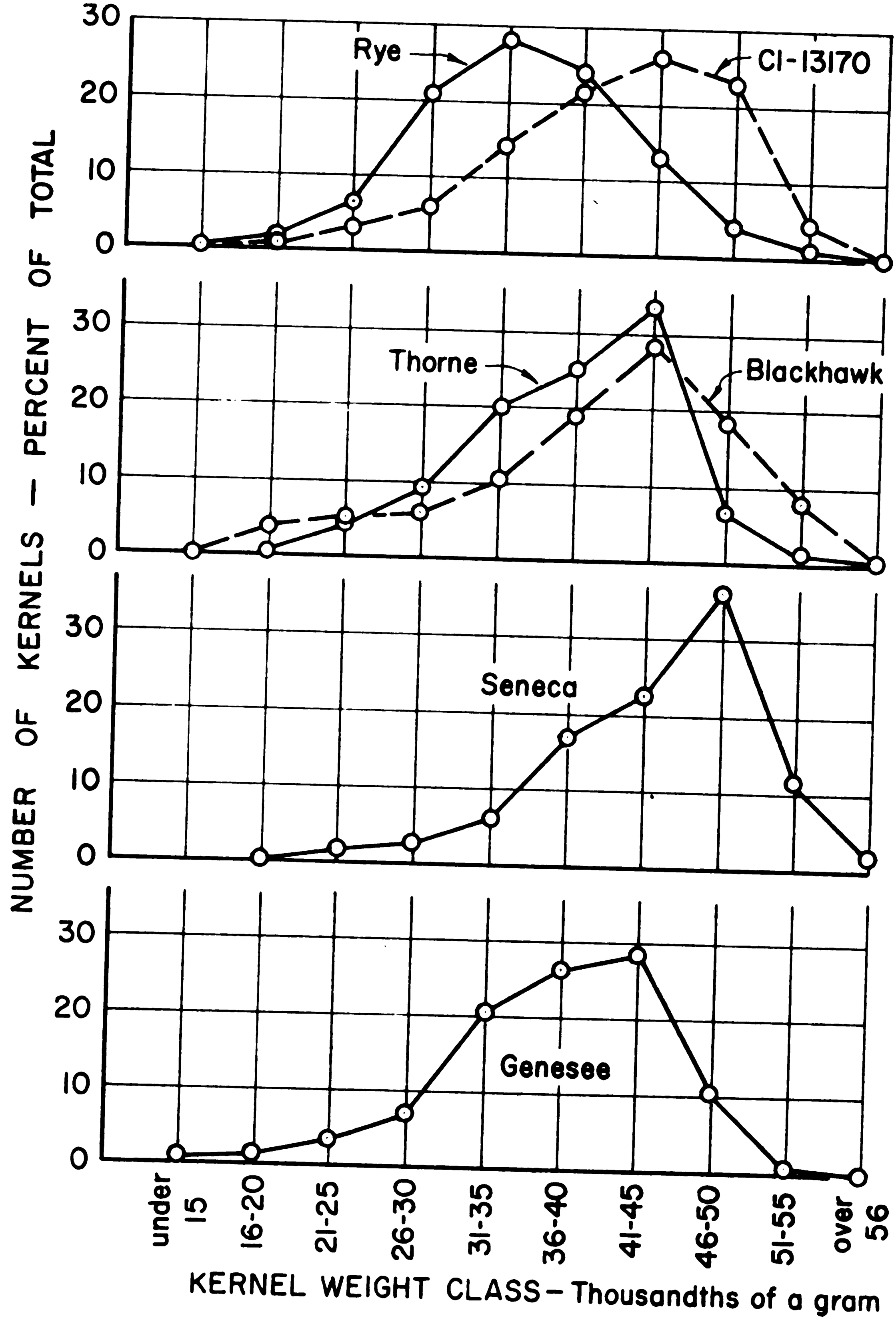


Figure 42. Kernel weight-frequency histograms for five wheat varieties and rye

Table 4. Weight frequency statistics for random sample of Genesee wheat

Weight Class	Frequency of Occurrence	Total weight in class	Cumulative total
grams		Percent	Percent
.053	1	.56	.56
.050	2	1.07	1.63
.049	2	1.04	2.68
.048	4	2.05	4.72
.047	2	1.00	5.72
.046	16	7.85	13.6
.045	10	4.80	18.4
.044	13	6.10	24.5
.043	11	5.04	29.5
.042	19	8.51	38.0
.041	18	7.87	45.9
.040	15	6.40	52.3
.039	13	5.40	57.7
.038	13	5.27	62.9
.037	10	3.94	66.9
.036	15	5.76	72.7
.035	12	4.48	77.1
.034	15	5.44	82.6
.033	9	3.17	85.6
.032	6	2.05	87.8
.031	10	3.30	91.1
.030	3	.96	92.0
.029	3	.93	93.0
.028	4	1.19	94.2
.027	3	.86	95.0
.026	5	1.39	96.4
.025	3	.80	97.2
.024	4	1.02	98.2
.022	1	.23	98.5
.021	1	.22	98.7
.020	1	.21	98.9
.019	2	.41	99.3
.018	1	.19	99.5
.015	2	.32	99.8
.014	1	.15	100.0
Total	250	100.0	

Average kernel weight 0.0375 grams
Median kernel weight 0.036 grams

Kernel weight by location in the head

Ten Genesee wheat heads with 347 total kernels were analyzed by weighing each kernel and recording its position from the apical kernel. The kernel position within the spikelet was also recorded. Results are presented in Tables 5 and 6 and Figure 43. The minimum number of spikelets on any head analyzed was 13. Heads having more spikelets had the additional spikelets averaged in rows 5 through 9.

The center spikelets of a wheat head contained the heaviest kernels. Within any spikelet where more than 2 kernels had grown, the outside kernels were heavier than the inside kernels.

Kernel moisture variations within a wheat head

A kernel moisture by spikelet-position analysis was made for 3 heads of immature Seneca wheat. These results are shown in Table 7. Except for the apical kernels which were driest, relatively minor moisture variations existed within any head.

Straw Physical Properties

The problem of maintaining constant straw moistures complicated straw physical properties determinations. Straw moisture changes were very rapid when extreme moisture gradients existed. It would appear that straw determinations should be made in controlled atmosphere rooms. The results reported here, therefore, must be considered as exploratory in nature.

The results presented in Table 8 show values obtained under generally changing straw moisture conditions. These conditions are probably descriptive of the ranges a thresher would experience under field operation.

Table 5. Weight-frequency distribution by spikelet location on head for Genesee wheat

Spikelet from apical spikelet	Under .015	.016-.020	.021-.025	.026-.030	.031-.035	.036-.040	.041-.045	.046-.050	.051-.055	Over .056
	Number of kernels of each weight class									
1		2			2	3	1			
2			1	1	4	7	2	1		
3		1			3	7	6	1		
4						7	8	4		
5			1			5	12	12	4	
6			1	2	2	2	7	10	9	2
7				3	1	4	6	10	5	1
8	1		1		4	3	11	10	6	1
9			1	2	3	9	19	9	8	2
10				2	3	2	13	6	2	
11			1	3	5	6	8	3	2	
12	1	1	1	2	1	14	4	2		
13	1		1	3	4	5	2			

Table 6. Relationship of kernel position within spikelet to average and extreme weights of Genesee wheat

Spikelet from apical spikelet	Kernel position within spikelet			Average of all within spikelet	Extremes	
	Left	Middle	Right		Maximum weight	Minimum weight
	average weight - grams			grams	grams	grams
1		.0317		.0317	.0430	.0181
2	.0380	none	.0346	.0363	.0482	.0245
3	.0385	"	.0374	.0379	.0456	.0196
4	.0414	"	.0404	.0410	.0494	.0352
5	.0439	.0240	.0456	.0441	.0524	.0350
6	.0476	.0316	.0481	.0446	.0560	.0244
7	.0466	.0326	.0462	.0432	.0565	.0216
8	.0454	.0339	.0480	.0428	.0553	.0105
9	.0445	.0370	.0483	.0433	.0577	.0216
10	.0427	.0366	.0443	.0419	.0542	.0273
11	.0438	.0329	.0386	.0386	.0521	.0236
12	.0375	.0298	.0387	.0359	.0475	.0146
13	.0358	.0284	.0368	.0333	.0435	.0147

Composite Average .0409 grams

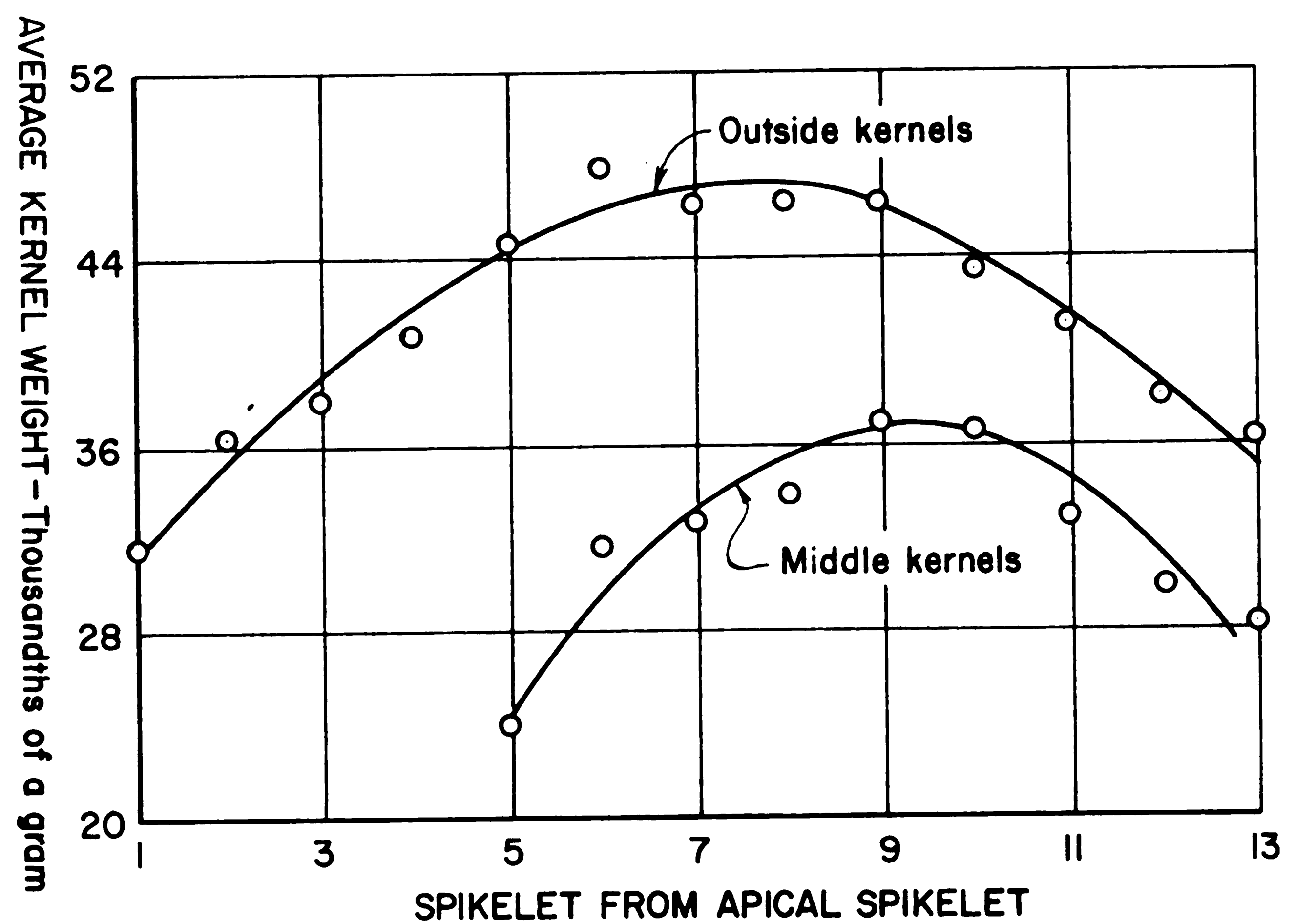


Figure 43. Relationship of kernel position on the head to kernel weight for Genesee wheat

Table 7. Kernel moisture by spikelet location for three heads of Seneca wheat

Spikelet from apical spikelet	Head 1	Head 2	Head 3
1	21.2	34.3	40.2
2	28.9	34.1	
3	28.2	38.1	42.2
4	18.6	45.4	39.0
5	30.5	43.7	40.9
6	34.1	43.0	43.9
7	33.6	42.4	46.3
8	36.2	46.5	43.8
9	34.5	43.9	43.2
10	34.7	43.0	41.9
11	36.4	43.6	43.0
12	35.7	43.7	
13	37.7	43.1	
14	36.6	45.2	
15		43.5	
16		43.7	
17		44.7	

Table 8. Physical characteristics of Genesee wheat straw under various conditions

Sample description	Straw moisture	Average breaking force	Tensile stress	Coefficient of friction	
				Dynamic	Static
	percent	pounds	pounds/ sq. in.		
High moisture grain, straw air dried for 12 hours	11.9	13.	5,704	.32	.54
High moisture grain, freezer stored	13.8	12.3	10,650	.34	.56
Mature grain, light rain	14.1	20.1	16,200	.34	.57
Mature grain oven dried, straw picked up moisture from high humidity	10.1	13.2	9,170	.34	.54
Freezer stored, straw very dry because of hole in sack	3.5	17.1	14,630	.39	.65
Field collected sample during heavy rain	38.0	11.0	7,890	.44	.77
Field sample - dry	9.7	23.0	16,800	- -	- -
Green - immature	41.0	9.4	2,610	- -	- -

Coefficients of friction

Table 8 is arranged in order of increasing dynamic coefficients. The dynamic coefficient ranges from 0.20 to 0.33 less than the static coefficient. The coefficients increase generally with decreasing straw moisture, although surface moisture reverses the relationship. The total range in dynamic coefficients for straw free of surface moisture was 0.07.

Breaking force and tensile stress

High moisture, immature grain straw was much more easily broken than dry straw. Excessive surface moisture also reduced the breaking force. The tensile stress followed the same relationship.

If the kernel attachment follows the same relationship as straw, there would be reason to assume that threshing might be easier under certain higher straw moisture conditions.

Field Research Results

The summarized data from the combine threshing tests are presented in Tables 19, 20 and 21 (Appendix). Thirty-five combine tests were run concurrent with centrifugal threshing. Eighteen additional tests were conducted to establish the quantity of grain separated at the cylinder.

Cylinder adjustment and threshing loss

The percentages of unthreshed grain were plotted corresponding to the conditions of cylinder adjustment. Lines of constant threshing loss (called threshing loss contours) were then drawn (Figure 44). The threshing loss contours indicated reduced threshing losses as cylinder aggressiveness was increased either by greater cylinder speed or through reduced clearance.

The effects of cylinder adjustment upon the percent of unthreshed grain and the percent of separation (rack) loss are presented in Tables 9 and 10. An analysis of variance of the data indicated that neither cylinder speed nor clearance gave significant results at the 95 percent level (Table 22, Appendix). The F values for significance were 3.88 and 3.48 for cylinder clearance and speed respectively whereas the calculated values were 3.75 and 3.19.

Cylinder adjustment and separation (rack) loss

The results suggested a relationship existed between cylinder adjustment and separation (rack) losses (Table 9). A scatter diagram of separation losses plotted against cylinder peripheral velocity is presented in Figure 45.

From the practical standpoint, all separation losses were less than 40 pounds per acre, an amount generally considered acceptable. The maximum loss occurred at the lowest and highest cylinder velocities (3200 and 6300 fpm respectively). The loss at the velocity extremes was nearly twice that occurring at 4700 fpm. The rack loss varied only slightly as cylinder clearance was varied from 3/16 to 7/16 inches.

Apparently, the lower cylinder velocities do not completely free the kernels from the straw, although the kernels can be shaken free. At the higher velocities, greater straw breakage decreases separation efficiency.

Cylinder adjustment and visual kernel damage, germination and test weight

The effect of cylinder adjustment upon kernel damage, germination and test weight is presented in Table 11. The analysis of variance is presented in Table 22 of the Appendix.

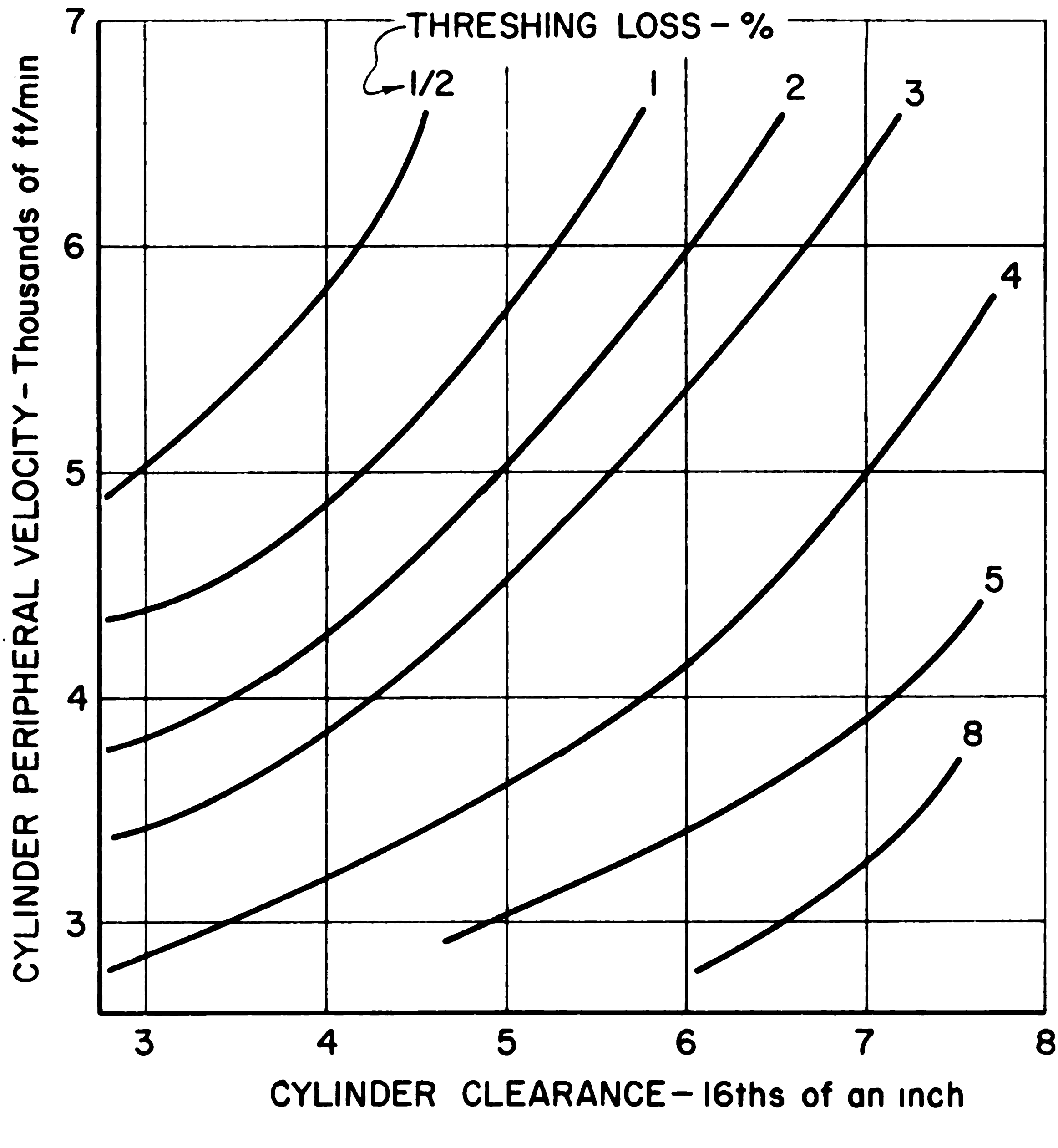


Figure 44. Relationship of cylinder adjustment to threshing loss for a rasp bar cylinder in dry Seneca wheat

Table 9. Effect of cylinder adjustment upon threshing and separation losses

Clearance	Cylinder speed	Threshing loss	Separation loss
inches	fpm	percent	percent
3/16	3100	3.49	.94
	3900	1.79	.81
	4700	.54	.59
	5500	.42	.70
	6300	.13	1.02
5/16	3100	4.98	1.10
	3900	3.34	.95
	4700	2.40	.55
	5500	.93	.93
	6300	.69	1.30
7/16	3100	8.59	1.47
	3900	4.63	.95
	4700	3.00	.42
	5500	3.36	1.43
	6300	3.00	.73

Table 10. Average effects of cylinder adjustment upon threshing and separation losses

Clearance	Mean threshing loss	Mean separation loss
inches	percent	percent
3/16	1.27	.81
5/16	2.47	.97
7/16	4.52	1.00
Speed		
fpm		
3100	5.69	1.17
3900	3.29	.90
4700	1.98	.52
5500	1.57	1.02
6300	1.27	1.02

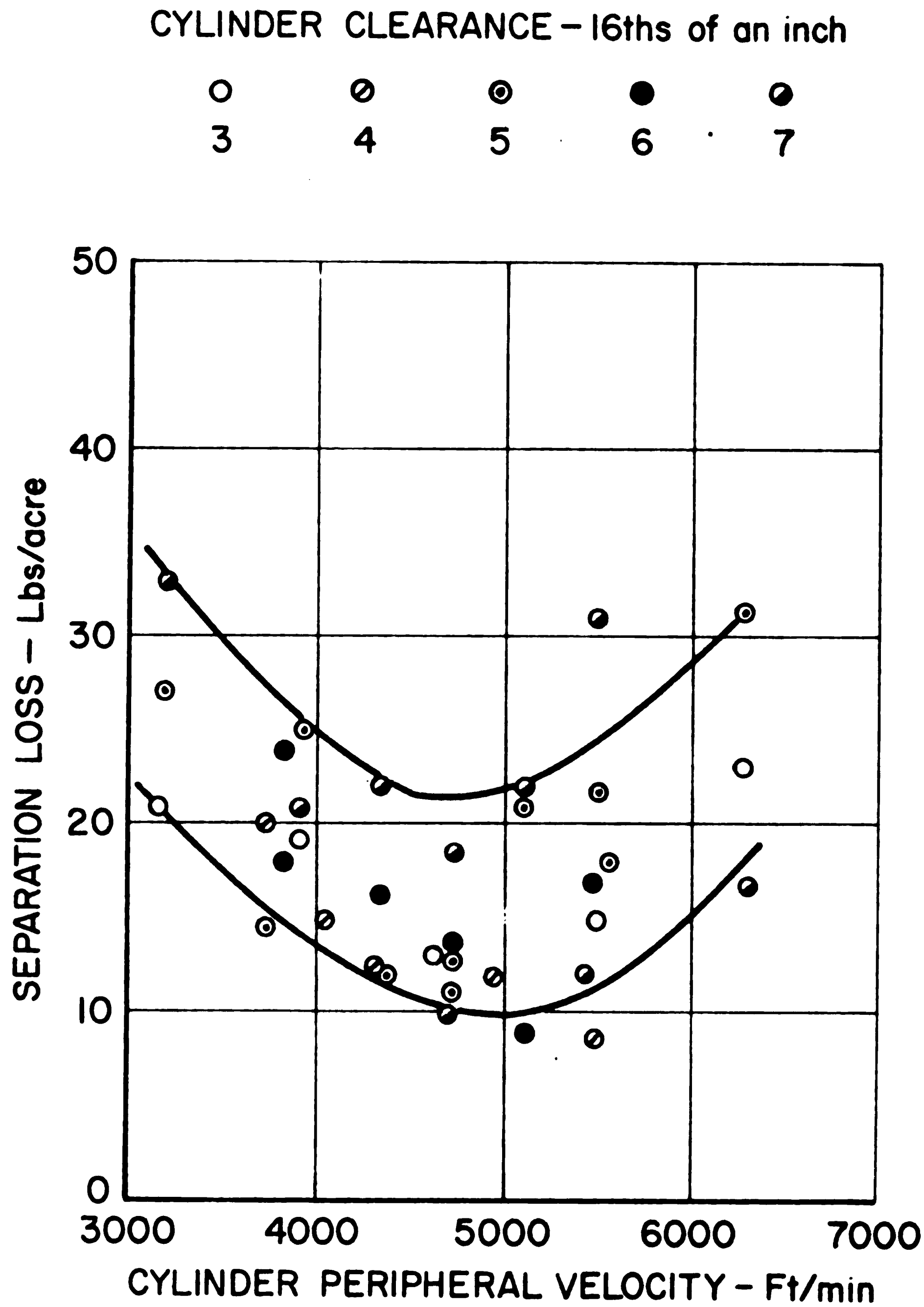


Figure 45. Relationship between cylinder adjustment and separation (rack) loss for dry Seneca wheat

Table 11. Effect of cylinder adjustment upon kernel damage, germination and test weight

Cylinder clearance	Cylinder peripheral velocity	Germi-nation	Test weight	Kernel damage
inches	fpm	percent	pounds/bushel	percent
3/16	3100	--	61.0	1.3
	3900	77	61.2	.6
	4700	73	60.8	3.1
	5500	80	61.1	4.8
	6300	70	60.5	3.1
5/16	3100	78	60.9	.6
	3900	75	61.0	1.8
	4700	--	60.5	2.0
	5500	75	60.5	2.3
	6300	75	60.1	4.3
7/16	3100	85	60.7	0
	3900	85	60.9	1.3
	4700	78	60.8	1.4
	5500	85	60.6	1.3
	6300	78	60.8	4.1

Figure 46 was prepared by plotting visual kernel damage versus cylinder adjustment and then connecting points of equal damage. The contours and the statistical analysis suggested that kernel damage is principally dependent upon cylinder speed. This result has been reported for corn by Pickard (1955).

The statistical analysis suggested, however, that cylinder clearance had a significant effect upon germination at the 95 percent level whereas cylinder speed was not significant. The germination was consistently low for all cylinder speeds and clearances, a fact which may have masked true effects.

Increased visual damage with higher cylinder speeds is an anticipated result, since kinetic energy imparted to the kernels is proportional to the square of the cylinder speed. Likewise, the kinetic energy is not directly related, if at all, to cylinder clearance. The germination results, however,

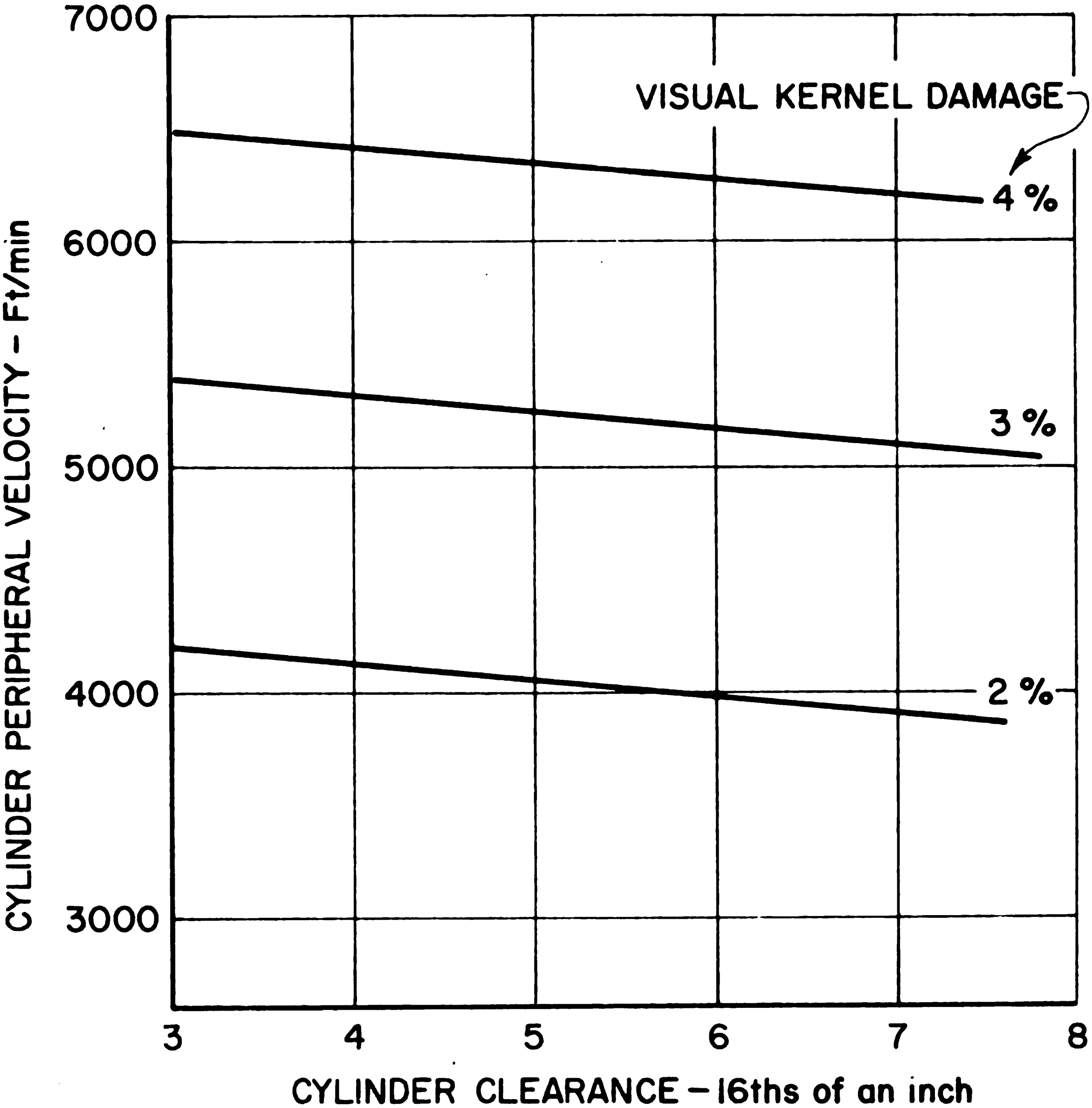


Figure 46. Relationship of cylinder adjustment to visual kernel damage for dry Seneca wheat

would not be anticipated, since a correlation would be anticipated between kernel visual damage and reduction in germination, and those factors causing kernel damage would be expected to cause germination damage.

Test weights of grain threshed at the various conditions of cylinder adjustment varied a little over 1 pound per bushel. The reduction appeared to be independent of cylinder adjustment.

Cylinder adjustment and grain separation at the cylinder

The amount of grain separated at the cylinder in percent of total grain is numerically presented in Table 12. Average effects of cylinder velocity and clearance is presented in Table 13. Figure 47 presents the same data graphically. The total grain separated at the cylinder increased with more aggressive cylinder adjustment. Increasing the cylinder velocity proved to increase the quantity separated at the cylinder with statistical significance at the 99 percent level (Table 22 in Appendix). Concave adjustments proved to give inconsistent results, although at cylinder velocities above 4800 fpm, the smaller clearance gave better separation. This result is in agreement with work by Johnson (1953).

The range of grain separation at the cylinder was 60 to 80 percent. From 30 to 45 percent of this was separated in the first part of the cylinder (zone 1). This fact suggests that a substantial part of the threshing occurs during initial acceleration.

Cylinder adjustment and location of grain separation over the rack

The effect of cylinder adjustment upon the separation pattern at the rack is shown in Figure 48 for four different cylinder adjustments. The adjustments shown permit comparisons caused by the extremes in cylinder

Table 12. Amount of grain separation at the cylinder at various cylinder adjustments

Cylinder peripheral velocity	Cylinder concave clearance	Grain separation Zone 1	Zone 2	Zone 3	Total Zone 1 and 2	Total Zone 1 2 and 3
fpm	inches	percent	percent	percent	percent	percent
3100	7/16	30.0	20.6	15.3	50.6	65.9
	5/16	30.6	26.3	6.3	56.9	63.2
	3/16	31.4	22.1	5.3	53.5	58.8
3900	7/16	31.4	29.3	7.7	60.7	68.4
	5/16	39.7	35.6	3.0	75.3	78.3
	3/16	40.0	28.6	6.2	68.6	74.8
4700	5/16	40.3	28.6	4.2	68.9	73.1
	3/16	43.9	27.3	2.8	71.2	74.0
5500	5/16	41.1	29.2	3.4	70.3	73.7
	3/16	46.3	30.1	2.2	76.4	78.6
6300	5/16	44.7	30.5	2.7	75.2	77.9
	3/16	47.3	32.4	1.5	79.7	81.2

Table 13. Average percentages of grain separated at zones 1 and 2 for all cylinder velocities and clearances

Cylinder to concave clearance	Cylinder peripheral velocity	Average separation at cylinder
inches	fpm	percent
7/16		55.6
5/16		69.3
3/16		69.9
	3100	55.2
	3900	72.0
	4700	70.0
	5500	73.3
	6300	77.4

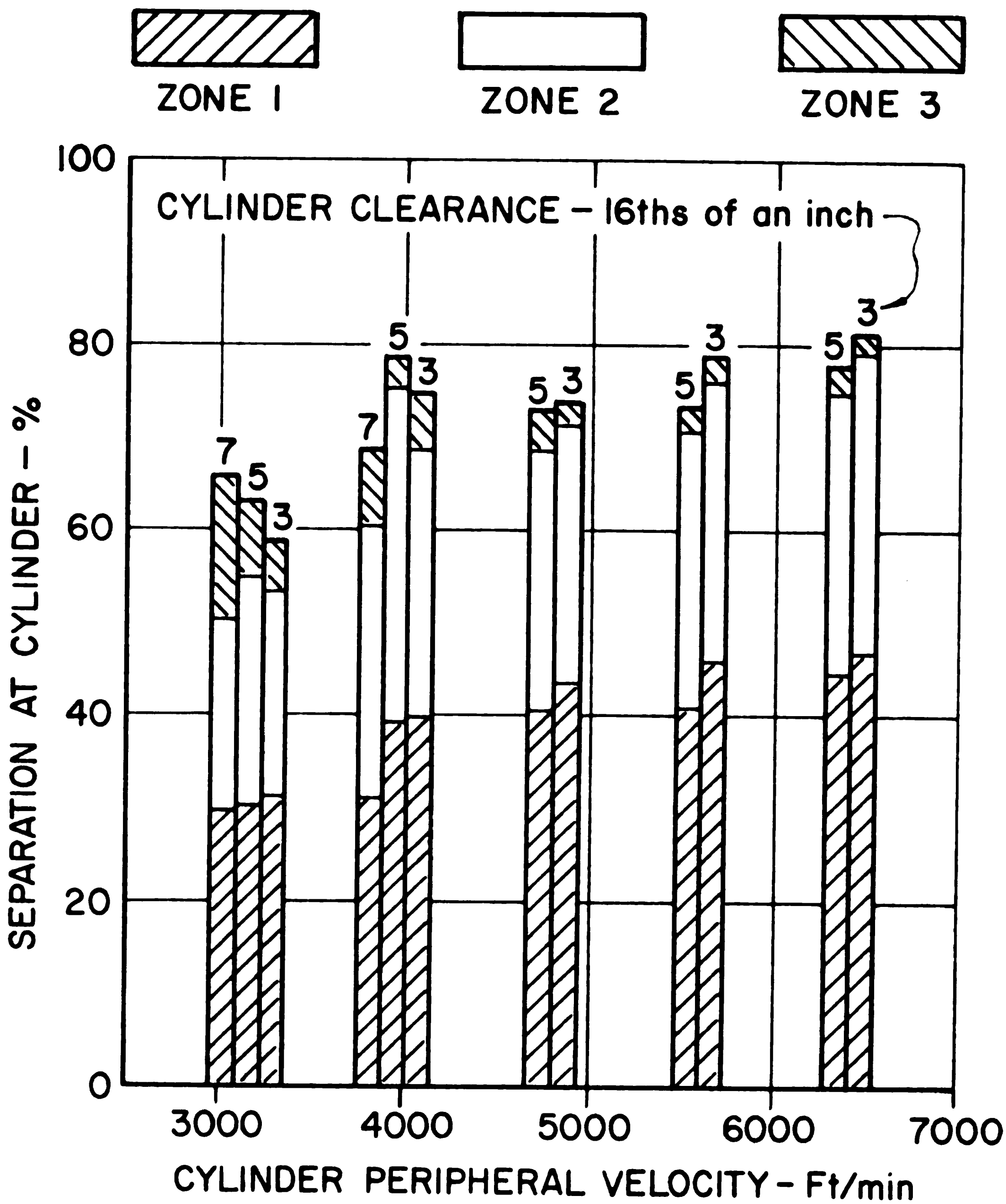


Figure 47. Effect of cylinder adjustment upon amount of grain separation at the cylinder

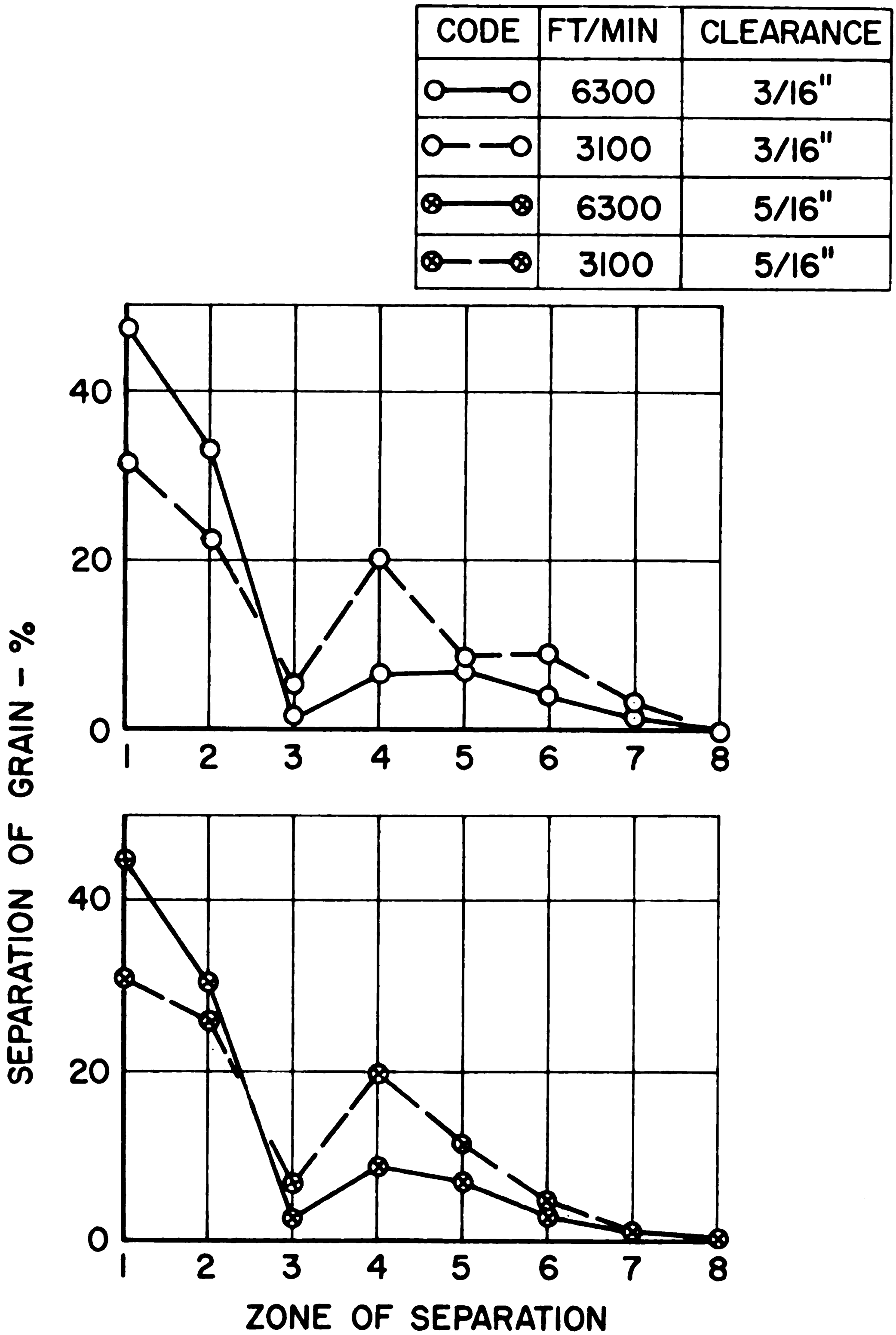


Figure 48. Influence of cylinder adjustment upon location of separation within a combine

adjustment. Differences in the rack separation patterns were small, although separation was completed quicker with the larger clearances.

<u>Cylinder adjustment and shoe load</u>

Increasing the shoe load can promote shoe overloading and subsequently excessive cleaning (or shoe) losses. A trend toward greater shoe loads with more aggressive cylinder adjustment was evident and is presented in Table 14. The shoe load as measured by chaff in pounds per minute increased 35 percent as the cylinder speed was increased from 3100 to 6300 fpm. Changing clearance from 5/16 to 3/16 inches increased shoe load by 15 percent.

Table 14. Shoe load as influenced by cylinder adjustment

Cylinder peripheral speed	Cylinder concave clearance	Chaff	Chaff to grain ratio	Shoe straw load	Shoe straw to grain ratio	Grain load	Total shoe load
fpm	inches	lbs/min		lbs/min		lbs/min	lbs/min
3100	7/16	23.7	.30	1.8	.024	82.7	108.2
	5/16	21.9	.31	1.8	.026	70.2	93.9
	3/16	23.1	.28	1.5	.019	79.8	104.4
3900	7/16	21.4	.26	2.1	.027	78.0	101.5
	5/16	20.9	.21	2.2	.022	98.6	121.7
	3/16	23.5	.30	1.0	.013	77.8	102.3
4700	5/16	23.4	.297	1.9	.024	78.8	104.1
	3/16	29.8	.33	3.5	.040	89.5	122.8
5500	5/16	25.4	.36	1.1	.016	70.5	97.0
	3/16	32.0	.33	.9	.009	95.8	128.7
6300	5/16	30.0	.38	1.5	.019	79.5	111.0
	3/16	31.9	.41	.8	.010	78.3	111.0

Feed rate and grain separation at the cylinder

Varying the feed rate had little effect upon the zone of separation at the cylinder as presented in Table 15 and Figure 49. There was slightly less separation on a percentage basis at the higher feed rates. This result would be expected since the thickness of the layer of material going through the cylinder increases with feed rate. The thicker layer would retard separation somewhat.

Feed rate and shoe load

Increased feeding rates resulted in larger shoe loads as seen in Table 16. The chaff to grain ratio remained essentially constant; a fact which suggests that the increase was directly proportional to feed rate.

Zone of separation and kernel weight

Kernel weights were made of grain separated in all the zones, the unseparated grain, and the unthreshed grain. All 100 kernel samples weighed within 2-1/2 percent of each other. This fact suggests that conventional threshing and separation are relatively independent of kernel weights.

Comparison of Centrifugal to Conventional Threshing

Threshing forces

The comparative results obtained when both types of threshing were accomplished concurrently are shown in Table 17. This table gives required threshing forces and cylinder adjustments for 96, 98 and 99 percent completeness of threshing. Any of the cylinder adjustment combinations give the same effect as the average indicated threshing force.

Table 15. Amount of grain separation at the cylinder by zones at various feed rates

Total straw and chaff feed rate	Grain separation Zone 1	Zone 2	Zone 3	Total Zone 1 and 2	Total Zone 1 2 and 3
pounds/minute	percent	percent	percent	percent	percent
87	41.2	31.1	2.7	72.3	75.0
103	35.9	22.6	23.2	58.5	81.7
133	43.8	29.0	3.6	72.8	76.4
210	41.8	27.4	4.3	69.2	73.5
252	40.5	26.2	6.7	66.7	73.4

Table 16. Shoe load at various feed rates

Total straw and chaff feed rate	Chaff	Chaff to grain ratio	Shoe straw	Shoe straw to grain ratio	Grain load
lbs/min	lbs/min		lbs/min		lbs/min
87	25.4	.333	1.64	.025	76
103	28.0	.290	1.50	.016	97
133	37.2	.334	1.67	.015	112
210	46.8	.274	4.53	.027	171
252	57.2	.338	2.70	.016	171

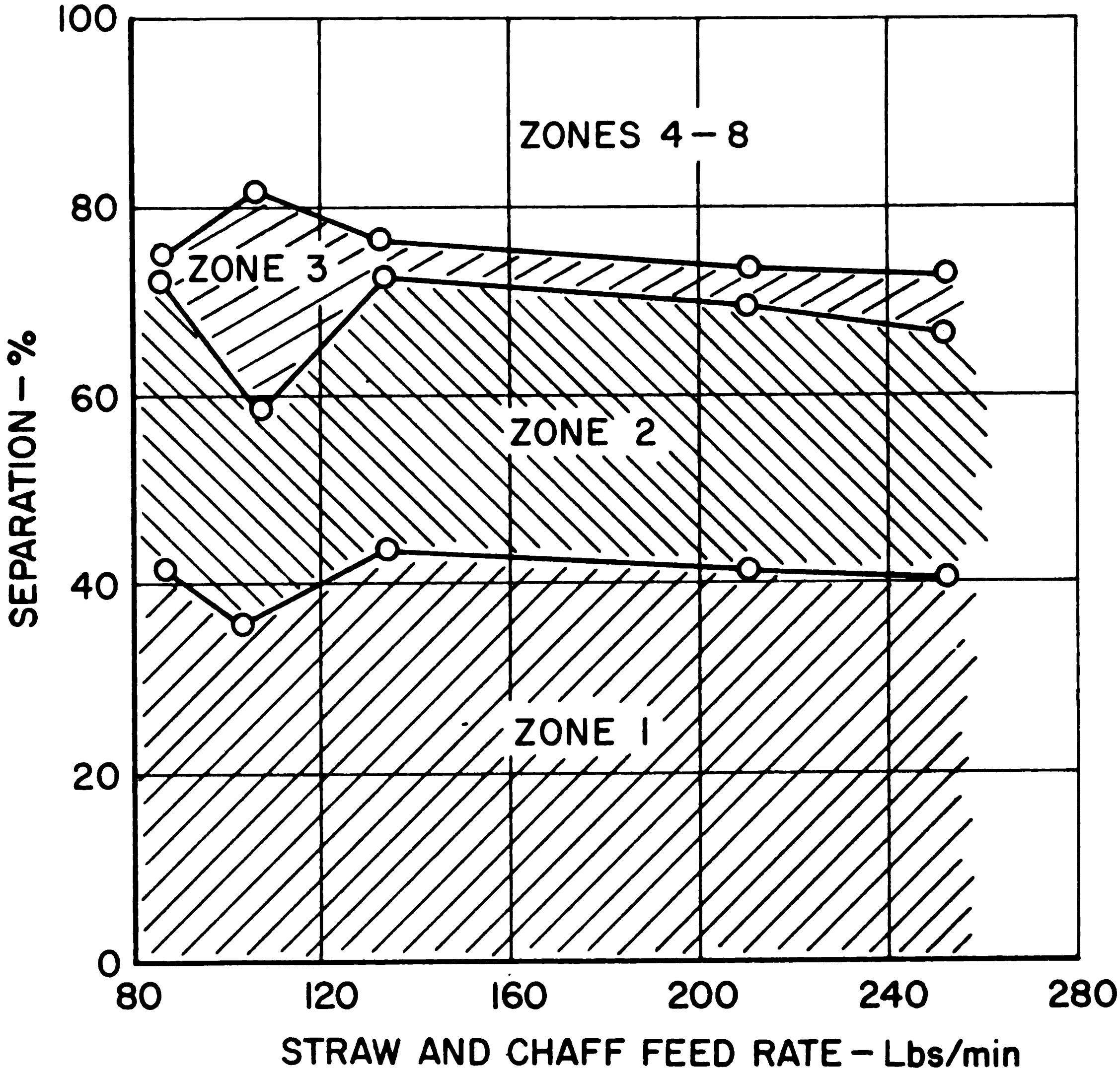


Figure 49. Effect of straw and chaff feed rate upon location of grain separation within a combine

Table 17. Comparative threshing forces and cylinder adjustment for 96, 98 and 99 percent threshing of dry, mature wheat

Threshing	Threshing force	Cylinder adjustment required to give same result: Peripheral velocity	Clearance
percent	pounds	fpm	inches
96	.19	5500	7.5/16
		5000	7/16
		4100	6/16
		3600	5/16
		3200	4/16
		2800	3/16
98	.23	6600	6.5/16
		6000	6/16
		5000	5/16
		4300	4/16
		3800	3/16
99	.27	6300	5.5/16
		5800	5/16
		4900	4/16
		4400	3/16

The moisture values obtained from oven drying (as all centrifugal threshed grain was tested) were 1 to 3 percent lower than the combined grain tested by an electric Steinlite moisture tester. Whether this difference was caused by the moisture testing equipment or by true moisture differences in the grain was not determined. A true difference could have existed because combined grain frequently picks up moisture during the threshing process from green material. The centrifugal threshing also has a drying effect upon the grain.

Application of the results of Table 17 into the theoretical threshing equations proves interesting. The threshing force was obtained by substitution of measured values into equation 24. Using the 6000 fpm cylinder speed at 98 percent threshing and a value for W_g of 1/10,000 pound in equation 21 gives an X value of 0.133 feet.

If this X value is substituted along with the previously assumed values into equation 19, a value for the quantity (E_g - E_s) is obtained. This value becomes 0.98. These answers, while feasible theoretically, need to be ascertained experimentally to establish their validity. The formulas for instance disregard cylinder clearance. The equivalent V_c needs to be established through the range of concave clearances.

To achieve a one percent improvement in threshing (98 to 99 percent), 17 percent increase in threshing force would be required. Likewise, a 14 percent cylinder speed would be necessary if clearances remained constant or nearly a 20 percent decrease in clearance if cylinder speed remained constant. Although energy relationships have not been thoroughly established, the grain gain (0.3 bushel per acre of 30 bushel per acre wheat) value must be carefully weighed against the increased costs of threshing.

Subsequent operations

The subsequent operations of separating the straw and cleaning the chaff from the wheat appear inescapable with conventional combines. Not more than 80 percent of grain could be separated from the straw during threshing. Even this quantity of grain needs to be subjected to some method of cleaning to remove the short pieces of straw and the chaff. An air blast would be sufficient to remove the chaff however. As reported in the literature review, some foreign machines by multiple and infinite diameter cylinders have increased the quantity separated during threshing. It would appear that any machine using the impulsive type of acceleration will need auxiliary equipment for separation.

In contrast, grain threshed centrifugally gives promise of not needing extra separation equipment, but that the threshing and separation can be integral. Further, if air resistance can be minimized or eliminated, even the cleaning operation would be superfluous. The latter condition would be difficult to obtain. Small quantities of chaff however are easily removed by air blast.

Chaff infestation in grain separated by a combine was twice that threshed centrifugally as measured by chaff-grain ratios. Combined samples averaged 0.33 whereas centrifugal threshed samples were less than 0.16.

The elimination of the additional equipment for separation would permit threshing on almost any grade with the centrifugal method.

Threshable moisture conditions

The research has indicated the wheat can be threshed centrifugally as soon as it is mature (approximately 40 percent kernel moisture). This can be accomplished without any visual damage and probably without internal damage as measured by germination tests. The practical limit with the cylinder-concave threshing mechanism has been established at 20 percent kernel moisture (Berg, 1949, Mitchell, 1955, Johnson 1959).

Rewetted straw makes centrifugal threshing functionally better. Less chaff is removed during the threshing. Threshing forces are not materially increased and because of the kernel weight increase from moisture, the grain can often be threshed at the same drum speed. Whether or not wrapping and balling would become problems at the higher straw moistures has not been established.

<u>Variable stage threshing</u>

As indicated in the literature review, some researchers believe a variation in threshing force has merit. The heavy, most mature grain would thresh at the lower speeds and the lighter grain at the higher speeds. Centrifugal threshing is well adapted to multi-stage threshing. Indeed, if the cone thresher becomes feasible, an infinite number of stages would exist.

This research has indicated average kernel weight differences up to 28 percent with centrifugal threshing. No grain weight differences could be found with the conventional threshing cylinder.

As previously discussed, the centrifugally threshed grain had better germination than the combined grain. The first to thresh grain averaged 8 percent better than combined threshed grain.

APPLICATIONS OF RESEARCH

Speeds and Forces Required for Threshing

This research has defined the force requirements for centrifugal threshing of wheat at various moisture conditions. The intelligent development of a continuous centrifugal thresher is now possible using these force requirements.

A large range of threshing forces is required because of natural variations in kernel weights. This variation is probably greater than the variation caused by moisture.

Revolutions per minute required at uniform kernel radius for threshing

The rpm required for various degrees of threshing is shown in Figure 50. A constant radius of one foot was assumed for all kernels. It was assumed that all kernels would break loose when subjected to the same threshing force. In the figure 0.10, 0.15 and 0.20 pounds force are shown.

For the Genesee wheat population a speed range from 1600 to 2400 rpm would remove 98 percent of dry grain. To thresh the remaining 2 percent, the speed must be increased up to 3100 rpm. The value of the last 2 percent of small under-developed kernels is questionable.

Corresponding speeds for wet grain are 2300 to 3400 rpm for 98 percent threshing and 4300 rpm for complete threshing.

Revolutions per minute required at variable kernel radius

All centrifugal threshing tests reported in this research unless specially indicated otherwise, were conducted with the head extending on radial lines from the axis of rotation of the threshing head. Kernel weight by

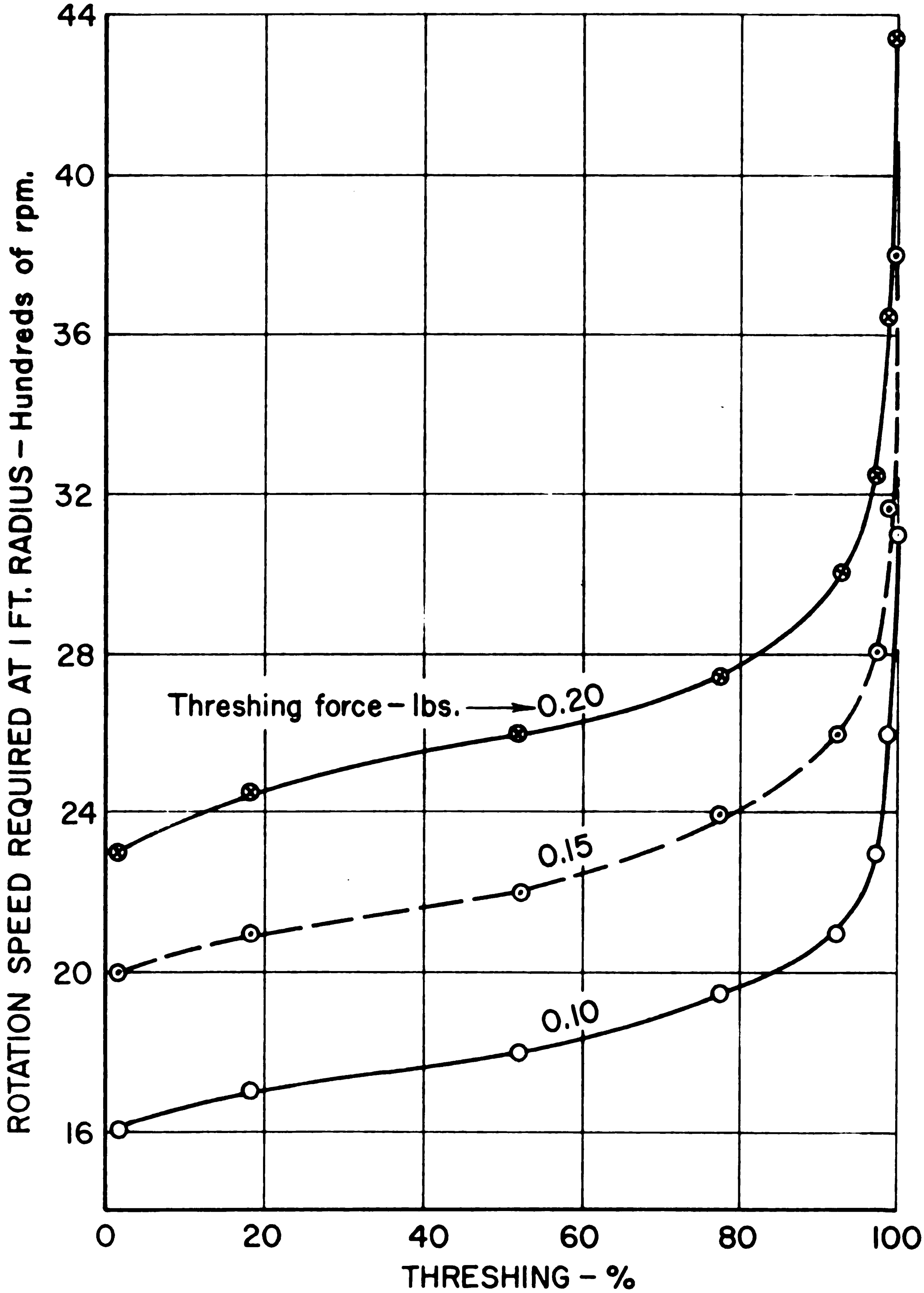


Figure 50. Speeds of rotation required for various degrees of threshing, and threshing forces (radius of rotation, one foot)

position in a head of grain is important therefore, in establishing speeds required for threshing.

The range in head length of Genesee wheat was from 2 to 4 inches with average length of 3 inches. In the test procedure, the apical kernel was placed at a radius of 11 inches.

Figure 51 presents the rpm required to thresh the heaviest, the average, and the lightest kernels by spikelet position counted from the apical spikelet. All speeds are based upon a threshing force of 0.10 pounds and are to the closest 50 rpm. The maximum radius of rotation is 11 inches.

The first kernels to be threshed would be in spikelets 4 through 8 while the last kernels to be threshed (the lighter kernels) would be in the last spikelet. It should be noted that the variation in speed caused by the variable radius is relatively minor compared to kernel weight variations.

Threshing force developed at variable kernel radius

Figure 52 compares forces exerted on the kernels by the kernel position in the head. A constant speed of rotation was assumed in making the table.

A force range from 0.05 to 0.21 pounds would be common for the typical head. If the same unit stress is required for threshing, it is apparent that the heavier kernels would be threshed and separated first.

Theoretical Equations of Threshing

The theories of threshing presented in this research will challenge designers, inventors, and serious students. Several constants and the general validity of the equations remain to be proved.

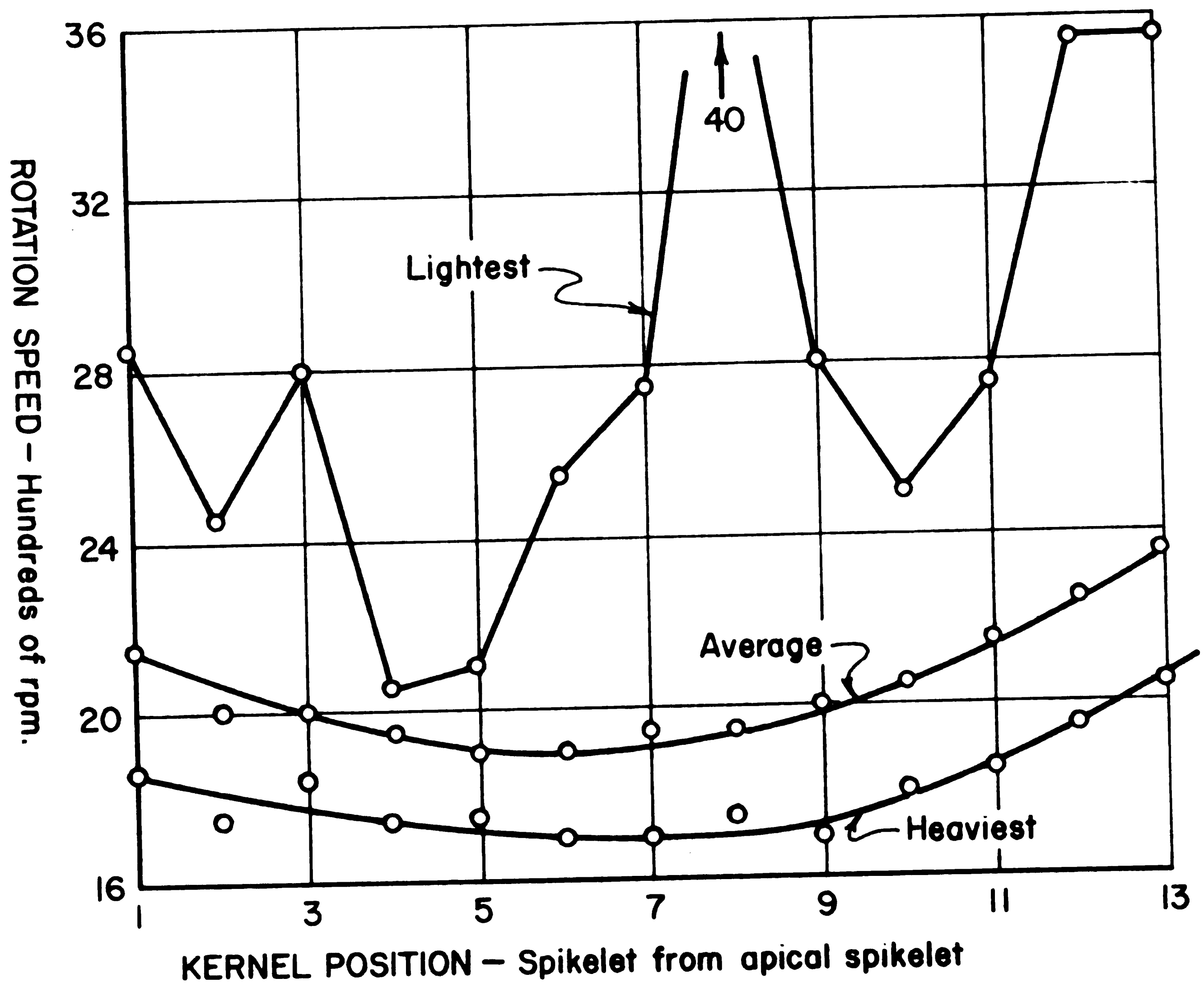


Figure 51. Relationship of kernel weight by position within the head to speeds of rotation required for threshing (Genesee wheat)

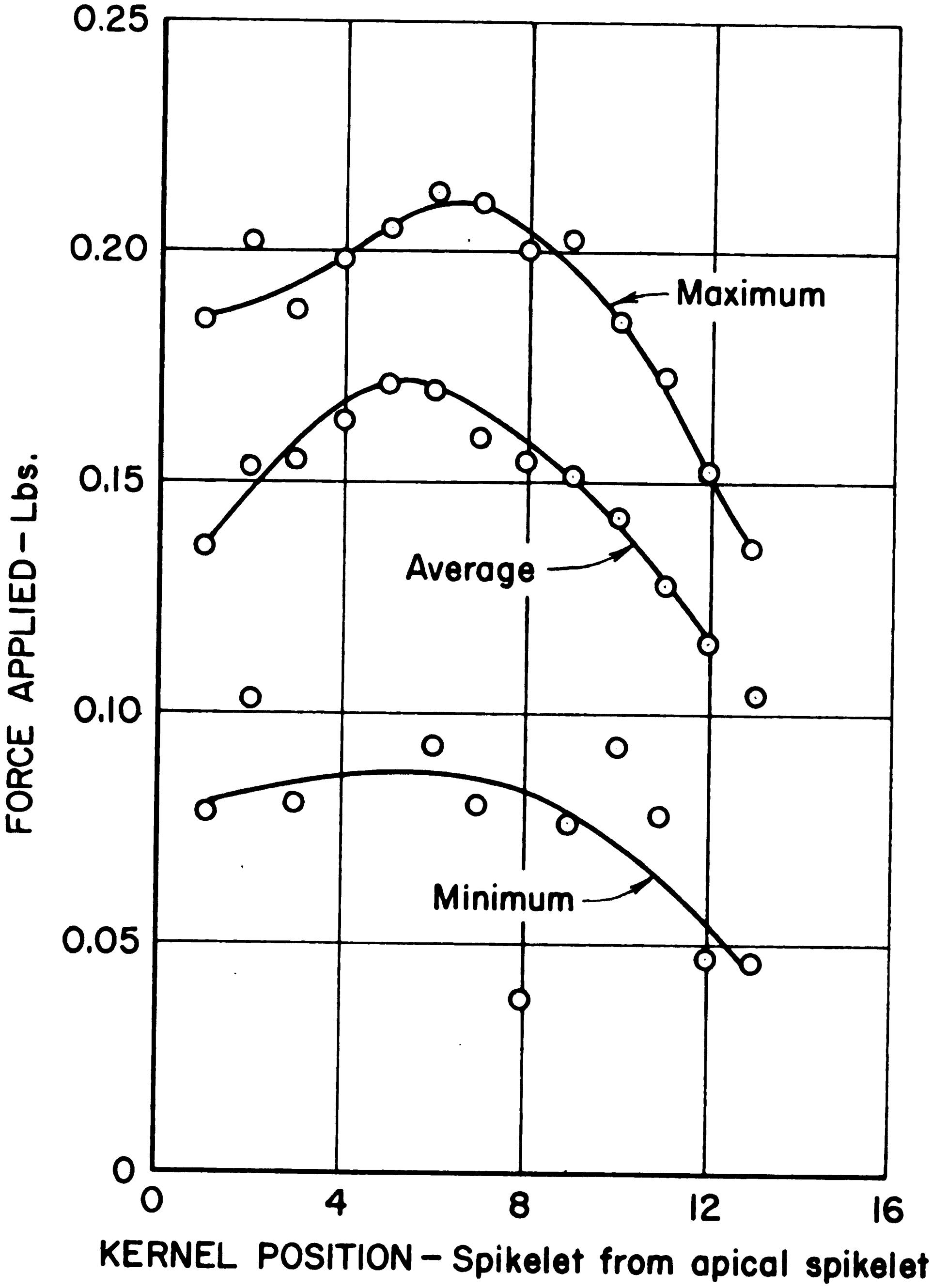


Figure 52. Relationship between kernel position and relative kernel weight to threshing force applied (constant speed of rotation)

THEORETICAL ASPECTS OF CONTINUOUS-FLOW CENTRIFUGAL CONE THRESHER

It is obvious that the methods used to obtain the basic data for centrifugal threshing in this research would have no commercial value. Some continuous flow method is required. The following theoretical analysis suggests a possible approach.

Concepts

Integration of the separation and threshing functions would have interesting possibilities for reducing the weight and size of harvesting machines. If the threshing force could also be used for moving the material through the machine, straw condition would remain unbroken and machine design again simplified.

Suppose a machine configuration were selected so that the centrifugal force would have an axial component exceeding straw friction on the supporting surface. This axial centrifugal force component would be available for accelerating the material through the thresher-separator mechanism.

Figure 53-A presents a frustum of a right cone. The surfaces of the rotating cone would be made of perforated metal. Material to be threshed would be introduced inside the frustum and accelerated to cone surface speed. The resulting centrifugal force would thresh the easy to thresh kernels and exit them through the holes. The centrifugal force would make the remaining material go to a greater radius and likewise expose it to greater centrifugal force.

The configuration shown with straight surface was more conveniently subjected to theoretical motion analysis than curved surfaces and therefore

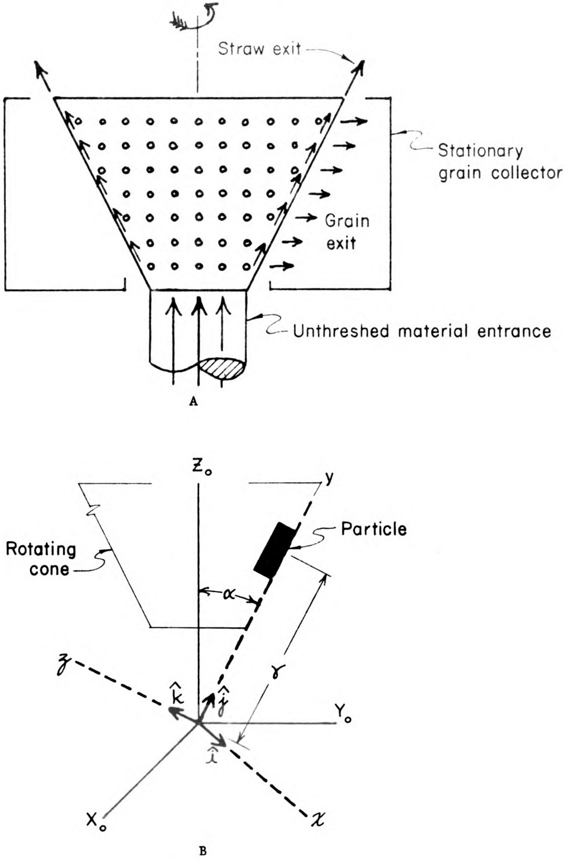


Figure 53. Schematic diagram (A above) of proposed centrifugal thresher and system of assumed axes (B) for theoretical calculations

was selected. Without vanes on the inside surface, the straw would rotate relative to the cone surface, perhaps causing some functional difficulties. Equations of motion have been developed for the cone with and without vanes.

Theoretical Motion Analysis for Rotating Cone

Symbols, definitions and assumptions

Vector notation has been used in the derivations. A dash (-) over a symbol signifies a vector. A dash dotted ($\dot{-}$) and double dotted ($\ddot{-}$) indicates the first and second time derivative of a vector. The following symbols have the meanings indicated.

a acceleration of particle in accelerated reference system (acceleration of particle relative to cone surface) feet per second.

F force on particle in pounds.

m mass of particle.

ω (omega) angular velocity of cone in radians per second.

θ (theta) angular velocity of particle relative to cone in radians per second.

r radius of rotation in feet.

g acceleration of gravity, 32.2 feet per second squared.

α angle that cone surface makes to axis of rotation.

N normal force perpendicular to the cone wall.

N_x normal force in (X) direction.

F_x friction force along (X) axis.

F_y friction force along (Y) axis.

$\underline{\omega}$ angular velocity of particle in radians per second

u coefficient of friction.

$\hat{i}$ unit vector along X axis.

$\hat{j}$ unit vector along Y axis.

$\hat{k}$ unit vector along Z axis.

x vector cross product.

The assumption was made that a set of rotating axes have origin at the cone apex and are positioned so that the particle always moves along the (Y) axis, and the (X) axis always remains in the plane passing perpendicular to the cone axis through the apex. See Figure 53-B.

Motion equations without directional vanes

The equation of motion of the particle on a moving surface is (Becker, 1954):

$$\bar{a} = \frac{\bar{F}}{m} - 2\,\bar{\omega} \times \bar{v} - \dot{\bar{\omega}} \times r - \bar{\omega} \times (\bar{\omega} \times r) \qquad (37)$$

The force ($\bar{F}$) is according to

$$\bar{F} = (-F_x)\,\hat{i} - (mg\,\mathrm{Cos}\,\alpha + F_y)\,\hat{j} + (N - mg\,\mathrm{Sin}\,\alpha)\,\hat{k} \qquad (38)$$

Omega $\bar{\omega}$ and $\dot{\bar{\omega}}$ are

$$\bar{\omega} = (\omega - \dot{\theta})(\mathrm{Cos}\,\alpha\,\hat{j} + \mathrm{Sin}\,\alpha\,\hat{k}) \qquad (39)$$

$$\dot{\bar{\omega}} = -\ddot{\theta}\,(\mathrm{Cos}\,\alpha\,\hat{j} + \mathrm{Sin}\,\alpha\,\hat{k}) \qquad (40)$$

The radius $\bar{r}$ and $\dot{\bar{r}}$ become:

$$\bar{r} = (y)\,\hat{j} \qquad (41)$$

$$\dot{\bar{r}} = \bar{v} = (\dot{y})\,\hat{j} \qquad (42)$$

Since acceleration is possible only along the (y) axis the acceleration becomes:

$$\bar{a} = \ddot{y}\,\hat{j} \qquad (43)$$

When equations 38 through 43 are placed into equation 37, the vector multiplications performed, and like directions equated, the following equations of motion evolve.

$$\text{(X) direction, } 0 = \frac{F_x}{m} + 2(\omega - \dot{\theta})\dot{y}\sin\alpha - \ddot{\theta}\, y \sin\alpha \quad (44)$$

$$\text{(Y) direction, } \ddot{y} = -g\cos\alpha - \frac{F_y}{m} + (\omega - \dot{\theta})^2 y \sin^2\alpha \quad (45)$$

$$\text{(Z) direction, } 0 = -g\sin\alpha + \frac{N}{m} - (\omega - \dot{\theta})^2 y \sin\alpha\cos\alpha \quad (46)$$

Equations 44 and 45 give the rotation of the particle relative to the surface and the velocity along the surface respectively. Equation 46 when solved for (N) gives an approximate threshing force.

The friction in the lateral direction (F_x) would surely be much less than that along the slope. Then the assumption that (F_y) approximately equals (uN) becomes valid. Equations 44 and 45 become:

$$\frac{2\dot{y}}{y} = \frac{\ddot{\theta}}{\omega - \dot{\theta}} \quad (44a)$$

$$\ddot{y} = g\cos\alpha - \frac{uN}{m} + (\omega - \dot{\theta})^2 y \sin^2\alpha \quad (45a)$$

Equations 45a and 46 can now be combined to eliminate the mass (m) and the normal force (N), yielding equation 47.

$$\frac{\ddot{y}}{y} = (\omega - \dot{\theta})^2 A^2 - \frac{B}{y} \quad (47)$$

in which A^2 and B are constants equal to

$$A^2 = \sin^2\alpha - u\sin\alpha\cos\alpha \quad (48)$$

$$B = g(\cos\alpha - u\sin\alpha) \quad (49)$$

Equations 44a and 47 result as the equations of motion. These equations were also derived using the method of Lagrande. (Becker).

If the quantity ($\frac{B}{y}$) is small compared to other terms in equation 47, the simplified equation can be solved to yield the displacement and velocity of the particle at any time (t).

$$\bar{y} \equiv \text{displacement} \equiv Y_i \operatorname{Cosh}(\omega At) + \frac{V_i}{\omega A} \operatorname{Sinh}(\omega AT) \qquad (50)$$

$$\dot{\bar{y}} \equiv \text{velocity} \equiv \omega A \left[Y_i \operatorname{Sinh}(\omega AT) + \frac{V_i}{\omega A} \operatorname{Cosh}(\omega AT) \right] \qquad (51)$$

The initial conditions are expressed as (Y_i) and (V_i).

When equations 50 and 51 are substituted into equation 44a and the assumption made that (ω) is much larger than ($\dot{\theta}$) so that ($\omega - \dot{\theta}$) becomes approximately ω, the result is:

$$\ddot{\theta} \equiv 2\omega^2 A \left[\frac{y_i \operatorname{Sinh}(\omega AT) + \frac{V_i}{\omega A} \operatorname{Cosh}(\omega AT)}{y_i \operatorname{Cosh}(\omega AT) + \frac{V_i}{\omega A} \operatorname{Sinh}(\omega AT)} \right] \qquad (52)$$

But the term $(\frac{V_i}{\omega A})$ approaches zero, so that

$$\ddot{\theta} \equiv 2\omega^2 A \tanh(\omega AT) \text{ and} \qquad (53)$$

$$\theta \equiv 2\omega^2 A \iint \tanh(\omega AT)\, dt^2 \qquad (54)$$

The first integration yields:

$$\dot{\theta} \equiv 2\omega \int \ln \operatorname{Cosh}(\omega AT)\, dt \qquad (54a)$$

when the time is zero. The techniques of graphical calculus can well be used to complete the solution when specific values of the variables and constants are established.

<u>Motion equations with direction vanes</u>

Assume that straight radial vanes are located on the cone surface to prevent the angular rotation of the material relative to the cone surface. The force which the vane exerts on the material (N_x) now enters the analysis and the motion equations are:

$$\text{along (X) direction, } 0 \equiv \frac{N_x}{m} + 2\dot{y}\omega \operatorname{Sin}\alpha \qquad (55)$$

$$\text{along (Y) direction, } \ddot{y} \equiv -g \operatorname{Cos}\alpha - \frac{uN}{m} + \frac{uN_x}{m} + y\omega^2 \operatorname{Sin}^2\alpha \qquad (56)$$

$$\text{along (Z) direction, } 0 \equiv -g \operatorname{Sin}\alpha + \frac{N}{m} - y\omega^2 \operatorname{Sin}\alpha \operatorname{Cos}\alpha \qquad (57)$$

Equation 55 can be solved for $\frac{N_x}{m}$ and equation 57 solved for $(\frac{N}{m})$. The result of substituting these expressions into equation 56 is (after neglecting the very small gravity components):

$$\ddot{\bar{y}} + \dot{\bar{y}}\ 2A - \bar{y}B = 0 \tag{58}$$

The terms A and B are constants if ω remains a fixed value and are equal to

$$A = u \sin\alpha\ \omega \tag{59}$$

$$B = \omega^2(\sin^2\alpha + u\frac{\sin 2\alpha}{2}) \tag{60}$$

The general solution to equation 58 is (Sokolnikoff, 1941)

$$\bar{y} = c_1 e^{m_1 t} + c_2 e^{m_2 t} \tag{61}$$

The roots of equation 61 are

$$m_1 = -A + \sqrt{A^2 + B} \tag{62}$$

$$m_2 = -A - \sqrt{A^2 + B} \tag{63}$$

Solving for the arbitary constants in terms of the initial conditions Y_i and V_i, the results are

$$C_1 = \frac{y_1 m_2 - V_i}{m_2 - m_1} \tag{64}$$

$$C_2 = \frac{V_i - m_1 y_i}{m_2 - m_1} \tag{65}$$

The final solution then is

$$\bar{y} = (\frac{y_1 m_2 - V_i}{m_2 - m_1})\, e^{(-A + \sqrt{A^2 + B})\, t} + (\frac{V_i - m_1 y_i}{m_2 - m_1})\, e^{(-A - \sqrt{A^2 + B})\, t} \tag{66}$$

The velocity is easily found to be in abbreviated form by differentiation

$$\dot{\bar{y}} = c_1 m_1 e^{m_1 t} + c_2 m_2 e^{m_2 t} \tag{67}$$

Utility of equations

The final equations have coefficients which depend upon one crop condition (the coefficient of friction) and four design variables (angle of surface, rotating speed, initial straw velocity and initial straw position). By use of modern computing equipment, these equations could be solved for a wide range of conditions.

The approximations necessary to evolve equation 67 are for the most part minor. Therefore, it should give good results throughout a surface. The greatest accuracy will be obtained from the equations for the cone without vanes near the boundary conditions.

It should not be inferred that other concepts cannot be used in the design of a continuous flow centrifuge.

RECOMMENDATIONS FOR FUTURE RESEARCH

Although over 200 centrifugal tests were conducted under various conditions, the work to date must be considered as preliminary. The work has suggested many additional researches, which are listed below:

(1) Perform threshing of other grains by the centrifugal methods used in this study to establish threshing requirements.

(2) Design, construct and functionally evaluate continuous flow centrifuges. This would lead to several needs, among them

(a) Establishment of proper hole size in screen housing for the various crops.

(b) Evaluate the concept of using a component of the threshing force for accelerating the material through the thresher.

(c) Develop methods of forcing the straw through the thresher.

(d) Establish the flow rate, depth of flow, and separation relationships.

(e) Determine dynamic stress problems.

(3) The continuous flow centrifuge should be used for much larger samples of grain under all conditions to completely define machine requirements and functional advantages.

(4) The coefficient of restitution of grain and straw should be studied and determined for all threshable grains and seeds and under various moisture conditions.

(5) Additional studies upon the cylinder-concave threshing mechanism should be made to determine:

   (a) The effect of clearance upon average straw velocity and acceleration.

   (b) The time and distance required for acceleration of the material.

   (c) The relationship between power requirement and cylinder adjustments.

(6) The coefficients of friction should be established for the straw under controlled moisture conditions. Other straw properties need to be established.

(7) The equations of motion for the cone configuration need to be solved for certain assumed conditions. Equations for other possible configurations should be investigated.

(8) A study of energy of impact and deterioration of grain germination should be made for different surfaces to establish padding materials.

(9) Other additional methods of threshing should be investigated.

(10) The threshing equations should be proved experimentally.

SUMMARY

Exploratory centrifugal threshing by mounting heads of wheat in a commercial centrifuge proved that the wheat would thresh and established the required forces for centrifugal threshing. An experimental batch-type centrifugal thresher was constructed to thresh 25 to 50 head samples and to permit immediate collection of the grain as it was threshed. This experimental machine was capable of peripheral speeds up to 250 miles per hour.

Wheat (five varieties), rye, corn and soybeans were centrifugally threshed. Threshing was conducted for all mature moisture conditions in wheat. Only exploratory threshing was completed in the other crops.

Forces of 0.30 pounds when placed on the kernel so that the attachment was in direct tension would thresh 98 percent of wheat under any mature moisture condition. A force of 0.24 pounds was sufficient to thresh 98 percent of any wheat with kernel moistures under 20 percent. When the force was applied so that the kernel attachment was sheared, the above forces were reduced by one half.

Centrifugally threshed grain was easily cleaned by air blast, since the normal separation of straw and grain occurred integrally with the threshing. Grain threshed in a centrifugal cup and not exposed to air resistance was sufficiently clean for immediate storage without additional cleaning.

Visual kernel damage was not a problem at any speed after a 1/4 inch hard rubber matting was placed around the threshing head to dissipate kernel kinetic energy. Germination tests indicated invisible damage occurred at kernel moistures above 35 percent.

Centrifugal threshing and field combining tests were conducted simultaneously for performance comparison purposes. A centrifugal threshing force of 0.23 pounds gave the same degree of threshing as the following cylinder speed and concave clearance adjustments for a rasp bar cylinder: 6000, 3/8; 5000, 5/16; 4300, 1/4; and 3800, 3/16 (feet per minute and inches respectively).

The combine was adapted to permit three zones of grain collection at the cylinder mechanism and five zones under the rack. The total chaff separated by the combine was more than twice that produced by the centrifugal thresher as measured by chaff-grain ratios.

The last kernels threshed by centrifugal force weighed 22 percent less per kernel than the early threshed grain. There was no differences in kernel weight of the combined grain in any of the eight zones of separation or of unthreshed grain.

Straw strength was reduced with wetness and immaturity. Coefficients of friction increased generally with decreasing straw moistures, although procedures were not entirely satisfactory to establish definite relationships.

Theoretical threshing equations were developed for impulsive and non-impulsive accelerations. Values of the threshing force for use with the formulas were established. Other quantities remain to be determined by research methods.

Concepts and equations of motion were derived for possible use in development of continuous-flow centrifugal threshers.

CONCLUSIONS

The following conclusions evolved as a result of this research:

(1) Wheat and other grains can be successfully threshed by the application of centrifugal force.

(a) Wheat can be centrifugally threshed without visual kernel damage at all mature kernel moistures.

(b) Forces greater than 0.30 pounds are required to thresh 98 percent or more of the mature grain independent of the method of holding. Forces greater than 0.20 pounds are sufficient to thresh 98 percent of the grain under all typical harvesting conditions.

(c) Applying the force so that the kernels bend the attachment reduce the required threshing force up to 50 percent.

(2) The threshing and separation processes can be integrated with centrifugal threshing, eliminating the need for special straw separating equipment.

(3) An air blast is sufficient to clean centrifugally threshed grain. If centrifugal threshing could be done without air resistance, the grain would not require subsequent cleaning.

(4) Seed grains need to be protected from damage to germination capacity caused by impact associated with the sudden deacceleration required at the thresher outer surface.

(5) Degrees of seed separation occur according to weight and germination ability during centrifugal threshing.

(6) The conventional threshing mechanism is not able to separate sufficient grain integral with the threshing process to eliminate the need for a straw separating device.

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APPENDIX

Table 18. Forces required to thresh 100, 98, 95, 90 and 80 percent of total grain at various moisture contents

Seneca Wheat

Test No.	Moisture content		Threshing force for					Test time or conditions
	Grain	Straw	100%	98%	95%	90%	80%	
	Pct.	Pct.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	
30-1	11.8	9.5	.43	.22	.166	.154	.133	8:30 A.M.
30-2	11.2	5.6	.33	.216	.169	.144	.106	"
30-3	10.6	4.8	.33	.244	.234	.217	.186	11:30 A.M.
30-4	11.4	5.1	.33	.311	.288	.248	.187	"
30-5	11.3	3.5	.43	.247	.224	.186	.141	1:30 P.M.
30-6	11.3	3.6	.33	.216	.17	.158	.132	"
30-7	10.0	4.0	.33	.184	.108	.105	.100	3:00 P.M.
30-8	11.0	- -	.33	.275	.204	.157	.124	"
30-9	9.2	- -	.169	.198	.106	.103	.096	4:00 P.M.
1-1	14.5	11.9	.348	.236	.182	.165	.148	8:30 A.M.
1-2	14.9	- -	.453	.233	.172	.154	.120	"
1-4	38.6	14.3	- -	- -	.458	.400	.325	Very Green
1-5	33.1	9.0	.447	.346	.275	.216	.177	Green
1-6	23.0	- -	.506	.194	.182	.164	.125	Straw Dry
1-7	10.8	10.5	.43	.239	.21	.164	.104	1:00 P.M.
1-8	10.4	- -	.33	.22	.176	.122	.101	"
1-10	39.4	18.6	- -	- -	.455	.335	.248	Very Green
2-1	11.7	3.7	.244	.162	.148	.128	.100	8:30 A.M.
2-2	12.2	3.1	.44	.195	.164	.148	.118	"
2-3	13.7	3.6	.34	.191	.168	.159	.140	10:30 A.M.
2-4	13.5	- -	.34	.232	.20	.161	.122	"
2-5	17.1	5.0	.36	.236	.185	.178	.165	1:30 P.M.
2-6	17.4	9.6	.36	.224	.182	.173	.154	"
2-7	33.4	21.8	- -	- -	.436	.353	.278	Green
2-9	11.2	- -	.43	.196	.167	.158	.145	3:00 P.M.
2-10	10.5	- -	.33	.186	.115	.106	.100	"
3-1	12.3	5.4	.33	.20	.164	.145	.109	8:30 A.M.
3-2	12.1	- -	.33	.229	.195	.124	.103	"
3-3	17.6	- -	.36	.248	.183	.172	.148	Dry
3-4	17.6	- -	.47	.336	.29	.22	.17	"
3-6	36.4	21.4	- -	- -	.447	.41	.328	Turning
3-7	11.7	8.7	.33	.221	.186	.121	.098	1:00 P.M.
3-8	10.2	3.3	.33	.185	.159	.143	.104	"
3-10	13.2	3.3	.33	.232	.193	.163	.145	Dry
3-11	9.6	8.3	.43	.215	.172	.112	.100	4:30 P.M.

Table 18. (cont'd.)

Test No.	Moisture content: Grain	Moisture content: Straw	Threshing force for: 100%	98%	95%	90%	80%	Test time or conditions
	Pct.	Pct.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	
4-1	11.8	4.4	.436	.252	.191	.159	.13	10:00 A.M.
4-2	10.7	- -	.33	.217	.174	.105	.100	"
4-3	39.0	- -	- -	- -	.476	.432	.352	"
4-4	11.0	4.0	.434	.23	.164	.108	.101	2:15 P.M.
4-5	11.1	4.8	.33	.186	.148	.105	.100	"
4-6	38.1	21.2	- -	- -	- -	.468	.318	Green
6-1	20.2	9.8	.49	.24	.170	.127	.116	8:30 A.M.
6-2	19.4	10.5	.37	.254	.18	.148	.117	"
6-3	17.2	8.3	.36	.204	.174	.152	.11	10:00 A.M.
6-4	17.3	6.5	.36	.248	.176	.13	.112	"
6-5	15.5	6.2	.35	.234	.156	.109	.091	1:00 P.M.
6-6	14.8	5.0	.33	.233	.180	.146	.108	"
6-7	12.2	2.5	.25	.165	.140	.109	.097	3:00 P.M.
6-8	12.2	1.7	.19	.12	.11	.10	.08	Reverse
7-1	13.8	1.9	.28	.156	.112	.11	.104	8:30 A.M.
7-2	14.6	3.8	.26	.176	.154	.12	.094	"
7-3	11.3	1.8	.243	.208	.16	.11	.096	10:00 A.M.
7-4	12.1	4.3	.17	.13	.12	.10	.08	Reverse
7-5	11.0	1.5	.33	.213	.164	.112	.103	11:30 A.M.
7-6	8.4	3.6	.33	.236	.19	.12	.08	"
7-7	- -	- -	.33	.22	.14	.103	.09	
8-1	16.7	11.1	.266	.196	.172	.147	.104	8:30 A.M.
8-2	13.4	6.2	.26	.177	.162	.136	.096	"
8-3	13.8	8.3	.35	.224	.169	.131	.107	9:00 A.M.
8-4	14.6	3.7	.45	.253	.228	.184	.112	"
8-5	11.6	7.2	.46	.20	.146	.104	.09	4:30 P.M.
9-1	12.1	10.6	.24	.165	.149	.12	.102	8:30 A.M.
9-2	13.7	9.1	.45	.24	.171	.143	.093	"
10-1	19.0	7.0	.37	.207	.179	.158	.119	"
10-2	12.1	6.0	.43	.22	.132	.101	.086	"
10-3	10.5	7.5	.33	.21	.161	.105	.084	5:15 P.M.
13-1	16.3	8.9	.26	.176	.153	.113	.105	8:30 A.M.
13-2	16.2	10.2	.46	.228	.132	.111	.107	"
13-3	14.1	6.4	.26	.17	.112	.106	.094	11:00 A.M.
13-4	13.3	- -	.34	.204	.132	.107	.097	"

Table 18. (cont'd.)

Test No.	Moisture content		Threshing force for					Test time or conditions
	Grain	Straw	100%	98%	95%	90%	80%	
	Pct.	Pct.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	
Genesee Wheat								
15-1	11.3	7.1	.32	.146	.103	.10	.096	11:00 A.M.
15-2	10.2	8.7	.32	.168	.137	.102	.056	"
15-3	12.3	- -	.404	.158	.144	.124	.092	1:30 P.M.
15-6	10.5	6.0	.318	.116	.098	.09	.074	3:25 P.M.
15-9	10.8	7.6	.306	.133	.098	.092	.074	"
15-10	11.0	6.0	.306	.154	.127	.112	.081	5:00 P.M.
16-1	11.6	9.2	.414	.157	.149	.132	.102	7:30 A.M.
16-2	11.6	10.3	.299	.14	.122	.096	.091	9:00 A.M.
16-3	10.7	5.9	.40	.20	.156	.134	.098	11:00 A.M.
16-4	10.8	9.1	.33	.154	.145	.13	.10	"
16-5	12.7	2.7	.303	.20	.138	.103	.091	Freezer 7-10
16-6	12.1	4.3	.398	.154	.14	.12	.092	"
16-8	41.6	11.9	.404	.294	.274	.25	.202	Freezer 7-3-D
16-9	9.7	1.9	.306	.12	.095	.09	.074	5:00 P.M.
16-10	9.6	2.0	.23	.101	.094	.083	.06	"
17-1	11.6	22.2	.32	.174	.156	.143	.116	8:00 A.M.
17-2			.306	.174	.124	.096	.085	"
17-3	10.8	11.7	.40	.177	.118	.097	.091	10:00 A.M.-Rain
17-4	9.4	14.1	.40	.16	.142	.112	.092	11:00 A.M.-Rain
17-5	37.8	10.8	.438	.371	.308	.262	.198	Freezer 7-3-D
17-6	41.5	14.1	.466	.30	.232	.192	.128	Freezer 6-29
17-9	8.0	2.8	.228	.154	.148	.136	.114	5:00 P.M.
17-10	10.6	10.6	.395	.24	.18	.133	.096	"
18-1	16.1	37.3	.422	.26	.214	.166	.148	8:00 A.M.-Heavy Rain
18-2	16.5	39.4	.43	.236	.196	.161	.136	"
18-3	1.4	7.7	.35	.12	.08	.058	.044	Oven Dried
18-4	.7	12.5	.196	.087	.075	.057	.046	" "
21-2	19.0	11.6	.42	.22	.163	.151	.126	8:00 A.M.
21-6	33.7	9.9	.45	.228	.184	.156	.094	Freezer 7-6
21-8	8.4	8.3	.40	.24	.153	.12	.095	11:30 A.M.
21-9	15.2	8.5	.31	.236	.136	.104	.095	1:25 P.M.
21-10	10.9	5.1	.29	.198	.159	.124	.081	Freezer 7-6
21-11	14.7	7.6	.325	.188	.104	.10	.09	Freezer 7-8
21-12	15.2		.323	.159	.148	.116	.101	"
21-13	10.7	2.7	.385	.22	.144	.122	.09	Freezer 7-13
21-14	10.5	6.8	.406	.245	.204	.151	.09	"
21-16	13.3	4.5	.256	.162	.10	.092	.08	5:00 P.M.

Table 18. (cont'd.)

Test No.	Moisture content		Threshing force for					Test time or conditions
	Grain	Straw	100%	98%	95%	90%	80%	
	Pct.	Pct.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	
22-1	11.7	11.3	.28	.21	.15	.112	.085	Over night dry
GW-2	29.0	15.8	- -	.25	.16	.135	.122	Greenhouse
GW-3	42.8	25.4	- -	- -	.28	.237	.163	"
GW-4	53.4	44.1	.44	.264	.233	.208	.168	"
GW-5	63.9		.218	.201	.18	.147	.123	Reversed Holding
GW-6	41.7	37.8	.40	.282	.274	.269	.258	Greenhouse
GW-7	44.4	39.1	- -	- -	.32	.263	.252	"
GW-9	44.8	40.7	.47	.388	.312	.238	.228	"
GW-10	51.3	43.3	.189	.172	.148	.119	.096	Reversed Holding
Blackhawk Wheat								
15-7	11.1	10.6	.39	.20	.146	.124	.068	3:30 P.M.
17-7	41.0	13.4	.468	.30	.249	.222	.18	Freezer 6-29
17-8	42.6	13.0	.48	.26	.24	.21	.18	" "
22-2	11.5	13.3	.36	.27	.19	.12	.10	Freezer 7-14
22-3	17.5	11.8	.28	.16	.14	.12	.10	Freezer 7-10
22-4	28.2	17.2	.32	.21	.17	.15	.12	Freezer 7-8
22-5	36.7	24.7	.27	.27	.25	.21	.19	Freezer 7-6
22-6	40.2	32.8	.34	.32	.29	.26	.21	Freezer 7-3
22-7	11.7	9.8	.16	.15	.12	.10	.09	Freezer 7-14
Thorne Wheat								
15-5	0.7	8.0	.23	.20	.15	.12	.10	2:45 P.M.
15-8	10.3	9.0	.32	.21	.17	.13	.10	"
CI-13170 Wheat								
21-5	10.5	9.2	.40	.23	.20	.16	.13	Freezer 7-14
21-7	12.2	6.7	.40	.28	.24	.19	.13	" "

Table 18. (cont'd.)

Test No.	Moisture content		Threshing force for					Test time or conditions
	Grain	Straw	100%	98%	95%	90%	80%	
	Pct.	Pct.	Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	
Burt Wheat								
21-15	9.7	- -	.20	.14	.13	.11	.10	Freezer 7-14
GW-8	37.5	22.2	- -	- -	- -	.21	.19	Greenhouse
Rye								
22-8	11.2	8.5	.16	.13	.12	.10	.07	Freezer 7-14
22-9	16.0	8.3	.19	.12	.11	.10	.07	Freezer 7-13

Table 19. Combine threshing data

Grain and variety	Seneca wheat
Grain moisture	12-14 percent
Straw moisture	3-5 percent
Combine	John Deere Model 30
Test area	One hundredth

Test Sequence A

Cylinder Concave clearance	Cyl-inder speed	Straw	Grain	Cyl-inder loss	Cyl-inder loss	Rack loss	Rack loss	Kernel damage	Kernel Germi-nation
inches	fpm	Lbs.	Lbs.	Lbs.	Pct.	Lbs.	Pct.	Pct.	Pct.
4/16	3700	29	28	1.04	3.58	.20	.69	1.9	81
	4000	25	23½	.62	2.57	.15	.62	2.5	84
	4300	22½	32	.41	1.27	.13	.40	2.5	81
	4900	22½	24	.21	.87	.12	.49	2.9	83
	5500	23½	26	.17	.63	.09	.34	2.9	54
5/16	3800	27	24	1.21	4.79	.14	.55	2.3	80
	4300	21	25½	.72	2.73	.12	.46	2.0	91
	4700	24	24	.62	2.53	.11	.45	1.3	85
	5100	21½	25	.56	2.17	.21	.82	2.6	85
	5600	17	24	.29	1.19	.18	.74	2.8	87
6/16	3800	24½	22	1.35	5.78	.19	.80	1.9	86
	4300	25	27	.94	3.35	.17	.61	1.2	80
	4700	24	27	.92	3.30	.14	.50	1.3	91
	5100	27	25½	.85	3.23	.09	.34	2.4	85
	5400	27½	26	.78	2.91	.17	.63	3.9	87
7/16	3800	27½	21	2.12	9.16	.24	1.03	2.0	86
	4300	21	22½	1.81	7.44	.23	.94	1.2	84
	4700	24½	27½	1.71	5.85	.19	.65	1.3	82
	5100	25½	23½	1.42	5.71	.22	.88	4.3	91
	5400	23	25	1.44	5.43	.12	.45	6.1	88

Table 19. (cont'd.)

Test Sequence B

Cylinder concave clearance	Cyl-inder speed	Straw	Grain	Cyl-inder loss	Cyl-inder loss	Rack loss	Rack loss	Kernel damage	Kernel Germi-nation	Test Wt.
inches	fpm	lbs.	lbs.	lbs.	pct.	lbs.	pct.	pct.	pct.	lbs.
3/16	3100	27½	21½	.78	3.49	.21	.94	1.3	--	61.0
	3900	22	23	.42	1.79	.19	.81	.6	77	61.2
	4700	19	22	.12	.54	.13	.59	3.1	73	60.8
	5500	21½	21½	.09	.42	.15	.70	4.8	80	61.1
	6300	22	22½	.03	.13	.23	1.02	3.1	70	60.5
5/16	3100	31½	23½	1.23	4.98	.27	1.10	.6	78	60.9
	3900	28	25½	.88	3.34	.25	.95	1.8	75	61.0
	4700	23½	23	.57	2.40	.13	.55	2.0	--	60.5
	5500	23	23½	.22	.93	.22	.93	2.3	75	60.5
	6300	21	24½	.17	.69	.32	1.30	4.3	75	60.1
7/16	3100	27½	20½	1.93	8.59	.33	1.47	0	85	60.7
	3900	25½	21	1.02	4.63	.21	.95	1.3	85	60.9
	4700	29	23	.71	3.00	.10	.42	1.4	78	60.8
	5500	21	21	.73	3.36	.31	1.43	1.3	85	60.6
	6300	23½	22½	.70	3.00	.17	.73	4.1	78	60.8

Table 20. Combine separation data -- cylinder adjustment, straw to grain relationships and losses

Test No.	Cyl-inder speed	Cyl-inder clear-ance	Total grain	Total straw	Chaff to shoe	Straw to shoe	Total chaff and straw to shoe	Thre-shing loss	Sepa-ration loss
	fpm	inches	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
T-2	5500	5/16	25.05	19	7.27	.39	7.63	.13	.02
T-3	"	"	19.10	15	6.35	.41	6.76	.09	.04
T-4	"	"	21.90	20				.07	.09
T-5	"	"	20.05	17	6.68	.30	6.98	.13	.06
T-6	"	"	22.22	20½	6.08	.59	6.67	.05	.20
T-7	"	"	22.01	25	7.44	.35	7.79	.05	.18
M-7	3100	7/16	20.77	16½	6.17	.48	6.65	.27	.07
N-7	3900	"	20.30	21	5.57	.54	6.11		
M-5	3100	5/16	18.22	20	5.70	.48	6.18	.40	.12
N-5	3900	"	25.65	15	5.45	.56	6.11	.12	.02
O-5	4700	"	20.45	20	6.09	.49	6.58	.14	.06
R-5	5500	"	18.32	20	6.61	.29	6.90	.12	.03
S-5	6300	"	20.63	21½	7.80	.39	8.19	.03	.07
M-3	3100	3/16	21.50	20	6.01	.40	6.41	.20	.04
N-3	3900	"	20.20	23½	6.13	.27	6.40	- -	- -
O-3	4700	"	23.25	23	7.75	.92	8.67	.04	.08
R-3	5500	"	24.94	20½	8.32	.23	8.55	.07	.03
S-3	6300	"	20.39	17½	8.31	.20	8.51	.03	.02

Table 21. Combine separation data -- separation of grain, chaff and straw by zones

Test No.	Item	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Total Zone 1 - 7	Zone 8
		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
T-2	Grain	9.00	5.65	5.81	2.56	1.32	.56	.15	25.05	.02
	Chaff	1.24	1.40	1.58	1.31	.85	.56	.33	7.27	
	Straw	.17	.07	.08	.02	.02	.02	.01	.39	19
T-3	Grain	7.86	5.94	.52	1.89	1.44	.72	.73	19.10	.04
	Chaff	1.00	1.13	.77	1.27	.69	.49	1.00	6.35	
	Straw	.19	.16	.02	.01	.02	0	.01	.41	15
T-4	Grain	5.57	8.90	1.24	2.93	1.37	.66	.24	20.91	.09
	Chaff	- -	- -	1.05	1.34	.76	.59	.40	- -	
	Straw	- -	- -	.01	.02	.02	.01	0	- -	20
T-5	Grain	8.78	5.81	.73	2.70	1.21	.62	.20	20.05	.06
	Chaff	.85	2.17	1.06	1.17	.69	.50	.24	6.68	
	Straw	.17	.04	.01	.03	.02	.02	.01	.30	17
T-6	Grain	9.28	6.10	.95	2.97	1.67	.90	.35	22.22	.20
	Chaff	1.07	1.28	.94	1.14	.74	.57	.34	6.08	
	Straw	.24	.28	.01	.02	.02	.02	0	.59	20½
T-7	Grain	8.91	5.76	1.48	2.96	1.69	.90	.31	22.01	.18
	Chaff	1.35	1.21	1.30	1.42	.97	.74	.45	7.44	
	Straw	.18	.10	.01	.02	.01	.02	.01	.35	25
M-7	Grain	6.24	4.28	3.19	4.54	1.74	.68	.10	20.77	.07
	Chaff	.95	.79	1.27	1.36	.99	.43	.38	6.17	
	Straw	.19	.13	.04	.06	.04	.01	.01	.48	16½
N-7	Grain	6.37	5.94	1.56	3.80	1.84	.65	.14	20.30	- -
	Chaff	.78	.97	.98	1.33	.70	.57	.24	5.57	
	Straw	.23	.13	.02	.07	.06	.02	.01	.54	21
M-5	Grain	5.57	4.81	1.14	3.62	2.07	.84	.17	18.22	.12
	Chaff	1.02	.75	1.17	1.24	.75	.52	.25	5.70	
	Straw	.20	.13	.02	.06	.04	.02	.01	.48	20
N-5	Grain	10.15	9.13	.78	3.00	1.47	.93	.19	25.65	.02
	Chaff	1.01	.36	.75	1.13	1.46	.48	.26	5.45	
	Straw	.37	.10	.01	.03	.01	.03	.01	.56	15

Table 21. (cont'd.)

Test No.	Item	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Total Zone 1 - 7	Zone 8
		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
O-5	Grain	8.24	5.86	.85	2.91	1.73	.67	.19	20.45	.06
	Chaff	.95	1.23	1.07	1.34	.73	.48	.29	6.09	
	Straw	.29	.11	.01	.03	.02	.02	.01	.49	20
R-5	Grain	7.52	5.34	.62	2.50	1.52	.63	.19	18.32	.03
	Chaff	1.10	1.34	1.02	1.33	.82	.63	.37	6.61	
	Straw	.16	.04	.02	.03	.03	.01	0	.29	20
S-5	Grain	9.23	6.30	.56	2.20	1.47	.66	.21	20.63	.07
	Chaff	1.38	1.73	1.11	1.62	.94	.64	.38	7.80	
	Straw	.23	.08	.01	.04	.01	.01	.01	.39	21½
M-3	Grain	6.75	4.76	1.14	4.33	1.84	1.97	.71	21.50	.04
	Chaff	.80	.81	1.01	1.18	1.06	.71	.44	6.01	
	Straw	.17	.12	.02	.03	.01	.03	.02	.40	20
N-3	Grain	8.09	5.76	1.26	4.00	.74	.19	.16	20.20	- -
	Chaff	1.19	1.22	1.21	1.42	.53	.33	.23	6.13	
	Straw	.14	.05	.01	.03	.02	.01	.01	.27	23½
O-3	Grain	10.20	6.35	.66	2.62	2.10	.93	.39	23.25	.08
	Chaff	1.29	1.65	1.15	1.73	.77	.74	.42	7.75	
	Straw	.61	.07	0	.01	.20	.02	.01	.92	23
R-3	Grain	11.55	7.50	0.55	2.14	1.82	.95	.43	24.94	.03
	Chaff	1.86	1.87	1.05	1.42	.93	.72	.47	8.32	
	Straw	.11	.09	.01	.01	0	0	.01	.23	20½
S-3	Grain	9.65	6.61	.31	1.30	1.32	.81	.39	20.39	.02
	Chaff	1.86	1.89	.93	1.36	1.01	.75	.51	8.31	
	Straw	.05	.07	.01	.02	.03	.01	.01	.20	17½

Table 22. Analysis of Variance

Source of Variation	Degrees of freedom	Sums of squares	Mean squares	F	F 5%
Threshing losses as influenced by clearance and speed					
Clearance	2	26.86	13.4	3.75	3.88
Error	12	42.90	3.57		
Speed	4	39.11	9.77	3.19	3.48
Error	10	30.65	3.06		
Total	14	69.76			
Separation losses as influenced by clearance and speed					
Clearance	2	.102	.051	- -	
Error	12	1.25	.10		
Speed	4	.73	.18	2.9	3.48
Error	10	.62	.062		
Total	14	1.35			
Kernel damage as influenced by clearance and speed					
Clearance	2	2.34	1.17	N.S.	4.10
Error	10	27.24	2.72		
Speed	4	19.19	4.8	3.7	3.84
Error	8	10.39	1.30		
Total	12	29.58			
Germination as influenced by clearance and speed					
Clearance	2	146.	73.	5.89	4.10
Error	10	124.	1.24		
Speed	4	94.	23.5	1.1	3.84
Error	8	176.	22.0		
Total	12	270.			
Cylinder separation as influenced by speed and clearance (7/16" clearance not included)					
Clearance	1	.80			
Error	8	636.			
Speed	4	577.5	144.4	12.1	5.19
Error	5	59.6	11.9		
Total	9	633.14			