EVALUATION OF THE DESIGN PARAMETERS OF A THRESHING CONE

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William F. Lalor

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EVALUATION OF THE DESIGN PARAMETERS OF A THRESHING CONE

by

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AN ABSTRACT

Submitted to the Colleges of Agriculture and Engineering, of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN AGRICULTURAL ENGINEERING

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Approved by Wesley F. Buchele

orientation-angle were increased. The results indicated that with proper slot orientation an improvement of at least 25 per cent in the separating efficiency was possible.

At low rotor speeds most of the separation occurred within 2 feet of the cone entrance; as the speed was increased, more separation occurred at distances greater than 2 feet from the entrance and less separation in the first 2 feet of cone length.

The straw and chaff content of the material from the oriented portion was greater than that of the material from the control area. The actual per cent of straw and chaff in the material separated by the cone was similar to that found in the material on the cleaning shoe of a conventional combine.

High-speed motion pictures were taken to study the action of a threshing cone. The amount of impact between the material and the rotor was small and the action of the rotor was to rub the material which was observed to rotate at one-third the speed of the rotor. The high-speed motion pictures, together with photographs taken at a shutter speed of 1/30 second, indicated the magnitude of the helix angle of the path of the material as it passed through the cone.

ABSTRACT WILLIAM F. LALOR

A horizontal threshing cone was constructed using perforated sheet-metal in the outer cone and rubber-covered angle-bars in the rotor. The apical angle of the cone was 54° and its truncated length was 4 feet measured along the cone surface. The diameter of the entrance was 16 inches and the diameter of the base was 59 inches. The material was fed axially into the thresher by means of an auger mounted on the rotor shaft. A tangential straw outlet was located at the base of the cone. Threshing tests were performed on wheat at rotor speeds of 300, 350, 400, 450, and 500 R.P.M. Threshing efficiency was above 99 per cent at all speeds. The feed-auger did not operate satisfactorily below 350 R.P.M. Separating efficiency decreased from 77.4 per cent to 67.5 per cent as the speed was increased from 300 to 500 R.P.M.

The material passed through the cone along a helical path. A circular area was cut from the cone, reshaped, and placed in position with the slots at various angles to the plane of the base. This provided a means of determining the slot angle at which separating efficiency was maximum. The weight of grain separated at this portion of the cone was compared to that separated at a control area where the slots were parallel to the base of the cone. Except at low rotor speeds, the relative amount of grain emerging from the oriented portion was greater than that emerging from the control area and it increased as the rotor speed and

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*Michigan State University Photographic Service negative number.

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LIST OF SYMBOLS

Symbol	Meaning
a	Constant in the threshing cone equation
b	Constant in the threshing cone equation
F	Force (general)
i	Unit vector in x direction
j	Unit vector in y direction
k	Unit vector in z direction
L_e	Effective slot length
m	Mass
N	Normal force
O	Origin of coordinate system
R	Relative separating efficiency
r	Radius of cone
r_s	Radius of cone entrance
s	Slot width
t	Time
u	Coefficient of friction
v	Velocity (linear)
w	Velocity (angular)
x	Displacement in x direction
$\dot{x}$	Velocity in x direction $\frac{dx}{dt}$
$\ddot{x}$	Acceleration in x direction $\frac{d^2x}{dt^2}$
z	Slot length
α	Helix angle of path of material through the cone
2θ	Apical angle of cone

INTRODUCTION

The first patent covering a combine harvester was issued in 1828. In spite of this early date of invention the development of the combine was slow, due mainly to a lack of adequate and versatile power units. The production of satisfactory power units in the early part of this century enabled the combine to commence the growth leading to the popularity which it now enjoys.

The design of combines has undergone many changes and improvements since the idea was originally conceived, but the threshing and separating mechanisms have remained essentially unchanged. The reason for this is because combines, in their early days, were used mainly to harvest the cereals and for this purpose the threshing and separating mechanisms were reasonably efficient. The use of combines for harvesting such crops as clover has brought to light a serious deficiency in the threshing mechanism. The fact that a large part of the world's grain is still harvested by primitive means, emphasizes the need for greater efforts toward developing the "perfect combine."

Most of the research done on combines has been in connection with their threshing and separating efficiencies and the effect of present threshing mechanisms on the quality of the seed. Until recently, almost no information was available concerning the actual threshing process. The objective of this research is to develop information regarding new threshing and separating principles and to evaluate the various design features that will enable these principles to be incorporated into a complete harvester.

The use of this knowledge should contribute to the development of efficient, inexpensive, and improved versions of the combine, which will have wider applications than present machines.

REVIEW OF LITERATURE

History of Combines

According to Nyberg (1), the idea of a combined reaping and threshing machine is over 130 years old. The first patent on such a machine was granted to Samuel Lane of Hallowell, Michigan, on August 8, 1828. There is, however, no record to show that Lane either built or tested a combine harvester. Several other patents relating to combine harvesters were granted about this time.

In 1836, a patent covering a combine was issued to Moore and Hascall of Kalamazoo, Michigan; they built and tested their machine in 1835. Nyberg (1) reports that on July 12, 1838, this machine (pulled by twenty horses and cutting a fifteen-foot swath) harvested a thirty-acre field. This machine harvested 800 acres during the 1854 season, before burning in the field from an overheated bearing. These early models of the combine were pulled by horses and were ground-driven from a bull-wheel.

Nyberg also reports that, in 1877, a twenty-two foot machine was built in California by Berry. This machine was powered by steam and required an operating crew of six. It was capable of harvesting fifty acres a day, but when rebuilt and equipped with a forty-foot cutter-bar, its capacity, with the same crew, was increased to ninety-two acres a day. Steam power was now beginning to replace horses.

From 1890 onwards, several machines were built with auxiliary engines as a source of power for the mechanism; the locomotive power was supplied by a traction engine. By 1912 internal combustion engines were in common use.

The earliest combines, therefore, were either self-propelled or pulled by horses and it was not until the mid-1930s that power-driven machines made their appearance with the introduction, at that time, of the power-take-off shaft for tractors.

A combine was developed and built in Australia around 1920 and brought to the United States and Canada in 1924. This machine merely stripped the heads from the standing crop and left the straw after it. Such a mechanism was described by Pliny in the first century as being at work in the fields of Gaul. Palladius also mentioned a similar machine in the fourth century.

Kahn (2) quotes a review by Higgins, in stating that in its early years the combine was not considered useful, due to adverse climatic conditions, except in the grain producing areas of the Pacific Coast and Great Plains States. The machine, however, was redesigned and modified and its use gradually spread to other areas of the United States. In the eastern regions, fields were smaller than those for which the combine was originally designed and, in addition, hilly land was often used for the production of grain. These factors led to the need for a machine that would function satisfactorily under widely varying conditions.

Kahn also reports that the first combines were introduced to Michigan in 1927. In that year there were seven machines at work and by 1929 there were fifty-four. Ninety years had elapsed from the time Moore and Hascall built their combine in Kalamazoo, until the machine evolved to a state in which it was acceptable to Michigan grain growers. In spite of this acceptance, early experiences with combines were often bad, due to the fact that fields and acreages were small, crops were diversified, and the straw had to be cut near the ground since it was needed for livestock bedding. Such features of Michigan agriculture as these, demanded modifications in the combines designed for use in the typically grain-producing areas. This, no doubt, was the experience in all of the Midwestern and Eastern states, as was it also in Western Europe. Redesign of the combine gradually took place and suitably modified types became available for nearly all situations. At the present time there are approximately 50,000 combines at work in Michigan.

Subsequent Development

The demand for combines that can be used in widely varying situations is evidenced by the numerous types and modifications of these types available. Some of the more extensive modifications were attempted in the early stages; for example, Witzel and Vogelaar (3) indicate that the development of the hillside combine had begun as far back as the decade 1890 to 1900. Heitshu (4), however, states that the production of hillside combines did not begin until 1950.

The development of the power-take-off for tractors in the mid-1930s led to the availability of power driven combines that were smaller and less expensive to purchase and operate than previous types. That such combines are more suited to small scale operation is borne out by the research performed by Barger (5). This investigation indicated that tractor driven combines are more suited to small scale grain harvesting, such as is found in Western Europe and many parts of the United States. This explains the popularity of such machines in those situations.

It is difficult to determine the exact time when the combine was first used to harvest crops other than the cereals; nevertheless, modern literature abounds with references to the use of combines for harvesting such crops as peas, beans, clover, the grasses, and corn. This extension of the use of the combine brought with it many modifications of the machine. The straw rack was enlarged to handle greater volumes of straw, pick-up attachments were developed to harvest windrowed crops, and the cleaning system was adapted to handle the large amounts of damp, green material often associated with some of the crops harvested.

Modern Developments

Hurlbut (6) states that, "In considering corn harvesters from the point of view of farmers who diversify the production of grain crops, it appears, that the ideal machine for harvesting corn should be versatile enough to harvest small grain crops as well." This statement sums up the modern trend in the design of all farm machinery. It is true to say that the modern farmer should specialize in one particular crop to reduce investments in machinery. This type of farming, however, is not yet widespread and thus it is necessary to design machinery that can be used to process more than one crop. The Harry Ferguson Company (7), recognizing the potential demand by small farmers for labor saving machinery, proceeded to develop a "multi-purpose, semi-self-propelled harvester." This machine was tractor mounted, designed for quick attachment, and was intended to perform the functions of corn, grain, and forage harvesters.

Reed (8) designed and constructed a trial machine by combining an existing forage chopper and an existing combine. This machine incorporated a "combination threshing-chopping cylinder." The chopping mechanism of the forage harvester was used as a basis for the combination-cylinder, since it was designed to transmit the power necessary for chopping, whereas, the combine cylinder was less ruggedly constructed. When the machine was used as a thresher, the cutter-head knives were replaced by rasp-bars. Functional evaluation of the threshing-chopping cylinder showed that the basic concepts were correct. An economic analysis by the same author indicated that the thresher-forage harvester combination could reduce harvesting costs for the average Iowa farmer. Design recommendations necessary for the construction of the machine were listed.

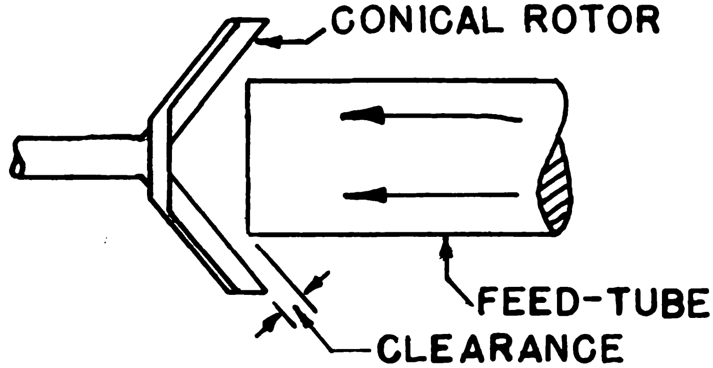


Fig. 1. Conical threshing-rotor.

Research concerning the threshing process within a conical rotor was reported by a German engineer, Wessel, in a translation by Klinner (9). Figure 1 shows the roter in diagrammatic form. The author called the process "radial-threshing" and pointed out that it consisted of four distinct phases as follows:

1. Separation within the feed tube due to relative motion of the various layers of straw, one over the other.

2. Separation due to the change in momentum resulting from the diversion of the material by the

beaters.

3. Separation due to an oscillating motion of the material resulting from slippage laterally on the beaters.

4. Impact against the surrounding casing after the material had left the rotor.

The distance between the beaters and the feed-tube outlet, called the clearance, was found to be significant. The peripheral speed at the outer end of the beaters was at least 7,800 feet per minute for good threshing efficiency; the usual speed was in the region of 10,000 feet per minute. Threshing efficiencies comparable with those to be expected from conventional machines were found. Losses from seed damage were also similar to those of conventional machines. The threshing efficiency and damage losses increased as the clearance was made smaller; however, the clearance was more than ten times that in ordinary cylinder and concave machines.

Buchele (10) developed and patented the machine to be investigated in the present study. He also developed, at the same time, a machine that achieved threshing by rubbing the material along the inside of a perforated cone by means of flaps attached to a rotating shaft and pressed against the material by the resulting centrifugal force. These machines were designed to harvest such hard-to-thresh crops as small legumes more efficiently than was possible with conventional combines. Separation resulted from the centrifugal force acting on the seed and causing it to pass through the perforated cone. It was claimed that superior threshing resulted from the fact that the threshing treatment could be applied for a longer period of time than was possible in cylinder-and-concave threshers. The threshing time was determined by the continuity-of-flow equation and the size of the cone. A cone thresher has been used by the Pioneer Hybrid Seed Corn Company of Johnson, Iowa, since 1955.

Lamp (11), recognizing the possibility of using centrifugal force as a means of threshing, performed extensive laboratory tests to determine the factors affecting the threshing of grain. The tests were conducted in a centrifuge which subjected the material to accelerating forces 312 to 5,000 times that of gravity. Straw breakage, in general, was not a problem and the force necessary to complete threshing was under 0.5 pound for the moisture ranges involved. In a series of tests with kernel moisture varying between 9 per cent and 12 per cent, complete threshing was accomplished with a force of 0.325 pounds.

Significantly different results were obtained by applying the force in different ways. For instance, when the head was mounted in the centrifuge so that its tip pointed radially outwards, twice as much force was required to complete threshing as when the tip pointed radially inwards. This phenomenon was especially noticeable at the higher moisture contents. Some heads were placed in a cylinder with perforated walls and subjected to centrifugal force with only the walls to constrain them. This method achieved less than 50 per cent threshing and the author concluded that for good results in this type of a system, relative motion between the straw and the cylinder must be accomplished. The threshing force was also applied without the effect of air resistance by enclosing the heads in centrifuge cups. It was found that the force required to achieve complete threshing was greater in all cases than when the air resistance was available to open the chaff. All of the chaff remained attached to the heads in the tests performed in centrifuge cups. In tests where the air resistance was allowed to have its effect, larger amounts of chaff remained on the heads when the moisture content was high than when it was low.

Lamp also noticed a separation by size as the threshing process proceeded, that is, as the speed of rotation increased. The grains threshed in the lower and medium speed ranges were larger than those threshed at the higher ranges and, consequently, required less force to separate them from the plant. The seed threshed at the upper end of the speed range was 20 to 28 per cent lighter than that threshed at the lower ranges which was considered superior in all respects to the light seed.

Harris (12) translated a report by Kolganov, a Russian scientist, in which the same phenomenon was reported. Differences were found between the grains of a single plant; ears from the main stems, the center part of spikes, and, in the case of oats, the upper part of the panicle, contained grains that developed and ripened earlier than those grains from other parts of the plant. Such grains were more mature, separated more easily from the plant, and damaged more readily than those from the other parts. Such grains were larger and heavier than the remainder and required only half of the cylinder velocity that the smaller ones did to thresh them. The Russian worker concluded that a multi-stage threshing mechanism was called for in order to get maximum use from the best grains in the plant, which probably had superior genetic characteristics. Such a threshing machine was built and the results showed that the grain from the first stage was heavier than that from the second and that damage to the grain in the second stage was 2 to 2½ times higher than that in the first. There was little difference in germination between seeds from the first and second threshing stages but the growth and vigor of the seeds from the first stage was greater than that of the remainder of the seed. He states that the greatest damage was caused to that grain which had a large absolute and specific weight, that is to say, to the most valuable grain.

The occurrence of damage to grain is extremely common and has been the object of much research. Lamp (11) recently conducted an extensive review of the subject; however, more information is now available. Urion, in a paper translated by Midgley (13), emphasizes the great significance from a commercial point of view, of the damage caused to the grain by high speed threshers. He states that great modifications resulted, not only in commercial methods but also in the quality of the product delivered, as a result of the introduction of the combine harvester and the high speed thresher. Malting barley was affected perhaps to a greater extent than any other grain for commercial as opposed to seed use. Barley for malting had to be stored in large quantities and then germinated. Not only did the direct damage, due to the combine cylinder, reduce germination but it also impaired the storage qualities and, as a result, the germination of the stored grain was poor. He notes that the damage was often visible to the unaided eye, but states that the seriousness of this problem is not the damage that can be seen but that damage that cannot be seen. He claims that the invisible damage may reach a level as high as 15 to 20 per cent, even the minutest cracks being a potential danger. He pointed out that damage to the testa was the essence of damage to the seed and recommended that the "tetrazolium test" be used in any attempt to determine the damage to the seed. One test with barley showed:

intact grains			74%
severe lesions -	embryo damage	10%	11%
	endosperm damage	1%	
smaller lesions			6%
very slight damage			9%

Most of the cracks were found on the embryo end.

Mechanical damage to the grain was the subject of the research by the Russian worker referred to above (12) in connection with the multiple stage thresher. This worker quotes Kovgan as stating that 75 per cent of the large grain is ruptured by impact with a cylinder bar at a speed of 35 meters per second, which is equivalent to 6,900 feet per minute. Kolganov states that the work required to separate one of the small grains from the head is 120 cm. gm. and that for the superior grain is 60 cm. gm. According to the expression that was used in relating the peripheral speed to the work done on the grain, these amounts of work correspond to speeds of 34 and 17 meters per second, respectively. The significance of this is clear when it is remembered that 35 meters per second ruptured 75 per cent of the best grain.

DeLong (14) found that more mechanical damage was done to grain by rasp-bar cylinders than by either angle-bar or spike-tooth types. The spike-tooth cylinder was found to do the least harm. He concluded that the rubber-faced angle-bar had a slight advantage, in that it accomplished adequate threshing without causing excessive kernel damage. This conclusion was based on results from tests on barley.

As a result of their investigations, King and Riddols (15) attributed the main cause of kernel damage to high cylinder speeds. A correlation was found to exist between the amounts of visible and invisible damage. The combined effects of small cylinder-concave clearances and high cylinder speeds was found to impair the germination of both the visibly and invisibly damaged seeds. In the same context, Arnold <u>et al</u>. (16) found that with correct cylinder adjustment the germination of mechanically threshed oat samples was the same as that of hand threshed samples.

Experiments performed in connection with clover by Park (17), indicated that the rasp-bar cylinder caused up to three times the damage caused by the angle-bar types. The same author reported threshing losses in clover as high as 40 per cent and found evidence to indicate that angle-bar threshers gave the highest threshing efficiency. Rasp-bar cylinders gave the lowest efficiencies and it was shown that the performance of a rasp-bar cylinder could be improved by replacing some of the rasp-bars with angle-bars.

In their work with small seed legumes, Bunelle <u>et al</u>. (18) found that the peripheral speed of the cylinder was the most important variable affecting seed damage. The amount of seed damage was found to decrease when the cylinder-load increased; when the straw was leafy and had a high moisture content, similar results were found. This reduction in seed damage was attributed to the padding afforded by the straw when the cylinder was heavily loaded. The threshing efficiency was found to be low at cylinder speeds of 5,000 feet per minute which did not damage the seed.

Hopkins and Pickard (19) found that a six-bar cylinder was inadequate for shelling corn and that increasing the number of bars to twelve reduced the shelling losses, but caused considerable kernel damage. The space between the bars of the cylinder was closed with sheet-metal to keep the material in contact with the concave.

McCuen (20) used a dynamometer to indicate the power being consumed by a combine. He hoped to find a correlation between the power consumption and the threshing efficiency. Though there was no statistical treatment of the data, some correlation was seen to exist. Cylinder losses were always much less significant than shoe and rack losses and one variety of hard-to-thresh wheat was more completely threshed when the cylinder load was larger.

High speed motion pictures of the threshing process in a conventional cylinder were made by Koniger and Schulze (21). The speed of the cylinder was approximately 6,000 feet per minute and the material approached the cylinder at a speed of 150 feet per minute. The threshing of wheat was photographed and the feed rate was 5,400 pounds per hour.

The wheat stem approached the cylinder with its axis parallel to the axis of the cylinder. The actual ear of wheat was at an angle to the stem and, although the author did not say so, it is to be presumed that this was due to the fact that the wheat was ripe, since this is a typical sign of ripeness in wheat. As the crop entered, some ears pointed toward the cylinder and some pointed away from it. The heads were seen to bounce around at the throat of the thresher and due to the impacts involved, most of the threshing took place at this location. At the entrance to the cylinder the heads were pressed together and some of the threshing was due to the rubbing action of one head on the other. In this event the grain left the head with a low velocity. In the event, however, of the head being struck by a beater, the grains left it with a high velocity.

The ears were seen to be accelerated more when the wheat was fed into the cylinder with its axis parallel to that of the cylinder, than when the stems made some angle with the axis of the cylinder. The direction and speed of the grain after it was hit by a rasp-bar depended on how it was hit by the bar and on the air currents in the vicinity. Most of the threshing in the cylinder was seen to take place as the result of impact, which substantiates the theory put forward by DeLong (14) and others who have worked in this field. Extensive photographic investigation of the threshing process has been performed by the makers of these films.

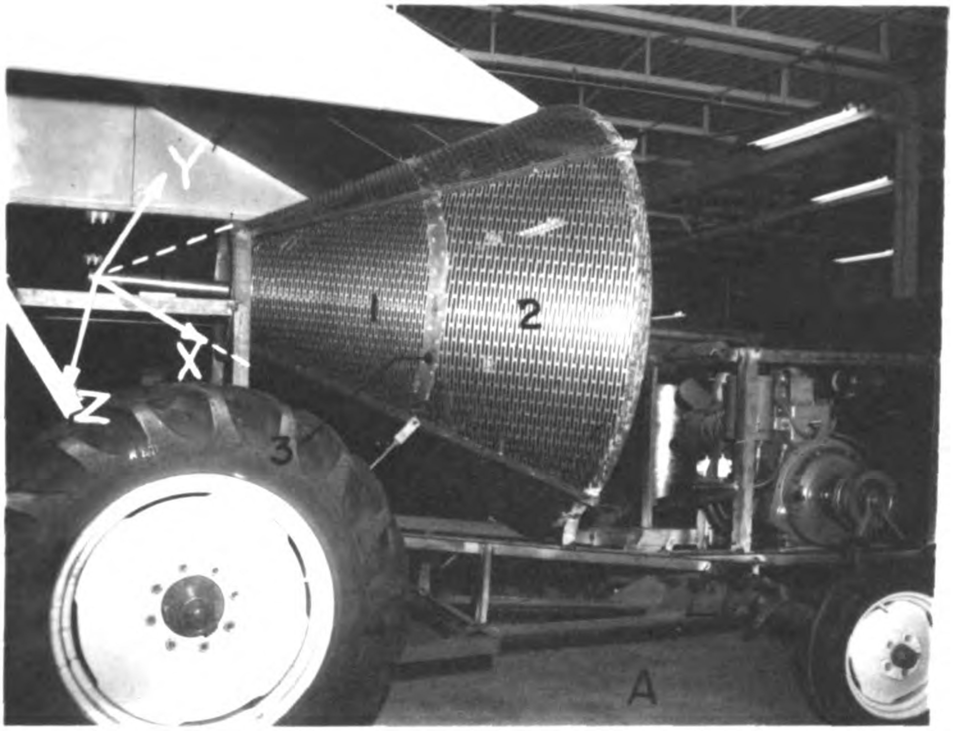
Øyjord (22) is working on the design and testing of a plot harvester at the present time. This harvester utilizes a flail-type threshing mechanism.

DESCRIPTION AND MODE OF OPERATION OF A THRESHING CONE

Figure 2 shows a cone which was fabricated from perforated sheet-metal. Let the apical angle of the cone be 2θ. A cone-shaped rotor rotates within the perforated sheet-metal cone. The apical angle of the rotor is slightly larger than that of the stationery cone in order to provide greater clearance between the rotor and screen at the small end than at the base. The actual clearance is of the order of $\frac{1}{2}$ inch and the rotor consists of a number of rubber-covered angle-bars similar to those found in some conventional threshers.

The material to be threshed enters the annular space between the two cones and moves in a spiral from the small end to the large end or base of the cone. By the time the material has reached the large end the threshing and separating processes should be complete.

Movement of the material within the cone is caused by contact between the material and the rotor which gives the material a rotating motion. The resulting centrifugal force presses the material against the cone surface and causes it to slide in the x direction as shown by the reference system in Figure 2A. This reference system will be used throughout this discussion and the various axes are directed as follows with respect to the cone: the x axis lies on the cone surface in a plane through the cone axis, the y axis is



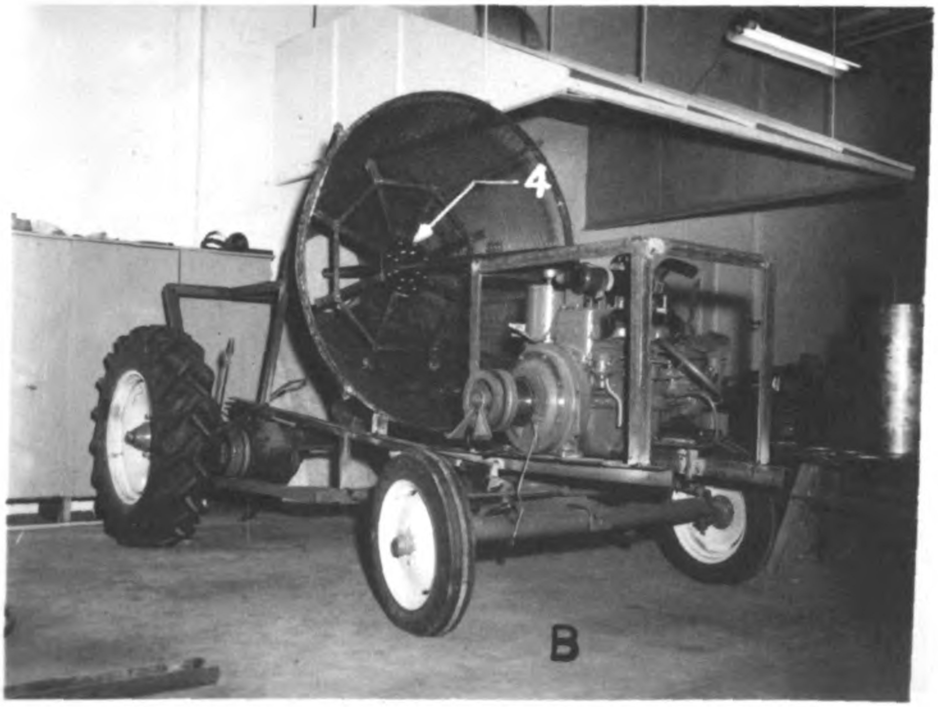


Fig 2. A - Completed cone showing reference axes, short perforations (1), long perforations (2), and steel band (3).

B - General view of cone showing partially completed rotor (4).

perpendicular to the cone surface and the z axis is perpendicular to the cone axis.

The action of centrifugal force in pressing the material against the screen, is analogous to the action of the gravitational force on a body that rests on an inclined plane. In making this analogy, it is assumed that the weight of the material is negligible by comparison with the centrifugal force to which it is subjected. Consequently, the force acting on the material is considered to be independent of the position of the material within the cone and of the orientation of the cone in space.

On the basis of the foregoing analogy, a value for θ can be found. Figure 3 shows a body resting on an inclined plane with a force F acting on it. The force may be the weight of the body or any other force. Let θ be the angle which the force makes with the normal to the plane. Consider the forces acting parallel to the surface; they are (1) the friction force, preventing the body from sliding down the plane and (2) the force, $F\sin\theta$, which tends to make the body slide. The maximum value of the friction force is uN, where u is the coefficient of friction between the surface and the body and N is the normal force, which in this case is $F\cos\theta$. Therefore, at the moment of impending motion

$$F \sin \theta = uF \cos \theta$$

and

$$u = \tan \theta. \tag{1}$$

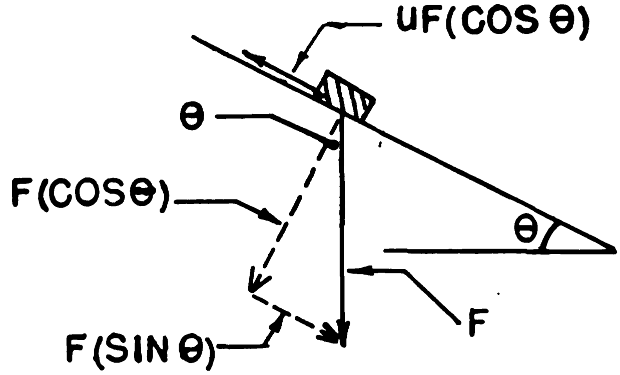


Fig. 3. Calculation of the cone-angle, θ.

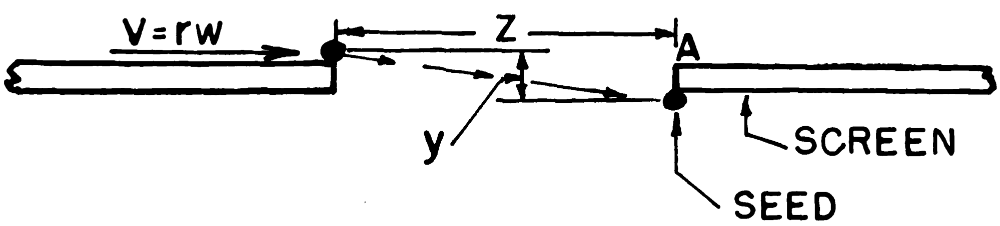


Fig. 4. Calculation of the slot-length, z.

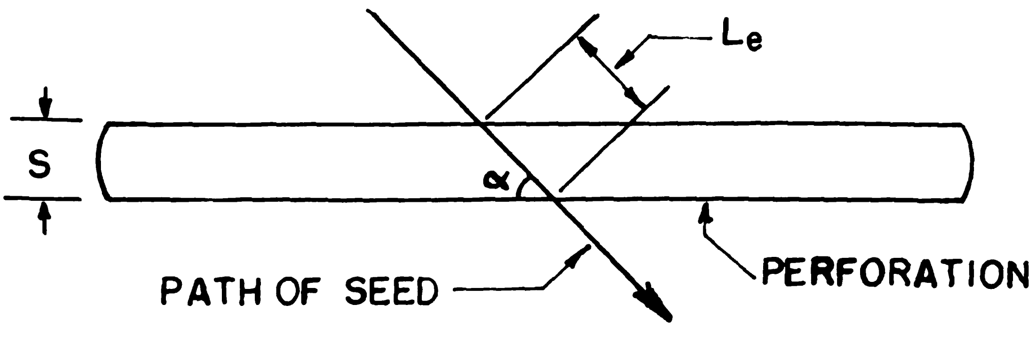


Fig. 5. Calculation of the effective slot-length, L_e.

It is clear that θ must be greater than $\mathrm{Tan}^{-1}u$ for the body to slip on the plane. Since the magnitude or origin of the force was not specified, the relationship in equation (1) must be true for all values of F. Therefore, let the inclined plane be the inner surface of the cone-thresher and let the force be the centrifugal force resulting from the motion of the material within the cone. This gives a value of 2θ based on equation (1), such that the material will slide in the x direction.

On the basis of this simplified approach a cone was designed and constructed. The approach, however, proved to be an over-simplification of the problem and further analysis (Appendix A) showed that provided θ was not zero, the material would have an acceleration in the x direction and would, consequently, start to move in that direction. Equation (2) is the differential equation which describes the motion of a particle of the material within the cone and its derivation is presented in Appendix A.

$$\ddot{x} = -u\left[\frac{\dot{x}bx}{\sqrt{\dot{x}^2 + x^2a^2}} + \frac{uabx^2}{\sqrt{\dot{x} + a^2x^2}} - 2a\dot{x}\right] + a^2x \qquad (2)$$

The solution to this equation provides information about the threshing force, the time for the material to pass through the cone, the power required to drive the rotor, and the angle which the path of the material makes with the z direction. This angle will be called the helix-angle, α.

The value of $\ddot{x}$ depends on the apical angle 2θ, so that the time for the material to pass through the cone for a given value of w will be determined by θ. The time taken by the material to pass through the cone will determine the capacity of the thresher and the amount of threshing that the crop receives. The value of θ, therefore, should be selected on the basis of the threshing and capacity requirements and not on the basis of the coefficient of friction. The cone dimensions must be kept within reason since any machine incorporating this threshing principle must be at least as compact as the conventional combines if it is to be of any value to small-scale grain producers.

The power required to drive the rotor can be estimated from the value of F_t and this is an important factor in design considerations. The use of the correct value of the helix-angle will permit a maximum amount of separation to occur within the threshing cone. Considerable air movement will occur as a result of the fanning action of the rotor and this air movement will consume some of the power supplied to the rotor. In designing a threshing cone, therefore, every effort should be made to utilize the air movement for conveying and cleaning the grain.

Size of Screen Perforations

The separation of the grain from the straw is achieved by the action of centrifugal force causing the grain to pass through the perforations in the screen. This is an important operation and some knowledge of how a seed passes through a perforated surface on which it is moving is essential.

For simplicity, let a grain in the cone have a circular motion which is parallel to the plane of the base of the cone. Figure 4 shows the grain approaching a perforation with a velocity rw, where r is the radius of the cone at that perforation. The z direction is that of the convention set up on page 19. Since the effect of gravity is negligible the only force to be considered is the centrifugal force causing the seed to pass through the perforation. The length of the perforation is z and let the distance through which that seed must move in order to pass through the perforation be y. The distance z must be great enough so that the seed will not have passed the end of the perforation (point A), in the time that it takes to accelerate it through the perforation. Setting the time required for the seed to pass through the screen equal to the time required for the seed to traverse the length of the perforation, gives the perforation length z, in terms of the radius of the cone, r. Thus:

$$z = rwt$$

$$\text{or } t = \frac{z}{rw} \qquad (3)$$

Similarly, $y = \frac{1}{2}rw^2t^2$

$$\text{or } t = \frac{1}{w}\sqrt{\frac{2y}{r}} \qquad (4)$$

Equating 3 and 4 gives:

$$z = \frac{rw}{w}\sqrt{\frac{2y}{r}}$$

or $$z = \sqrt{2ry} \tag{5}$$

Equation (5) shows that the length of the perforation is independent of the rotational speed of the particle and depends only on the radius of the cone, the size of the seed, and the thickness of the screen. The distance y is the screen thickness plus the diameter of the seed. It could be said that only half of the seed diameter should be included in the distance z. This approach, however, would permit the seed to strike the end of the perforation and be damaged before passing through.

The limitations of this method for finding the length of the slots in the cone should be clearly understood. In the first place, the assumption that the grain has a circular motion in a plane parallel to the base of the cone is not correct. The analysis of Appendix A shows that the seed moves in a helical path that makes an angle α with the plane of the base of the cone. This means that the full length of the slot will not be available for the grain to pass through and the effective slot length, L_e will be only $s/\sin\alpha$, where s is the width of the slot (see Figure 5). Hence the importance of designing the slots to make an angle α with the z direction, since this will result in maximum separation.

DESIGN OF A THRESHING CONE

Cone Angle

From the preceding theoretical analysis, the cone angle θ was seen to be the factor which determined whether or not material would pass through a threshing cone. It was shown that θ must be greater than $\tan^{-1}u$.

The angle, $\tan^{-1}u$, was determined by placing straw on a sheet of perforated steel, which was vibrated and tilted from the horizontal position until the straw slipped. The angle between the horizontal plane and the inclined sheet-metal was measured and its tangent was considered to be the quantity, u. On the basis of these measurements θ was chosen to be 27°.

Dimensions of the Cone

The length of the cone in the x direction was one of the factors to be determined in the course of this research. Consequently, it was necessary to make the cone longer than might have appeared adequate for complete threshing and separation so that the correct length could be determined. From consultations with Buchele (10), who had previously worked with a threshing cone, a length of four feet was decided upon. For convenience, the cone surface was divided into four quadrants which were joined together by bending the inch-wide margin, left around the edges of each, into a flange and securing one quadrant to the other by bolts. Furthermore, for reasons to be discussed below, each quadrant was divided into two equal lengths to give a total of eight sections--four in the small end and four in the large end of the cone. The small end of the cone had a diameter of 16" and the base was 59.6" in diameter.

Material in the Cone and Slot Length

The thickness of the material was 1/8" and the perforations were "side-staggered" and ¼" wide. The length of the perforations is given by equation (5), and is seen to vary with the radius of the cone. The expense of manufacturing perforated sheet metal with perforations varying in size was prohibitive. Consequently, in the sections comprising the small end of the cone, the perforations were 2" long and in the sections from the large end they were 3" long.

Construction of the Cone

The ends of the cone were reinforced by hoops of 2" by 3/8" steel, fitted on the inside of the screen to which they were welded. This reinforcement provided the rigidity necessary to mount the cone in a horizontal position. The flanges by which the quadrants were bolted together were backed by 1" x ¼" steel strips which in turn were welded to the reinforcing hoops at each end. The joint between the front and rear sections was lapped with 1/8" steel and secured to the screen by means of screws countersunk in the perforations. Figure 2 shows the completed cone.

<u>Design of conical rotor</u>. Eight rubber-covered angle-bars from a conventional combine were used as beaters for the cylinder or rotor of the threshing cone. The angle-bars were mounted with the rubber-covered surface in a radial plane. The general construction was rugged in order to avert the possibility of failure due to normal operating forces or due to forces caused by rotating unbalance. Estimation of the shaft loads likely to be encountered was little better than guesswork and a 2" diameter steel shaft was selected on the assumption that it would have sufficient strength and rigidity.

The hubs of the cylinder were made to be a sliding fit on the shaft and relative rotation between the shaft and the cylinder was prevented by means of 3/8" square keys. Axial movement of the cylinder along the shaft was prevented by the use of set screws. Thus, the clearance between the beaters and the cone could be changed by loosening the set screws and sliding the rotor along the shaft. The clearance varied from 1" at the small end to ½" at the large end. The clearance, however, at the large end varied due to the fact that the base of the cone was not a perfect circle.

<u>Feeding mechanism</u>. A side feeding mechanism was used by Buchele (10) in his work with the threshing cone. A means

of feeding the cone axially, however, offered advantages from the standpoint of the overall design of a machine incorporating the threshing cone principle. Furthermore, such a feeding device had not been tested previously. Consequently, a screw conveyor was designed, fabricated, and mounted on the rotor shaft so as to feed the grain into the cone. Relative rotation between the auger and shaft, under normal loads, was prevented by set-screws; in the event of an overload, however, the auger slipped on the shaft and thus possible damage resulting from the overload was avoided.

Power supply and transmission. The engine used to drive the mechanism was similar to that used on the "Massey-Ferguson-35" self-propelled combine. The power was transmitted to a gear-box by means of a flat rubber belt which also served as a clutch since the tension in the belt was easily released by means of an idler attached to a system of levers. The gear-box transmitted the power through a right-angle and a V-belt drive completed the transmission to the rotor. The V-pulleys were adjustable in size and permitted rotor speeds of 300 to 600 R.P.M. at the normal engine speed of about 2,200 R.P.M. A tachometer driven by a belt from the rotor shaft indicated the rotor speed in R.P.M.

Enclosure of the cone. The cone was enclosed by sheet metal to facilitate collection of the material passing through the perforations. A hinged door was provided, to allow easy access to the underside of the cone for the purpose of manipulating the sample-box which will be discussed later.

Straw exit. Since the straw leaving the cone had a circular motion with high peripheral velocity, an outlet was devised to permit it to leave at a tangent to the cone and be deposited at a convenient location. If necessary, the straw could be loaded on a wagon with this arrangement, see Figure 6.

Exploratory Tests and Consequent Modifications

The cylinder was rotated empty, at speeds up to 750 R.P.M., to check the machine for vibrations, rotating unbalance, and other difficulties that might arise at high speed operation.

A low frequency torsional vibration was observed in the entire chassis. The reason for this vibration was that the cone and the engine were each secured to the chassis but not to one another. Consequently, relative displacement between the cone and engine was possible and occurred in a manner best described by considering the chassis to be a torsion member to which two eccentric masses, to wit, the cone and the engine were attached. The vibration was such that the displacement of the cone was opposite to that of the engine and was eliminated by bracing the engine and cone together.

At high cylinder speeds the free ends of the angle-bars were deflected radially outwards by centrifugal force, until

Fig. 6. Material emerging from the straw outlet (1) being collected in container (2).

Fig. 7. Sampler box showing equally long sections 1-6.

Fig. 8. View of feed-auger showing: (1) steel strip, (2) conical part of auger, and (3) inner surface of the screen.

they contacted the screen where the clearance was less than ½" when the cylinder was stationary. Tie-bars were extended from each bar to the next to form an octagon with the beaters at its angles and thus prevent the deflection.

The feeding mechanism required considerable modification before satisfactory operation was achieved. The straw wrapped around the auger due to the large clearance between the auger and its housing. The clearance was reduced to a minimum and a strip of 3/8" x ¼" steel was spot-welded longitudinally on the housing floor to prevent the material from rotating with the auger, see Figure 8.

These measures eliminated the wrapping at the auger. When the straw entered the cone, however, it became wrapped around the small end of the rotor at the point where it joined on to the auger The reason for this wrapping was, that the circular motion of the material was not fast enough to cause it to be thrown outwards by centrifugal force against the walls of the cone and free of the rotor. A cone-shaped auger which enveloped the small end of the rotor was constructed as shown in Figure 8. This had the effect of positively feeding the material into the space between the rotor and the screen. The material, however, still possessed a slow circular motion and failed to move in the x direction. The addition of a spur which projected radially for 3/4" from the last flight of the conical auger eliminated the difficulty by engaging the material and causing it to rotate sufficiently fast to be thrown free of the rotor. This arrangement proved satisfactory and only minor chokages were encountered afterwards.

The exploratory threshing indicated that the threshing-efficiency would not have been satisfactory at rotor speeds below 300 R.P.M. Consequently, a speed range of 300 to 500 R.P.M. was selected for the quantitative testing. These speeds corresponded to peripheral velocities at the large end of the rotor of 4,700 to 7,850 feet per minute.

Speed variation by the use of a variable speed V-belt drive proved to be unsatisfactory and was abandoned. A tractor equipped with a belt-pulley was used to rotate the cylinder since the governor on the combine-engine was effective at full throttle only and, as a result, accurate control over the rotor speed was not possible when the power requirement varied. Power was supplied from the tractor to the gear box of the threshing cone in the same manner as when the combine-engine supplied the power. This arrangement (see Figure 9) provided good control over the rotor speed and functioned satisfactorily throughout the tests.

Bundles of wheat, oats, and barley were used in the preliminary tests and the threshing efficiency appeared equal for all three with the possible exception of some oat bundles which were cut before they had ripened completely and were, consequently, difficult to thresh. Since a plentiful supply of wheat bundles was available, Genessee wheat was used in the quanitative tests.

To prevent the escape of grain, the large end of the cone was enclosed with sheet metal, leaving an opening one foot square at the center, through which the shaft passed. The loss of grain from this end of the cone was particularly noticeable at high speeds.

Considerable air movement took place in the neighborhood of the rotor. Currents of air were drawn into the cone at the small end and at the center portion of the large end. At the periphery of the large end, however, air movement was outwards and a high velocity air stream emerged from the straw outlet. Air also moved outwards through the cone perforations.

EXPERIMENTAL METHODS

Material for Testing

The bundled grain used in the following tests was cut with a binder and stored. Five bundles of wheat (weighing from four to five pounds each) were used in each test. Some threshing had already occurred as a result of vermin infestation during storage.

The bundles were fed into the machine by hand and when no choking occurred, the feeding time was thirty to forty-five seconds.

General Procedure

The tests were performed at five different cylinder speeds as follows: 300, 350, 400, 450, and 500 R.P.M. In order to investigate the various factors under consideration, the total amount of grain passing through the machine during each test had to be determined. This posed a considerable problem due to the high air velocities in the neighborhood of the cone causing the various fractions of the material to be blown about and mixed together. After a process of trial and error, suitable shields and receptacles for the grain and straw were developed. Because the threshed but unseparated grain emerging with the straw still scattered, the tests were performed on calm dry days and on a strip of concrete pavement. The lost material was collected and returned

Fig. 9. General view of equipment; (1) circle-sample chute, (2) feeding mechanism, and (3) pulley, belt driven by the tractor.

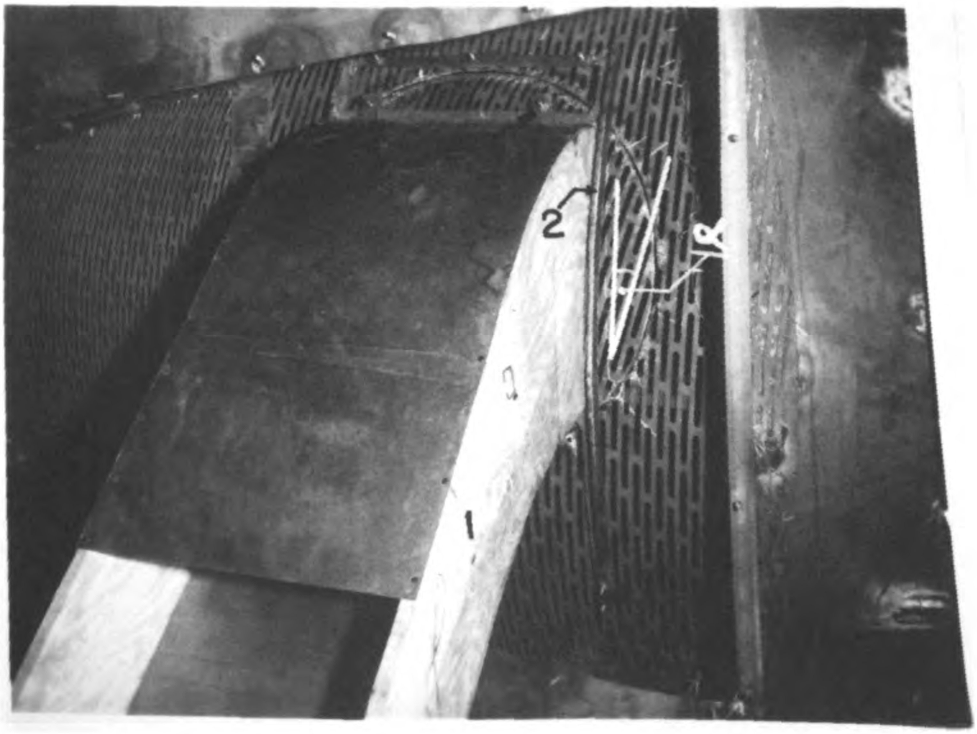


Fig. 10. View of circle-sampler showing the slot-angle α and the chute (1) to which the circle was attached by means of the mounting (2) and clamps (3).

to the straw container from which it had escaped. The straw container consisted of a large box placed under the straw outlet (see Figure 6).

The grain and broken straw passing through the cone perforations was divided into three fractions as follows:

(a) The majority of the material, which was collected in a box underneath the cone.

(b) A fraction collected in a sampler box, called the "box-sample" and which will be described later.

(c) A fraction called the "circle sample," which will also be described later.

Threshing Efficiency

The amount of grain unthreshed after each test was determined by passing the straw through a spike-tooth cylinder; it was assumed that this procedure accomplished complete threshing and that the grain retrieved in this way was the grain unthreshed by the threshing cone. Before re-threshing was done, the threshed but unseparated grain was removed from the straw by hand shaking.

Per Cent Separation Within the Cone

The material passing through the cone perforations was collected and cleaned. The weight of grain present was expressed as a per cent of the total grain and this figure was considered to be the separating efficiency of the combine.

Determination of the Relationship Between the Location of a Point on the x Axis and the Amount of Grain Passing Through the Screen at That Point

A box was constructed which covered a 30° arc of the cone and extended from the small to the large end. This box was placed against the cone surface on the under side of the cone. Grain passing through the perforations was trapped in one of the six equally long sections into which the box was divided (see Figure 7). The bottom of the box consisted of a fine wire screen which confined the contents and at the same time allowed free air movement. At the end of each test the sections were emptied and their contents cleaned and weighed. This procedure provided information concerning where, along the length of the cone, separation was being accomplished. The weight of grain in each section (hereafter referred to as the "box-sample") was expressed as a fraction of the total amount of grain in the entire box.

Effect of the Slot-Angle, α, on the Separating Efficiency

The angle between the z axis and the direction of the slots has been defined as the slot or helix angle, α. To determine the effect of the value of this angle on the separation of grain from straw, two areas of the surface equal in size and equidistant from the base of the cone, were chosen. A circular portion of the cone wall was cut from one of the areas and mounted on a chute. The chute was constructed so that it could be fixed to the cone surface in such a way as to hold the cut-away part of the screen in position, as shown in Figure 10. By re-shaping the cut-away portion it could be placed in the cone wall with the slots rotated to any desired value of α. Using this arrangement, an investigation of the effect of slot angle on separation efficiency was conducted. The material entering the chute through this part of the cone was collected and cleaned. The weight of grain found (hereafter called the "circle-sample") was compared to that collected from the other selected area, which was chosen so that the slots were parallel to the z axis. This comparison was used as a basis on which to select the optimum value of α and on which to predict the improvement to be expected when α was at this optimum value.

RESULTS AND DISCUSSION

Threshing Efficiency

The relationship between rotor speed and threshing efficiency is shown in Figure 11. The curve was plotted by calculating the average efficiency at each speed, for the two series of tests, from the data presented in Table 3, Appendix B.

The threshing efficiency was satisfactory at all speeds, however, at 300 and 350 R.P.M. the feeding mechanism clogged occasionally and was not considered to have operated satisfactorily. Above 350 R.P.M., operation of the feeding mechanism was completely satisfactory.

Separating Efficiency

The separating efficiency is defined as the weight of grain passing through the cone perforations expressed as a percentage of the total weight of grain entering the thresher. Figure 11 shows how the separating efficiency varied with rotor speed and the relevant data are presented in Table 3, Appendix B. The separating efficiency of the threshing cone compared favorably with the amount of separation that occurred in a conventional cylinder as reported by Lamp (11).

The cumulative separating efficiency is shown in Figure

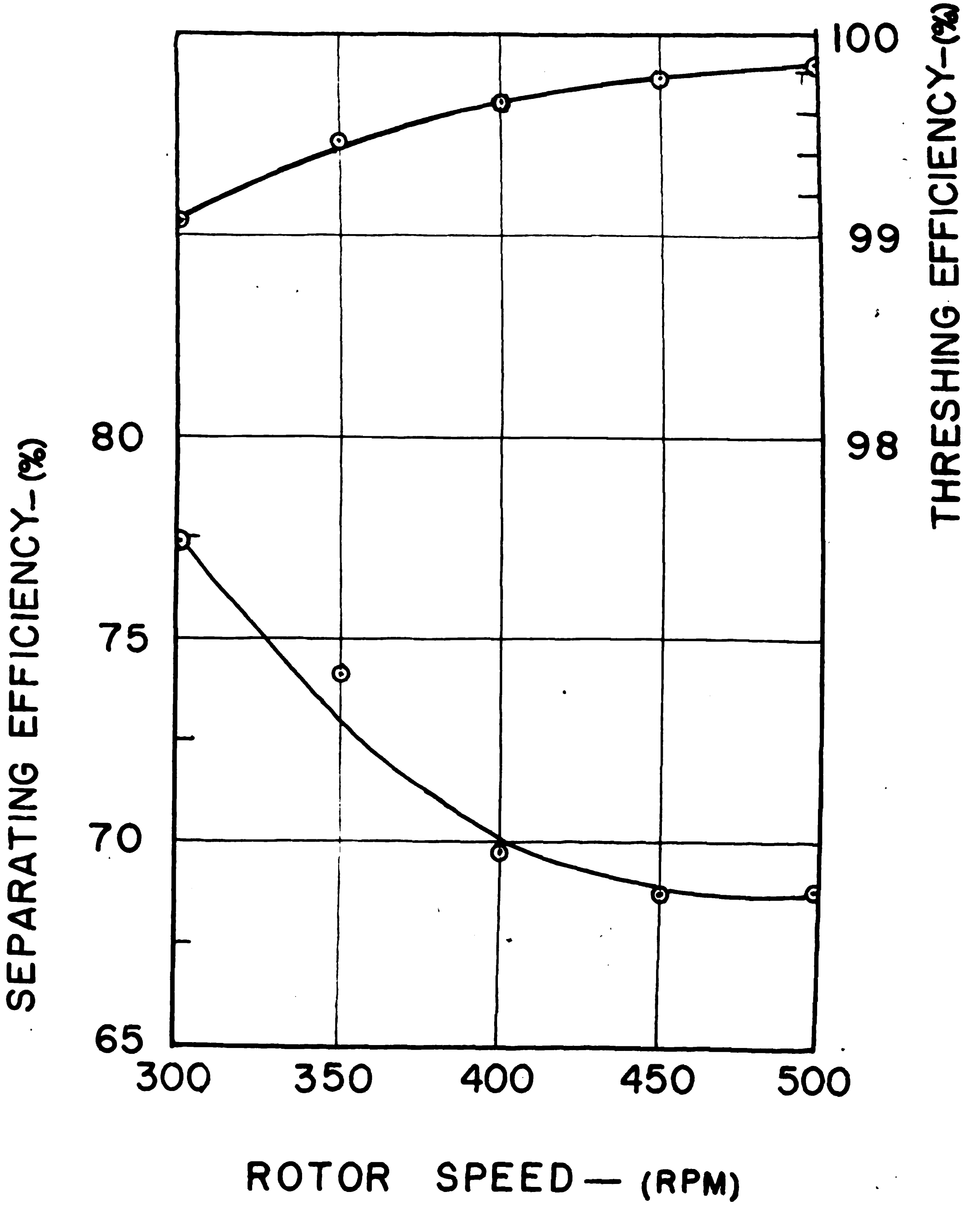


Fig. 11. Relationship between threshing efficiency, separating efficiency, and rotor speed.

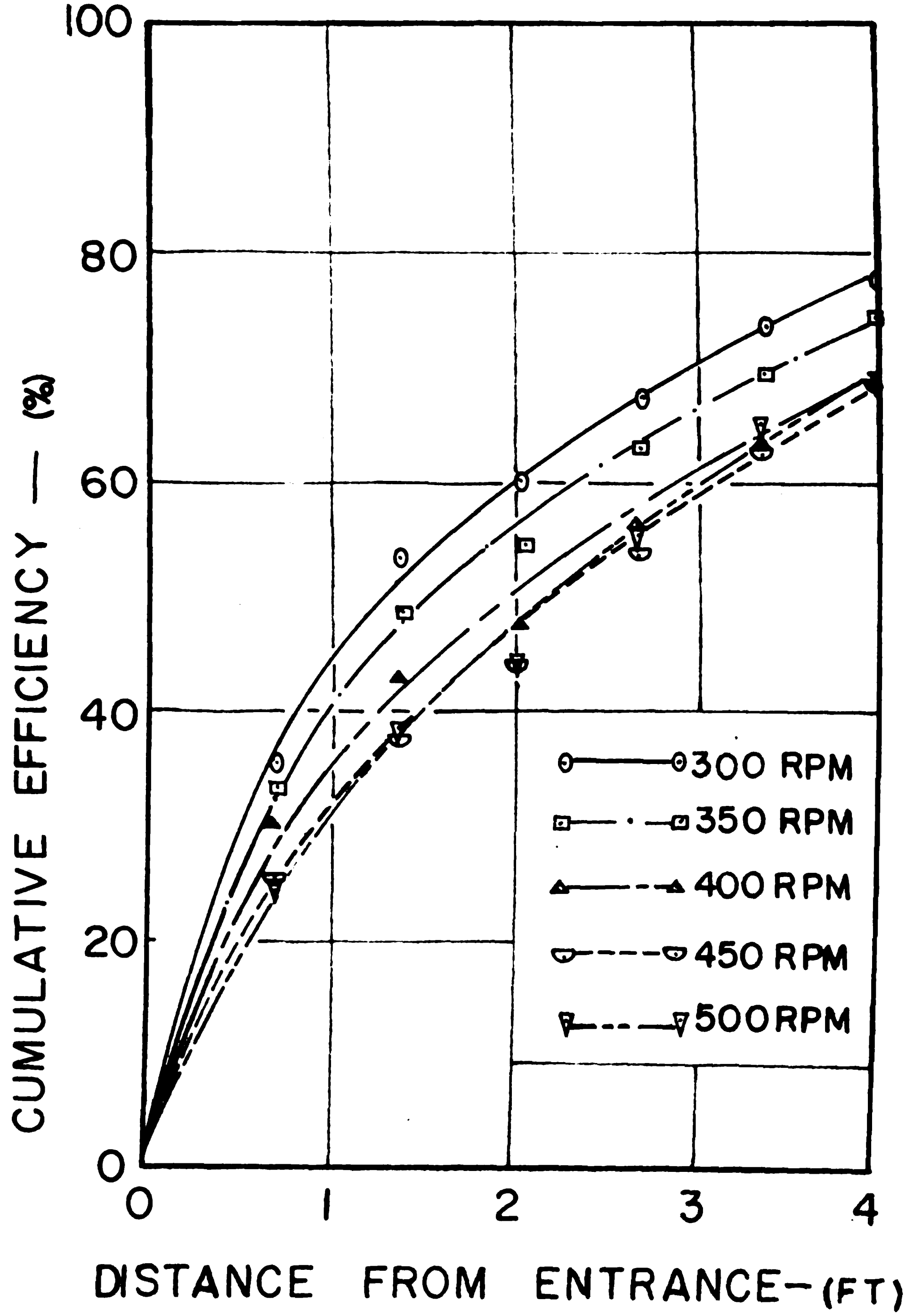


Fig. 12. Cumulative separating efficiency as a function of the distance (in the x direction) from the entrance of the threshing cone.

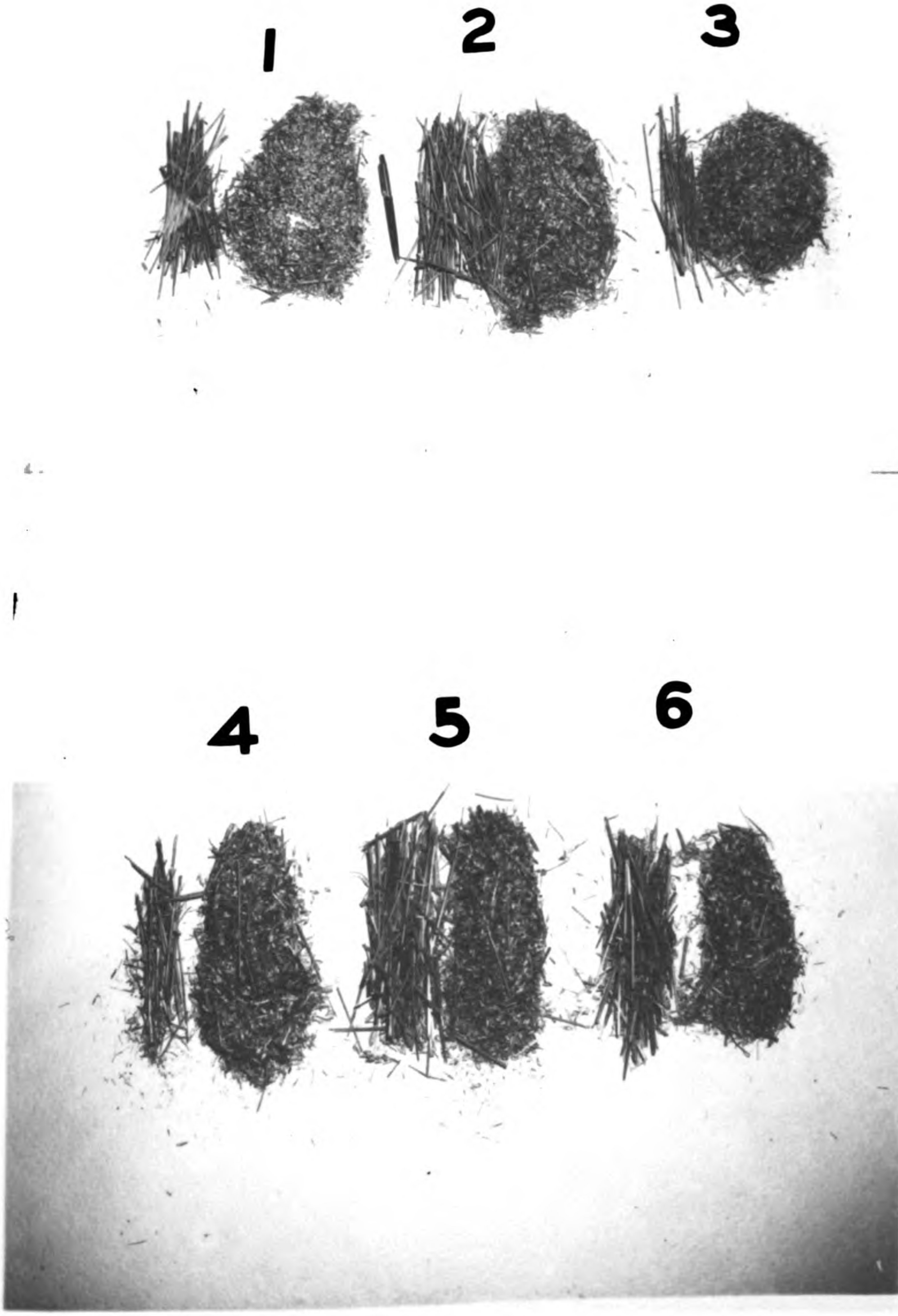


Fig. 13. Contents of the sampler box. The numbers correspond to those in Fig. 7. The pencil is $5\frac{1}{2}$ inches long.

12 as a function of the distance, in the x direction, from the entrance of the cone. The curves indicate that there is no advantage in operating the machine at high speeds, since the threshing efficiency was satisfactory at the low speeds which gave good separation. Instead, the feeding mechanism must be improved to give reliable performance at rotor speeds below 350 R.P.M.

During both the preliminary and quantitative tests, it was observed that the first material emerging from the straw outlet after the start of feeding was mostly grain. This was especially true at high rotor speeds and the possible explanation will be discussed in connection with the high-speed motion pictures. The possibilities of improving the separating efficiency of the cone will be investigated in connection with the slot angle.

Analysis of Data from the Sampler Box

The sampler box and a typical example of its contents are shown in Figures 7 and 13. The pencil in Figure 13 is 5½" long.

The weight of grain in each section of the box was expressed as a percentage of the weight of grain in the entire box. This indicated how the separation process was distributed along the length of the cone at the various speeds and the results are shown in Figure 14.

The location of the separating process shifted from the

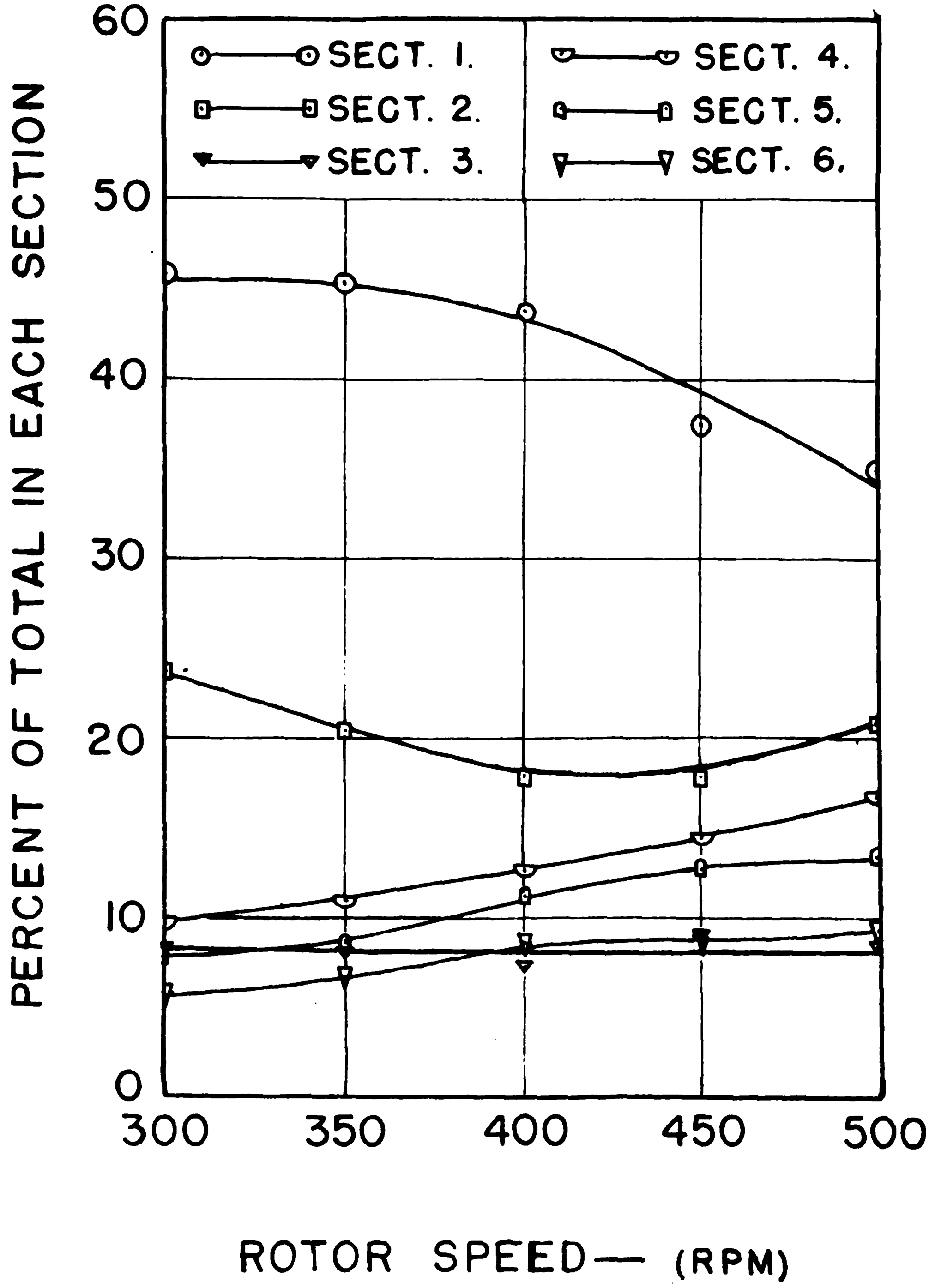


Fig. 14. Weight of grain in each sampler-box section, as a per cent of the total weight of grain in the sampler-box.

small to the large end of the cone as the rotor speed increased, with the result that sections 1 and 2 of the sampler box received less grain at high speeds than at low speeds, while sections 4, 5, and 6 received more grain. That fraction of the grain entering section 3 remained relatively constant and section 3 acted as a 'pivot' point about which the shift in separation, with change in speed, took place. The fraction of the total grain received by section 3 was smaller than might have been expected, due to the fact that in the neighborhood of this section, the screen was covered by the steel band which was screwed to it to lap the joint between the front and rear parts of the cone (see Figure 2). The increase, however, in the proportion of grain entering sections, 4, 5, and 6 did not compensate for the decrease in the proportion entering sections 1 and 2, with the result that there was a loss in total separation as the rotor speed increased.

Inspection of Figure 12 shows that in the first 8 inches of the cone length, approximately 35 per cent separation had been accomplished at 300 R.P.M. In the next 8 inches a further 18.25 per cent separation took place. In 16 inches or one-third of the total cone length, therefore, 53.75 per cent separation was accomplished; this corresponds to 69.42 per cent of the total separation which took place in the cone. At 450 R.P.M., 37.9 per cent separation had taken place over the same surface area; this corresponds to 55 per cent of the total separation. Thus, it can be concluded that high rotor speeds made inefficient use of the surface area for separating the threshed grain from the straw.

Observation of the thresher in action showed that, at low rotor speeds, the material moved slowly in the x direction and was subjected to more rubbing between the beaters and screen in the area immediately inside the entrance of the cone, than at high rotor speeds. This is a possible explanation for the higher amount of separation per unit length in the small end of the cone than in the large end. Two other factors may also have contributed: (1) the rotational speed of the material was low in this area and (2) grain threshed by the auger would have separated in this area since it was loose on entering the cone and would have passed through the screen under the effect of gravity before it was given any rotational motion. Figures 12 and 14 indicate that the slow rotational motion was probably the main cause for the good separation at the small end of the cone.

Figure 15 indicates the extent to which gravity may have affected separation in the cone. The sampler box covered a 30^{o} arc of the cone or 1/12 of the surface area. It should, therefore, have received 1/12 or $8\frac{1}{2}$ per cent of the material passing through the cone perforations. Considerably more than $8\frac{1}{2}$ per cent entered the box, as is evident from Figure 15. The effect was more pronounced at low rotor speed than at high speed--thus, it is reasonable to assume that gravity does affect the material in the cone to

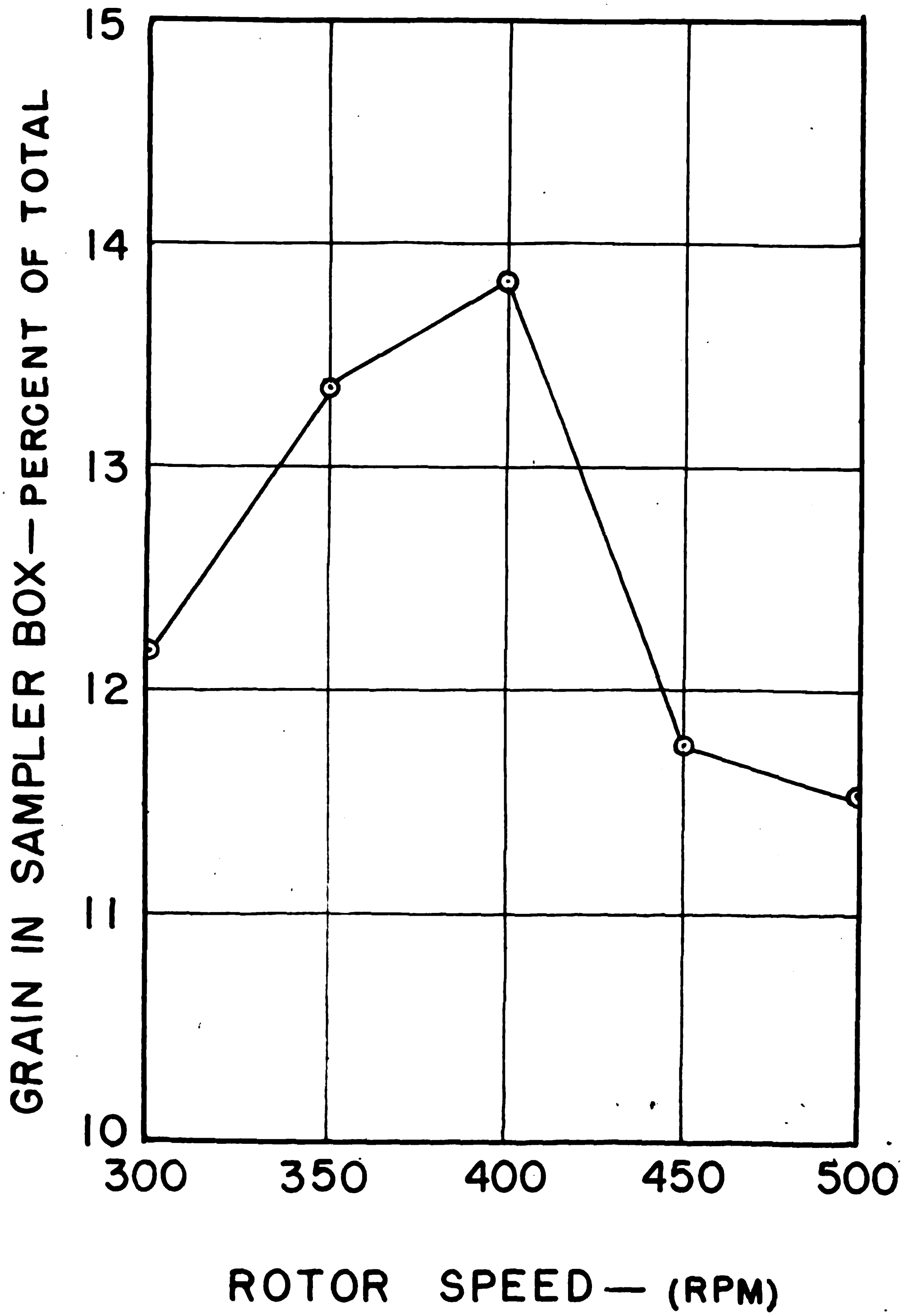


Fig. 15. Relationship between rotor speed and the per cent of the total separated grain found in the sampler-box.

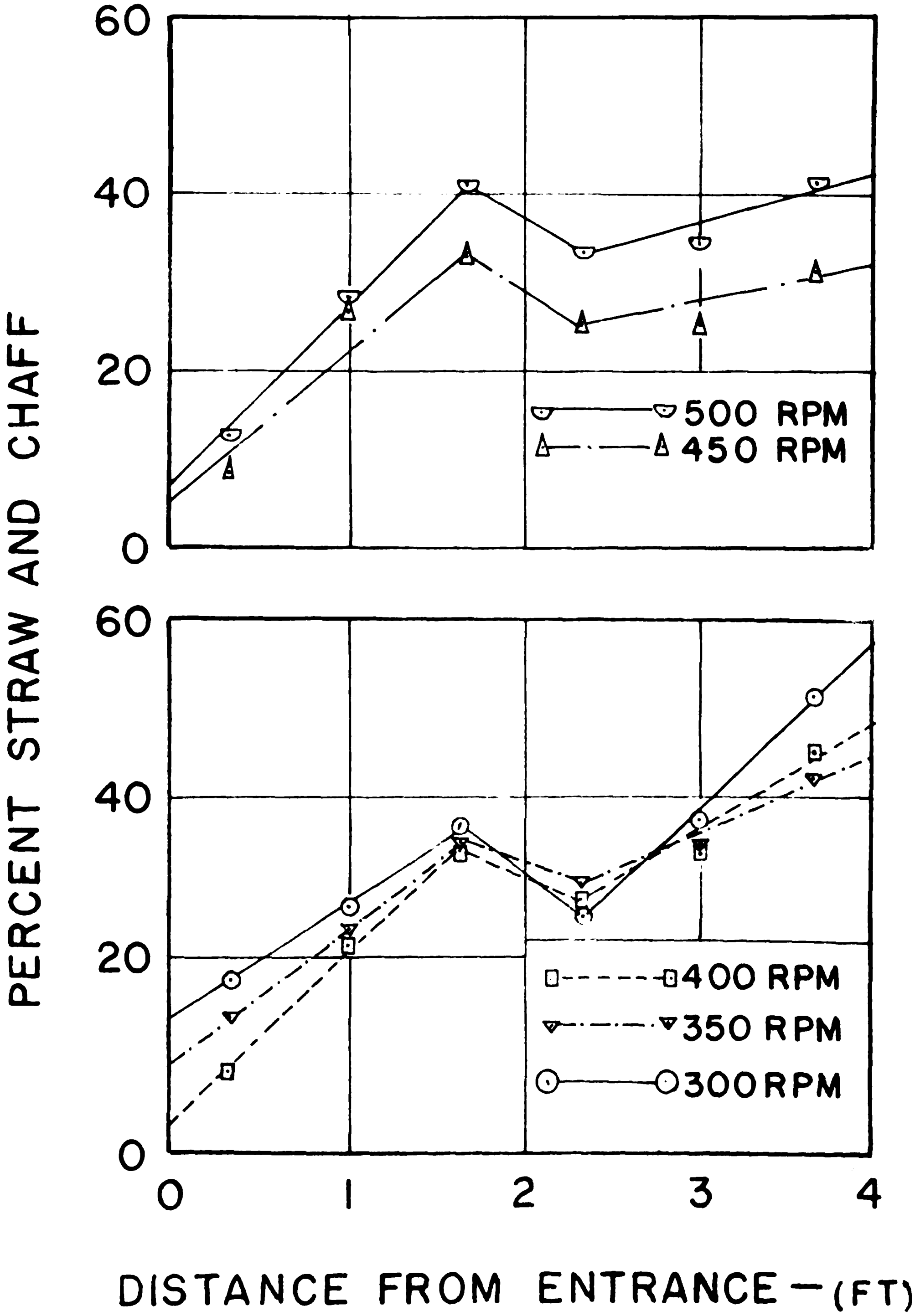


Fig. 16. Relationship between per cent straw and chaff in the separated material and the distance in the x direction from the cone entrance.

a considerable extent, since the sampler-box was on the underside of the cone.

Chaff and Straw in the Sampler Box

The amount of chaff and straw (debris) mixed with the threshed grain is important when a cleaning mechanism is considered. Lamp (11) found that the ratio of debris to grain, on the cleaning shoe of a conventional combine was in the neighborhood of 0.35. Figure 16 shows the relationship between the amount of debris and the distance from the cone entrance, for each speed, in the case of a threshing cone. With the exception of the fourth foot of cone length, the results compare favorably with those found by Lamp for a conventional thresher. The per cent of debris in the first two sections was, in fact, considerably lower for the cone thresher than for the conventional thresher. The question of debris is considered further under the discussion of the circle-sample data.

Figure 13 shows the nature of the debris found in each section and it is easily seen that the per cent debris increased as the distance from the cone entrance increased. The numbers in Figure 13 refer to the sampler-box sections shown in Figure 7.

Analysis of the Data from the Circle Sample

The relative separating efficiency is defined as the

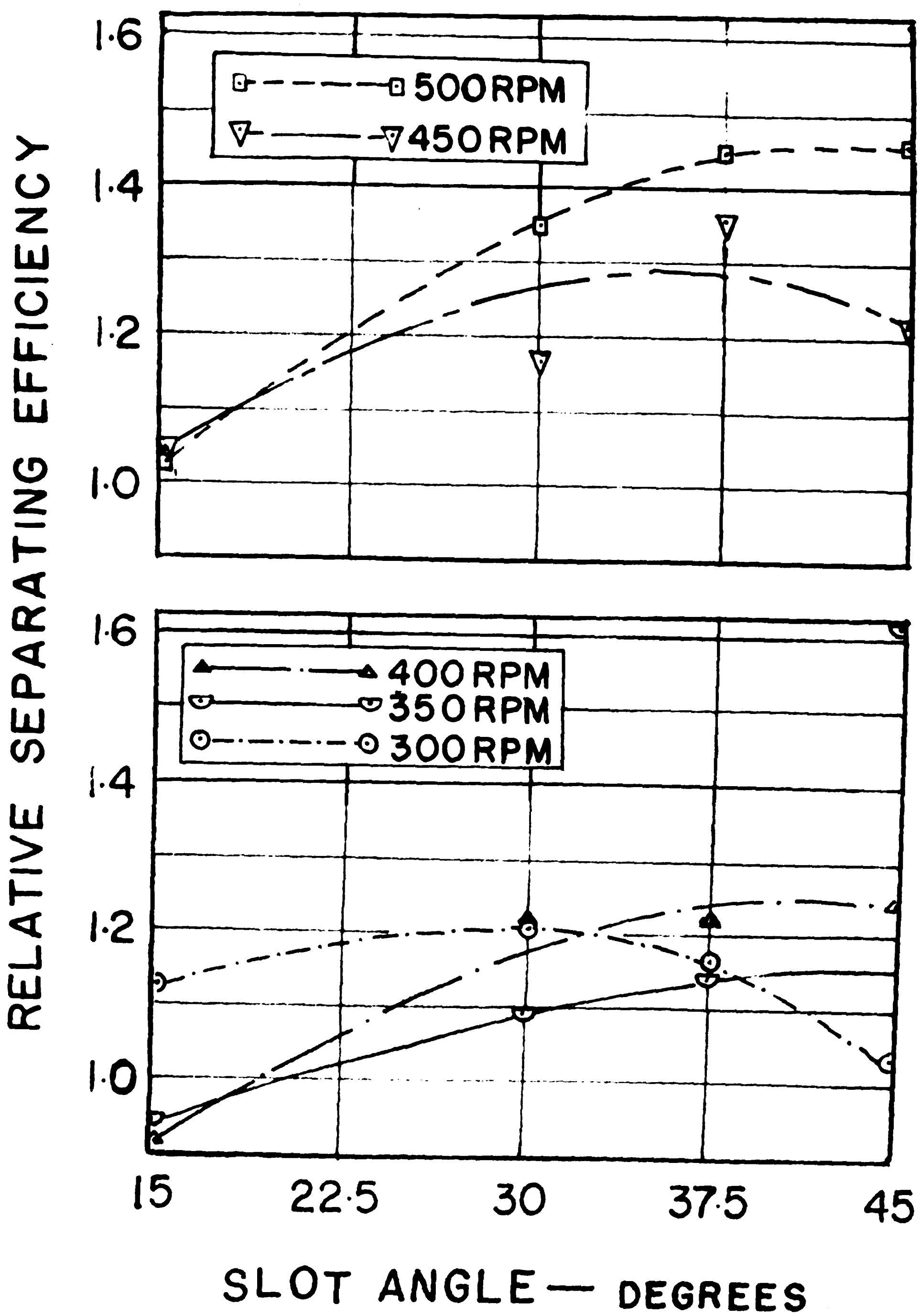


Fig. 17. Ratio of weight of grain in circle-sample to that in the control sample (relative separating efficiency) as a function of the slot angle α.

ratio of the weight of grain in the circle-sample (where the slot angle was not zero), to the weight of grain in the control sample (where the slot angle was zero). For an explanation of the foregoing terminology see page 39.

Figure 17 shows the relationship between the value of the slot angle, α and the relative separating efficiency, R. The relevant data are presented in Table 4, Appendix B. The maximum values of R occurred at high rotor speed and large values of α. The rate of increase of R with respect to α was greater at high than at low speeds. Figure 17 shows that the orientation of the slots is an important factor in governing the separation efficiency.

When the slots made an angle of 45° with the z direction (see Figure 17), 46 per cent more grain was found in the circle sample than in the control sample. Since the separation efficiency at 500 R.P.M. was 68.95 per cent (see Figure 11), the data from the circle-sample may be used to estimate the efficiency to be expected if the slots in the cone made an angle of 45° with the z direction. Thus, increasing the separation efficiency of 68.95 per cent, by 46 per cent, results in a total efficiency of 100.69 per cent for the entire cone. In other words, complete separation could be accomplished with proper orientation of the slots.

Since the control-sample was separated at the underside of the cone, the effect of gravity made it larger than if it had been separated at any other part of the cone. The effect of gravity was more marked at the lower speeds, where the value of R was less than unity, than at the higher speeds, where R was greater than unity. At 400 R.P.M., for example, R was less than unity for α equal to 15°; at α equal to 40°, however, the relative efficiency was 1.25. From the separation efficiency curves it can be seen that such an increase in the separation, at 400 R.P.M., would result in 87.5 per cent efficiency for the entire cone. The maximum value of the relative efficiency, at 300 R.P.M., indicates that the actual efficiency can be increased to 90 per cent at that speed. Considering the effect of gravity shown in Figures 15 and 17, it is possible that the value of R may even be greater than the present data indicate.

Straw and Chaff in the Circle Sample

Figure 18 shows the amount of straw and chaff in the circle sample relative to the amount in the control sample at 500 R.P.M. Up to 2½ times as much debris was mixed with the grain, for a slot angle of approximately 35°, as was mixed with the grain from the control area, where the slot angle was zero. At low rotor speeds the relative amount of debris in the circle sample was less than the amount present at 500 R.P.M., but in all cases there was more debris in the circle sample than in the control sample.

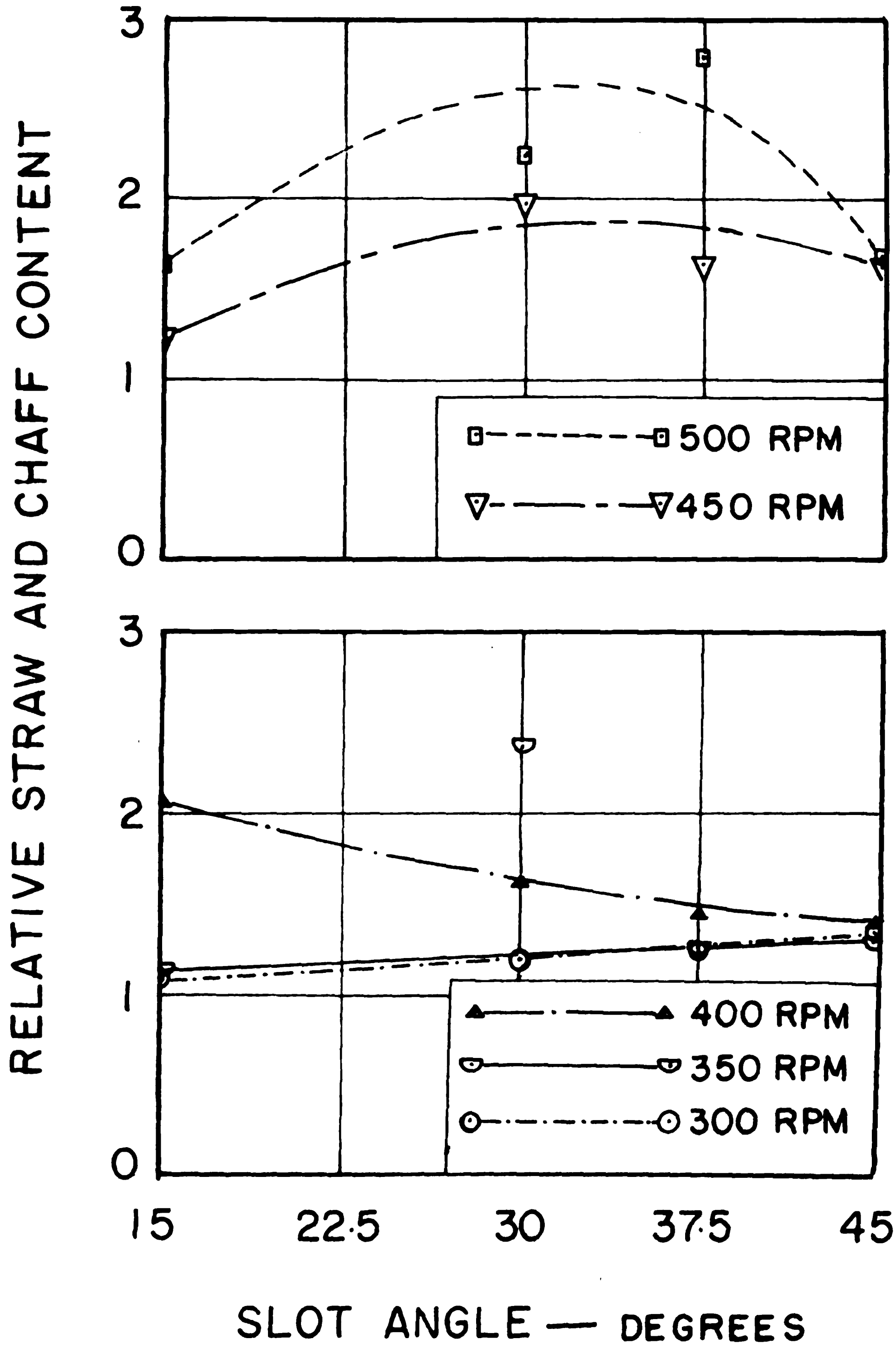


Fig. 18. Ratio of straw and chaff in circle-sample to that in the control sample (relative straw and chaff content) as a function of the slot-angle, α.

Analysis of High-Speed Motion Pictures

A camera speed of 2,000 frames per second was used to make high-speed motion pictures of the process occurring within the cone. The areas of the cone, labeled (1) and (2) in Figure 19 were photographed from the directions indicated by the arrows. Area (1) contained the circle sampler and area (2) was on the opposite side of the cone, a distance of 2½ feet from the entrance. The material moved vertically upwards in area (1) and vertically downwards in area (2).

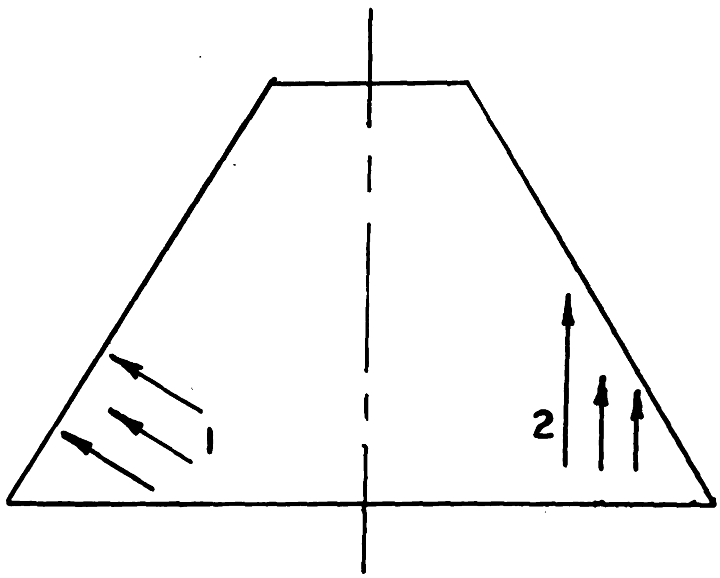


Fig. 19. Diagrammatic representation of the cone showing how the high-speed motion pictures were made.

Area (1). It was observed from the film that the motion of the material was more uniform in area (1) than in area (2). The force of gravity affected the material in area (1) to the extent that some particles moved downwards and in the case of grain, fell away from the screen; some grains actually fell inside the path of the beaters.

Although the pictures did not show what happened to this grain, it is logical to presume that it fell to the bottom of the cone, where it was hit again by a beater. After being struck by a beater, some grains were seen to rebound from the cone cone surface and move to positions inside the path of the beaters. This observation contains the most likely explanation for the fact grain was lost from the large end of the cone until suitable shields were fabricated.

Little impact between the material and the beaters was observed. Grains in the path of the beaters were struck, but the straw was not, since the centrifugal force threw it free of the beaters, with the result that there was little contact between the straw and the beaters. The straw was rubbed lightly by the beaters due to the relative motion between the two; the amount of relative motion is indicated by the data presented in Table 1.

Table 1. R.P.M. of beaters, straw, and grain as calculated from high-speed motion pictures.

	Area (1) (R.P.M.)	Area (2) (R.P.M.)
Beaters	450	450
Straw	150	130
Grain	180	180

Since the speed of the beaters was set at 450 R.P.M. while the pictures were being taken, it was possible to estimate the speed of the material. The time for ten beaters to cross the screen was measured with a stop-watch and the average of four such measurements was calculated. The same procedure was applied individually to the grain and straw. The timing was done over one particular part of the film so that the film speed was the same for all events timed.

Area (2). In area (2) the motion of the grain and straw was uniformly downwards and almost no impact between the material and the beaters was observed. No grains were seen to be in a position inside the path of the beaters and none moved in a direction opposite to the beaters. There was, however, some random motion of the grain due to collisions with the screen. The same rubbing action was observed in this area as in area (1) and Table 1 shows the velocities observed.

In both areas, it was observed that when a lot of straw was present, less impact between the grain and beaters occurred than when grain alone was present. This is a phenomenon similar to that reported by Bunnelle *et al*. (18), who claimed that there was less tendency for the grain to be damaged when the straw load on the cylinder was large enough to afford a protective padding around the seed. It is reasonable to assume that the effect of large straw loads on the threshing cone would also be to reduce the possibility of damage to the grain.

During the exploratory testing it was observed that after the start of feeding, grain emerged from the straw outlet before the straw (see page 44). An explanation for this phenomenon was seen in the motion pictures. The helix angle of the path of the grain was greater than that of the path of the straw. In addition, the velocity of the grain was greater than that of the straw, as is evident from Table 1. As a result, when a quantity of grain and straw entered the small end of the cone, the grain reached the large end before the straw and emerged first from the straw outlet. The difference in the helix angles of the straw and grain is also evident from the circle-sampler data, where it was seen that the greatest relative amount of grain passed through the cone at a greater value of the slot angle than did the relatively largest amount of debris. The relative amount of debris in the circle sample, however, did not reach a maximum value except at rotor speeds of 450 and 500 R.P.M. (see Figure 18). These observations indicate the possibility of using the different helix angles as a means of increasing the separating efficiency of a threshing cone.

The actual value of the helix angle was determined from the film, by projecting the picture on a poster-board and tracing the paths of the grain and straw separately, as the different particles passed over the poster-board. The position of the slots was also marked since it was known that the direction of the slot axis corresponded to a helix angle of 45°. The helix angles of the paths of the grain and straw were determined by relating their directions to the direction of the slot axis. It was observed that, unless grains were moving along paths nearly parallel to the slot axis, there was little chance of their passing through the screen. In fact, few grains were seen to pass through the screen unless they were actually moving along paths parallel to the slots. This emphasizes the importance of having the direction of the slots coincide with the direction of the path of the grain. This requirement is also supported by the data from the circle-sample.

The data from the circle-sample are compared with those from the motion pictures in Table 2. The helix angle, as determined from the circle-sample data, was taken to be the slot angle at which the maximum relative separating efficiency occurred. There is no ready explanation for the differences observed between the helix angles arrived at by the different methods. The theoretical value of the helix angle can be obtained from the solution of the equation of motion presented in Appendix A.

Table 2. Measured values of the helix angle of the path of the material.

Method	Helix angle (degrees)	
	Grain	Straw
Circle sample data	45	35
Motion pictures	24	17

The picture shown in Figure 20 was taken with a shutter speed of 1/30 second. Movement of the material during the exposure caused the streaks indicated by the direction of the arrow. In Figure 21 the string was taped to the path of a piece of chalk that was fed into the empty thresher and allowed to trace its path on the inside of the screen. Figures 20 and 21, therefore, indicate the direction of the path of the material in the thresher.

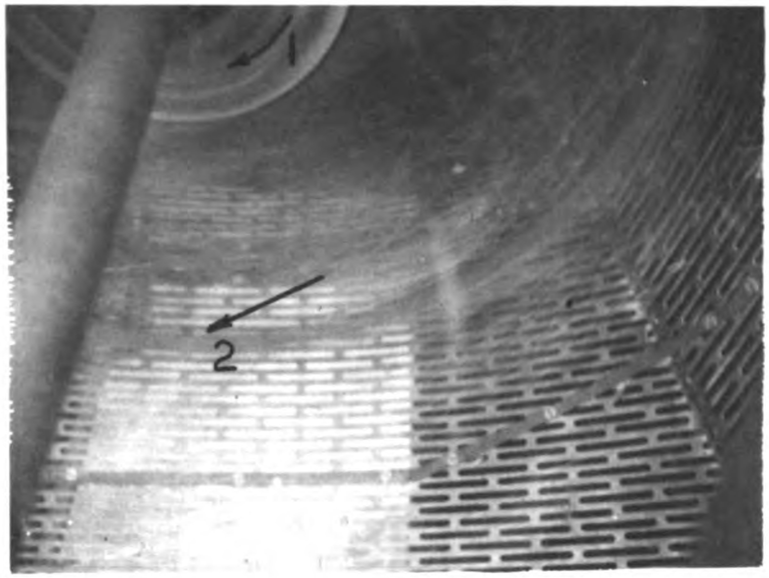


Fig. 20. Photograph taken at shutter speed of 1/30 sec. showing traces made by moving material in direction of arrow (2). The direction of rotation is shown by (1).

Fig. 21. Direction of the path of a piece of chalk which was fed into the empty cone and made a mark as it passed through.

SUMMARY

A threshing cone was designed, constructed, and tested in the Research Laboratory of the Agricultural Engineering Department of Michigan State University during 1961. The tests revealed that the threshing efficiency was satisfactory and that even though the separating efficiency was no better than that achieved by conventional combines, it was possible to improve the design, by judicious selection of the slot angle of the cone, to the extent that 100 per cent threshing efficiency could be expected. The feeding mechanism was functionally deficient at low speeds and an improvement in this mechanism is imperative if the machine is to be acceptable to the manufacturer and farmer.

The amount of straw and chaff mixed with the grain was similar to that found in the material on the cleaning shoe of a conventional combine. In certain instances, the amount of straw and chaff was considerably less than that found in the case of conventional threshers. There were indications that if the slot direction coincided with that of the path of the material, large amounts of straw and chaff would be found in the sample.

High-speed motion pictures of the threshing process were made and studied. The study showed that the threshing resulted from the material being rubbed by the beaters. Little impact between the beaters and the crop was observed

and the threshing action seemed to be a gentle one. Thus, mechanical damage to the grain is not likely to be a serious problem. No tests were made to determine the extent of mechanical damage since some of the grains had already been damaged by vermin during storage.

CONCLUSIONS

1. The basic concept of a threshing cone is correct.

2. The threshing efficiency, in the case of wheat, was satisfactory.

3. By judicious selection of the slot angle, the separating efficiency can be sufficiently increased to eliminate the need for straw-walkers or other separating mechanism.

4. The amount of chaff and straw mixed with the grain was similar to that found in the material on the cleaning shoe of a conventional combine.

5. The design of the feeding mechanism must be improved to permit operation at lower R.P.M.

6. If equipped with a satisfactory feeding mechanism, the threshing cone would have adequate field capacity.

7. Further research with a threshing cone is warranted.

SUGGESTIONS FOR FUTURE RESEARCH

1. The feeding mechanism should be redesigned to give satisfactory performance at low rotor speeds.

2. The cone should be redesigned on the basis of the information in Appendix A. A cone angle of 20° is suggested on the basis of the predictions in Appendix A and the behavior of the threshing cone used in this research.

3. The space between the beaters should be covered with sheet-metal to keep the material near the screen and eliminate some of the air movement.

4. Threshing tests should be performed with the redesigned cone to determine the threshing efficiency, separating efficiency, capacity, seed damage, and power requirements of the machine.

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APPENDIX A

Derivation of Threshing Cone Equation

The motion of a particle in a threshing cone can be described by the general equation for the motion of a body that moves in an accelerated reference frame, as presented by Becker (23).

Consider the cone as shown in Figure 22. The sides of the cone have been extended to the point where they intersect; the apex of the cone would be at this point if the cone were complete. The system of axes shown is fixed at the apex and rotates with the same rotational speed as the material. The x, y, and z axes have the same directions as those described on page 18.

Assume that the particle begins its motion in the cone by being given a rotational motion, such that the radius from the particle to the cone axis has an angular velocity of w radians per second. For simplicity, it is assumed that this angular velocity remains constant while the particle traverses the cone. This assumption is in reasonable agreement with the data presented in Table 1. The particle is kept in motion by the action of a beater which also rotates with angular velocity, w.

Since the axes are fixed in position and rotate with the same angular velocity as the particle, the only motion

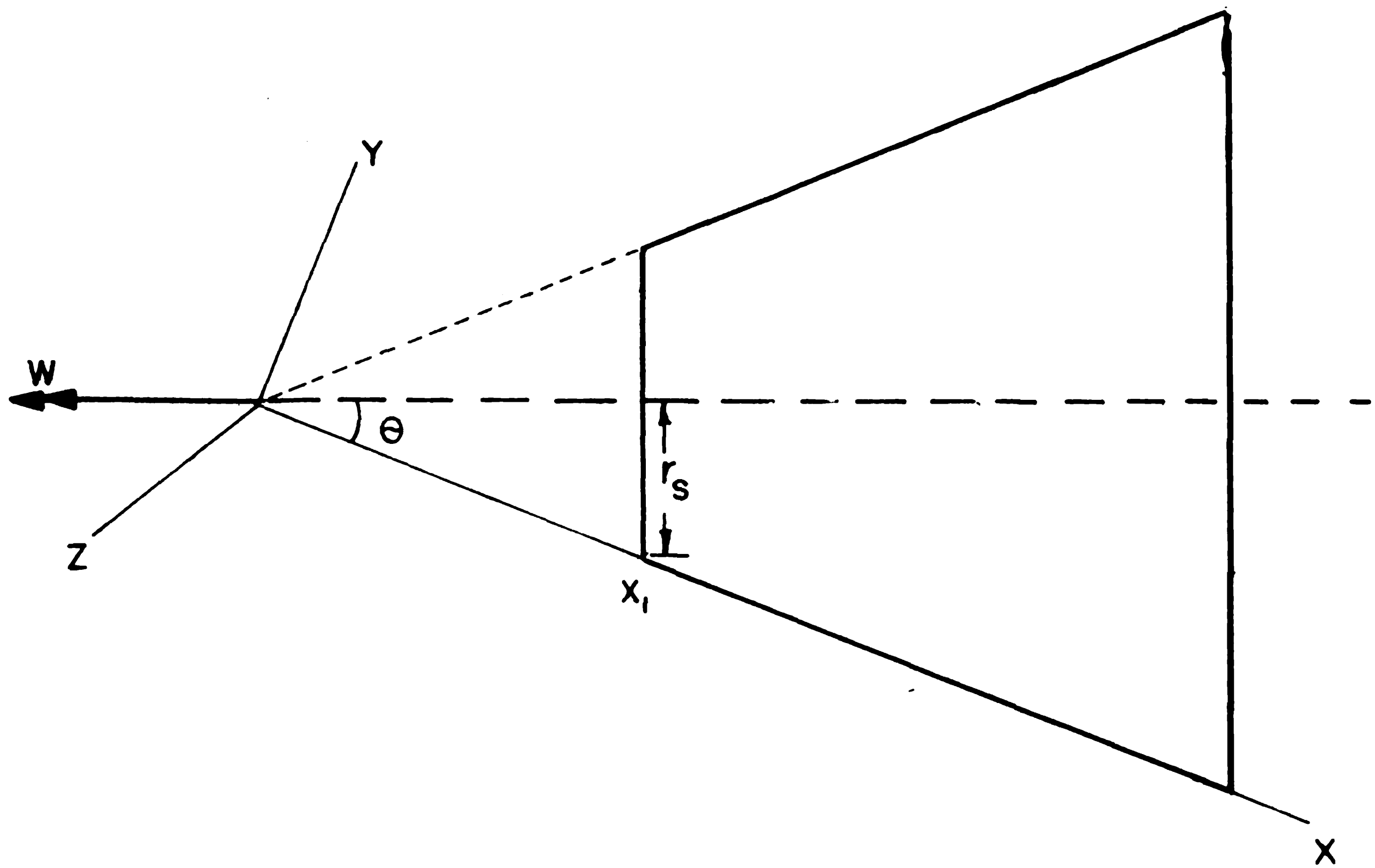

Fig. 22. Diagrammatic representation of the cone showing the reference system.

apparent to an observer, seated at the origin, is along the x axis. Therefore, the generalized equation of motion, as given by Becker, takes the following form for the present set of conditions.

$$m\ddot{x} = R_x i + R_y j + R_z k - 2mw_o\left[(\text{Cos}\theta i + \text{Sin}\theta j) \times (\dot{x}i)\right] - mw^2\left[\text{Cos}\theta i + \text{Sin}\theta j\right] \times \left[(\text{Cos}\theta i + \text{Sin}\theta j) \times (xi)\right] \quad \text{(A1)}$$

<u>Forces in the x direction</u>. The sum of the external forces, acting on the particle in the x direction, is R_x. Such forces are due entirely to friction. The phenomenon of friction is associated with the normal force or forces between a body and any plane or planes on which it slides or tends to slide. In this case, the particle slides while in contact with two surfaces at right-angles to one another, namely, the screen and the beater, both of which exert a normal force on the particle.

The force exerted by the beater, supplies the particle with the energy necessary to overcome the frictional and inertial forces acting on it, as it moves through the cone in a spiral of increasing diameter. The force exerted by the screen opposes the centrifugal force resulting from the circular motion of the particle. The centrifugal force can be resolved into components perpendicular and parallel to the cone surface; the component perpendicular to the cone surface is responsible for the friction between the screen and the particle.

Forces in the z direction. R_z is the sum of the external forces acting on the particle in the z direction and may be written as

$$R_z = F_b - \text{Friction force} \qquad (A2)$$

The force, F_b, is the force exerted on the particle by the beater and may be regarded as the threshing force.

Forces in the y direction and the friction forces between the particle and the screen. R_y is the normal force between the screen and the particle. The friction force associated with the slipping of the particle on the screen is, therefore, uR_y. The direction of this force still remains to be found.

Direction of friction between particle and screen. Since a friction force is always directed opposite to velocity of a body, the direction of the friction force acting on the particle can be found. The velocity of the particle can be resolved into its x and z components; the x component is simply $\dot{x}$ and the z component is rw, or the peripheral velocity due to the circular motion. The vector sum of these components gives the magnitude and direction of the velocity of the particle and consequently the direction of the friction force.

Let the helix angle which the path of the material makes with the z direction be α . The angle, α , therefore, also defines the direction of the friction force. From

Figure 23, the following relationships are seen to be true:

$$\text{Sin}\,\alpha = \frac{\dot{x}}{\sqrt{\dot{x}^2 + r^2w^2}} \tag{A3}$$

$$\text{Cos}\,\alpha = \frac{rw}{\sqrt{\dot{x}^2 + r^2w^2}} \tag{A4}$$

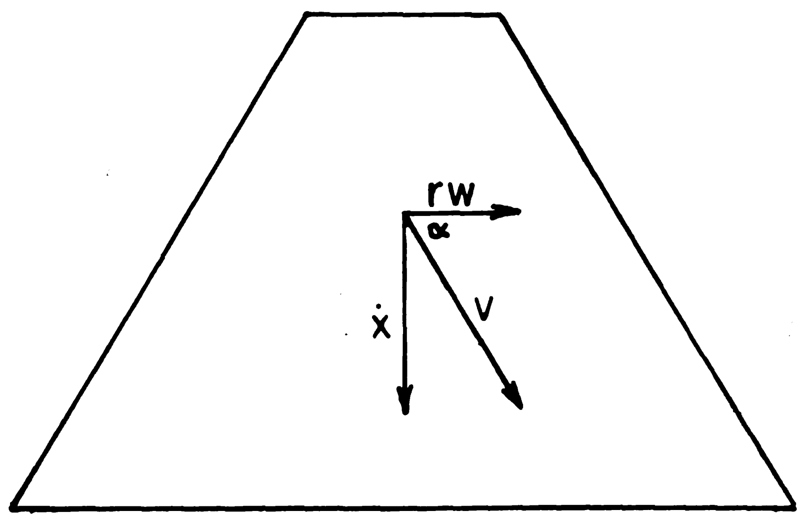

Fig. 23. Instantaneous velocity components of particle in the x and z directions.

The compoents of the friction force are, therefore,

$$R_{fx} = -u\ R_y\ \text{Sin}\,\alpha \tag{A5}$$

$$R_{fz} = -u\ R_y\ \text{Cos}\,\alpha \tag{A6}$$

The friction force due to the reaction of the beaters on the particle is simply, uF_b. Thus, the total friction force in the x direction is

$$R_x = R_{fx} - uF_b$$

$$= -u\ R_y \operatorname{Sin} \alpha - uF_b \qquad (A7)$$

When the indicated vector operations are performed on equation (A1), the following equation is obtained:

$$m\ddot{x}i = -u\ (R_y \operatorname{Sin} \alpha + F_b)i + R_y j + R_z k + 2mw\dot{x} \operatorname{Sin}\theta k$$

$$- mw^2\ (x\operatorname{Sin}\theta \operatorname{Cos}\theta j - x\operatorname{Sin}^2\theta i) \qquad (A8)$$

Three independent equations may be written from equation (A8), as follows:

$$m\ddot{x} = -u\ (R_y \operatorname{Sin} \alpha + F_b) + mw^2\ x \operatorname{Sin}^2\theta \qquad (A9)$$

$$0 = R_y - mw^2\ x \operatorname{Sin}\theta\operatorname{Cos}\theta \qquad (A10)$$

$$0 = R_z + 2mw^2\dot{x} \operatorname{Sin}\theta \qquad (A11)$$

Using the relationships obtained in equations (A2), (A11), and (A10), the value of F_b may be found as follows:

$$-2mw^2\operatorname{Sin}\theta = F_b - R_{fz}$$

$$\text{or} \quad F_b = uR_y\operatorname{Cos} \alpha - 2mw\dot{x}\operatorname{Sin}\theta \qquad (A12)$$

When the values of F_b and R_y, from equations (A12) and (A10), are substituted in equation (A9), equation (A13) is obtained.

$$m\ddot{x} = -u(mw^2\ x \operatorname{Sin} \alpha \operatorname{Cos}\theta \operatorname{Sin}\theta + umw^2\ x \operatorname{Cos}\alpha \operatorname{Cos}\theta$$

$$\operatorname{Sin}\theta - 2\ mw\dot{x} \operatorname{Sin}\theta) + mw^2\ x \operatorname{Sin}^2\theta \qquad (A13)$$

Since r, the radius of the cone at any point, is simply $x\operatorname{Sin}\theta$, the following relationships are obtained from equations (A3) and (A4):

$$\operatorname{Sin} \alpha = \frac{\dot{x}}{\sqrt{\dot{x}^2 + x^2w^2\operatorname{Sin}^2\theta}} \qquad (A14)$$

$$\text{Cos}\,\alpha = \frac{xw\text{Sin}\theta}{\sqrt{\dot{x}^2 + x^2w^2\text{Sin}^2\theta}} \qquad \text{(A15)}$$

Substitution of these relationships in equation (A13) gives equation (A16).

$$\ddot{x} = -u\,(w^2\,x\,\text{Cos}\theta\,\text{Sin}\theta\,\frac{\dot{x}}{\sqrt{\dot{x}^2 + x^2w^2\text{Sin}^2\theta}} +$$

$$uw^2\,x\,\text{Cos}\theta\,\text{Sin}\theta\,\frac{xw\text{Sin}\theta}{\sqrt{\dot{x}^2 + x^2w^2\text{Sin}^2\theta}}$$

$$-\,2w\dot{x}\,\text{Sin}\theta) + w^2x\,\text{Sin}^2\theta \qquad \text{(A16)}$$

Equation (A16) may be put in a more convenient form by the following substitution. Let

$w\text{Sin}\theta = a$ and

$w^2\text{Sin}\theta\ \text{Cos}\theta = b$

Equation (A16) now becomes

$$\ddot{x} = -u\left[\frac{bx\dot{x}}{\sqrt{\dot{x}^2 + a^2x^2}} + \frac{uabx}{\sqrt{\dot{x}^2 + a^2x^2}} - 2a\dot{x}\right] + a^2x \qquad \text{(A17)}$$

Since w, the angular velocity of the material in the cone thresher, is negative with respect to the sign convention used, the quantity, a, is also negative.

<u>Solution of the equation of motion</u>. A unique solution for equation (A17) was not readily obtainable and, consequently, the problem was programmed for the Mystic computer at Michigan State University, and numerical solutions were obtained for several values of the cone

parameters and the rotational speed, w. Each of five values of the cone-angle, θ, was combined with six different rotational speeds. This meant that the solution predicted the manner in which five different cones, each with an entrance 16 inches in diameter, would behave, when operating at six different speeds. The cone angles were: 15^{o}, 20^{o}, 25^{o}, 30^{o}, and 35^{o} and the six speeds were: 100, 125, 150, 175, 200, and 225 revolutions per minute. In all, predictions were obtained for thirty different sets of conditions.

Initial conditions. The initial conditions were as follows: at $t = 0$, $\dot{x} = 0$, and $x = x_1$, where x_1 is the distance from the origin of the reference system to the entrance of the threshing cone as shown in Figure 22. The quantity x_1 was different for each cone configuration and was given by the expression

$$x_1 = r_s/\mathrm{Sin}\theta$$

where r_s is the radius of the entrance.

The assumption that $\dot{x} = 0$ at time, t, equal to zero is probably not correct, but was considered to be equally as valid as any other assumption and it did simplify the computations.

The problem was solved for 0.5 seconds in every case, since observation of the threshing cone in operation indicated that this time would be sufficient. The following quantities were output from the computer after each 0.1

seconds: (1) the displacement in the x direction, (2) the velocity in the x direction, $\dot{x}$, and (3) Sinα or the quantity, $\dfrac{\dot{x}}{\sqrt{\dot{x}^2 + a^2x^2}}$.

Analysis of Computer Data

A detailed analysis of the computer data will not be undertaken at this time; however, some examples of the predicted behavior are given below.

Figure 24 shows the distance travelled by the particle, in the x direction, as a function of time, for each value of θ and at a rotational speed of 150 R.P.M. This rotational speed was chosen as an illustration since the straw, in the case of the threshing cone tested, had approximately this rotational speed, as shown by Table 1. Thus, the performance predicted for the 25° cone, can be compared to the performance of the cone used in the tests.

Threshing time. The time for the material to pass through the cone was too short to be measured with a stopwatch, even at low rotor speeds. Figure 25 shows the theoretical threshing time, as a function of the cone angle, for three different cone lengths at a rotational speed of 150 R.P.M. The threshing times predicted by the threshing cone equation were of the same order of magnitude as the actual threshing time in the case of the threshing cone that was used in the tests. Figure 25 shows that the threshing

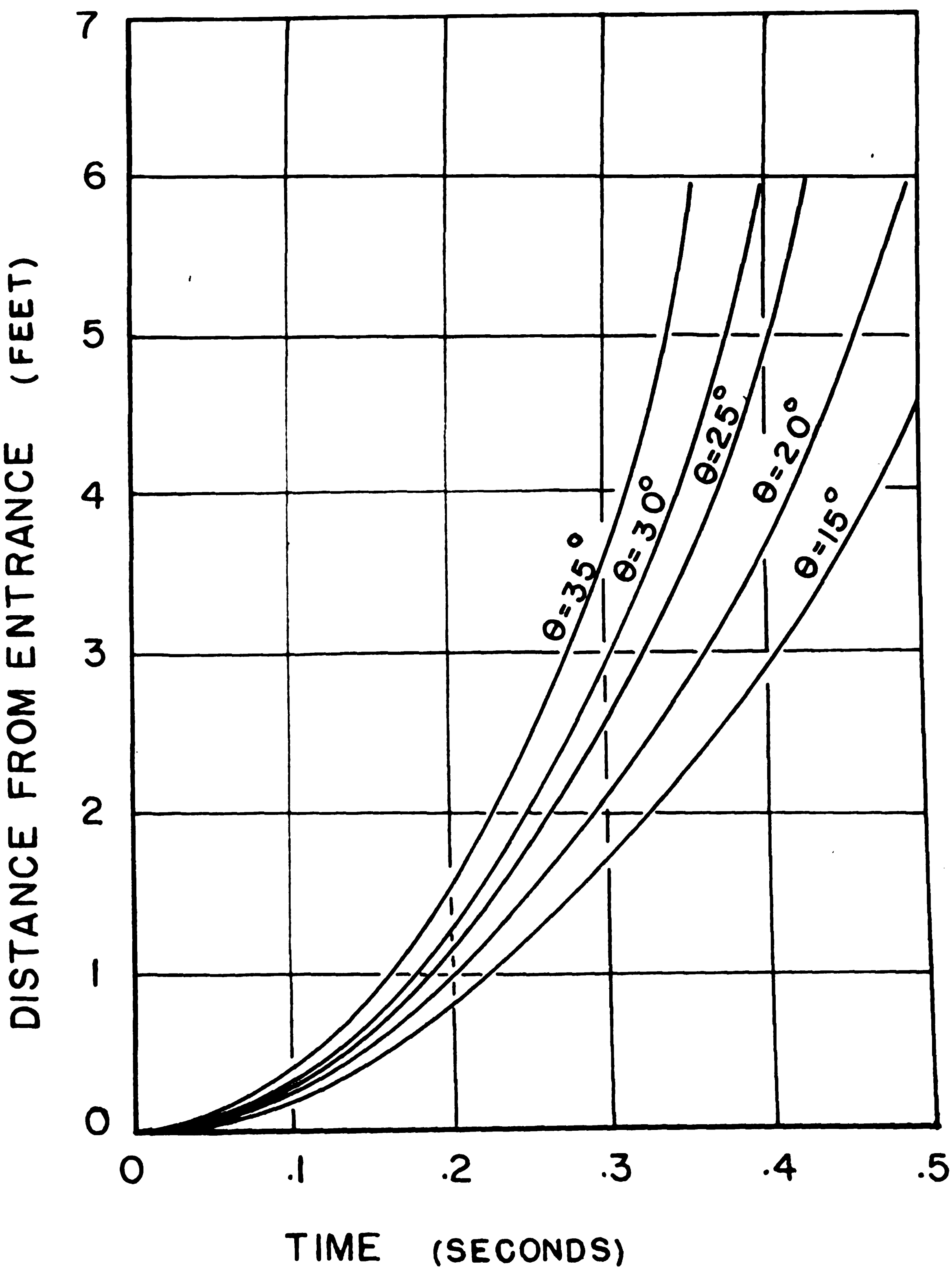

Fig. 24. Relationship between the theoretical displacement (from the entrance) and time at a rotational speed of 150 R.P.M.

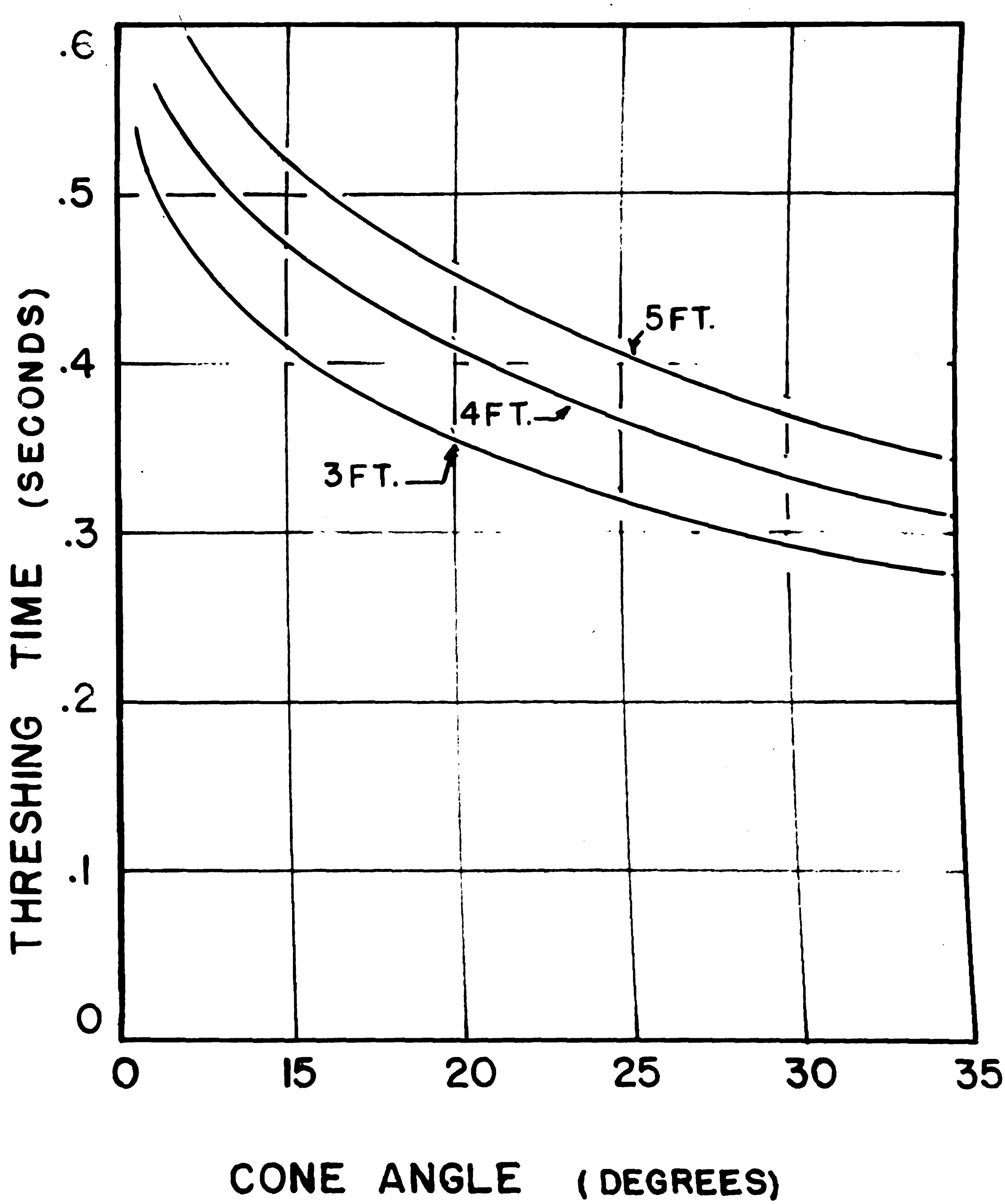

Fig. 25. Theoretical threshing time as a function of the cone-angle for three different cone lengths and a rotational speed of 150 R.P.M.

time increases rapidly as the cone angle is made less than 10°. The predicted threshing time, in the case of a four-foot cone similar to that tested, was .36 seconds. If the cone angle was 17° instead of 27° the threshing time would be increased to .45 seconds--an increase of 25 per cent. In the case of a five-foot cone the threshing time would be 0.5 seconds with a cone angle of 17°. The allowable threshing time is determined by the permissible crop density in the machine and the required capacity of the machine. The capacity of the machine must be kept within the limits dictated by the threshing and separating performance as determined in tests.

Predicted values of the helix angle. Figure 26 represents the relationship between the predicted values of the helix angle and the displacement from the entrance of the cone. Curve A represents the relationship for a cone angle equal to 35° and a rotational speed of 225 R.P.M. This combination gave the largest values of the helix angle at any particular distance from the entrance. Curve B represents the relationship for a cone angle equal to 15° and a rotational speed of 100 R.P.M. This combination gave the smallest values of the helix angle for a particular distance from the entrance. Curves A and B represent, respectively, the largest cone-angle-speed combination and the smallest cone-angle-speed combination. The curves representing the predicted relationship for all other

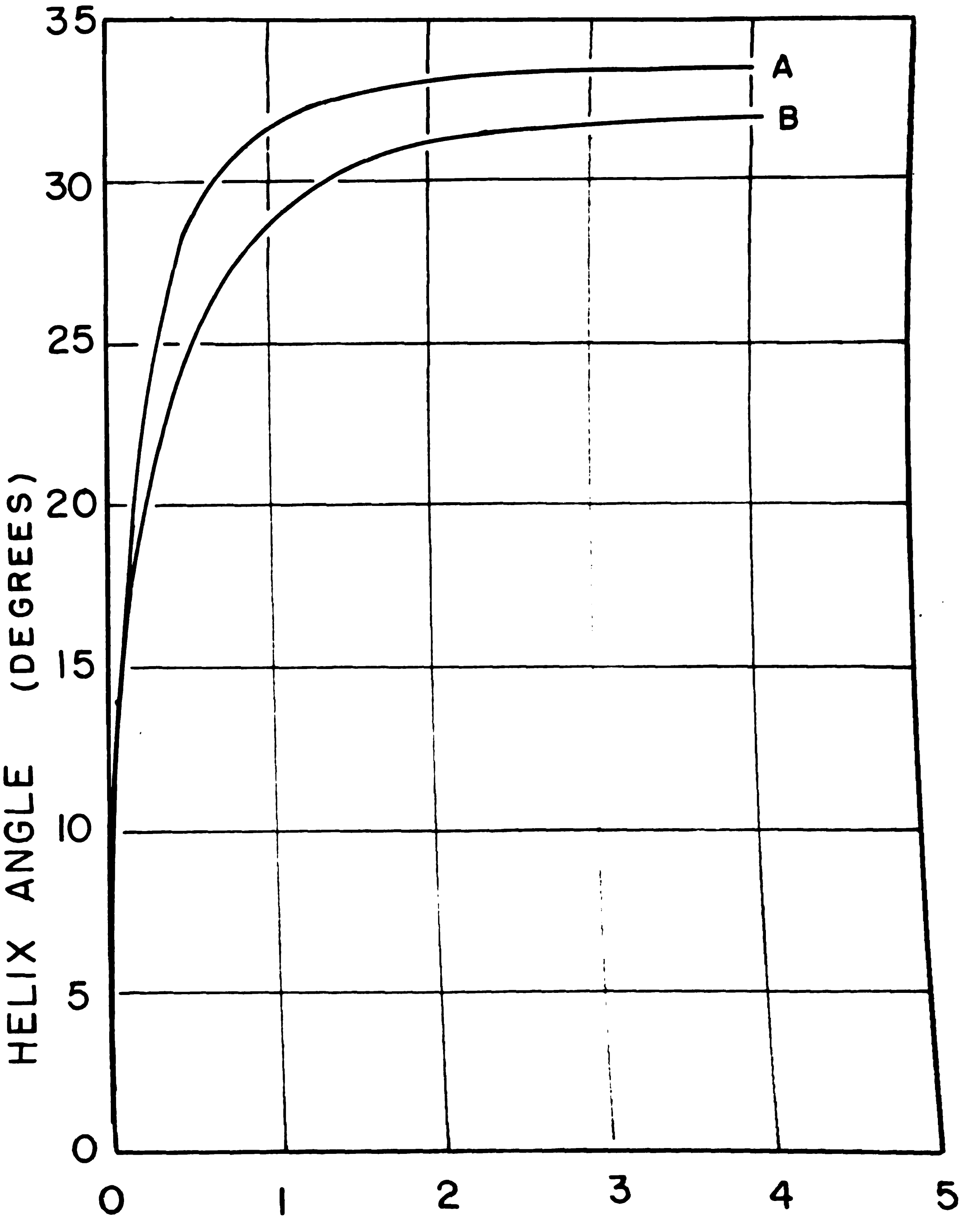

Fig. 26. Relationship between the helix angle, α and the distance from the entrance: A, for a cone-angle of 35° and a rotational speed of 225 R.P.M., and B, for a cone angle of 15° and a rotational speed of 100 R.P.M.

combinations of cone angle and speed lie between those shown in Figure 25. After the material had travelled one foot in the x direction, the helix angle of its path varied little and was found to approach a limit of 33.4^{o} for curve A. Sufficient data was not available, in the case of curve B, to indicate the limit of the helix angle, however, the shape of the curve indicated that the limiting value of the helix angle was rapidly approached.

Redesign of the threshing cone. The threshing cone should be redesigned on the basis of the theoretical data. A smaller cone angle should be used and advantage taken of the fact that the helix angle remains relatively constant after the first foot of cone length. The use of a smaller cone angle will permit the length of the threshing cone to be increased without causing the machine to become unduly cumbersome.

APPENDIX B

Table 3. Threshing and separating efficiencies for the various rotor speeds.

	Rotor speed (R.P.M.) 300	350	400	450	500
Threshing efficiency	99.08	99.56	99.60	99.78	99.84
Separating efficiency	77.50	74.25	69.87	68.75	68.95

Table 4. Ratio of the grain in the circle sample to that in the control sample for various values of the slot angle.

Slot angle (degrees)	Rotor speed (R.P.M.) 300	350	400	450	500
15	1.13	.95	.913	1.04	1.03
30	1.21	1.10	1.21	1.17	1.35
37.5	1.17	1.15	1.21	1.36	1.45
45	1.04	1.62*	1.24	1.22	1.46

* Control sample box slipped and some of its contents were lost.

Table 5. Per cent straw and chaff in each section of the sampler box for the various speeds.

Rotor speed (R.P.M.)	Section number 1	2	3	4	5	6
300	19.47	27.82	36.99	26.46	37.30	51.47
350	15.14	25.14	34.91	30.28	34.96	42.01
400	9.03	23.48	34.40	28.84	34.41	44.71
450	12.59	28.01	40.13	32.84	34.05	41.64
500	8.11	26.96	33.40	25.96	25.2	31.65

Table 6. Per cent of the total box-sample found in each section at the various rotor speeds.

Rotor speed (R.P.M.)	Section number 1	2	3	4	5	6
300	45.85	23.57	8.25	9.75	7.93	5.675
350	48.38	22.91	8.06	9.01	7.05	4.6
400	43.7	17.8	7.1	11.75	11.05	8.55
450	37.35	17.8	9.0	14.31	12.6	8.74
500	34.85	20.8	8.35	16.59	13.21	9.05

Table 7. Cumulative per cent separating efficiency at the various rotor speeds.

Rotor speed (R.P.M.)	Section number 1	2	3	4	5	6
300	35.5	53.75	60.2	67.5	73.9	77.75
350	33.8	48.8	54.8	62.9	69.2	74.25
400	30.5	43.0	47.9	56.0	63.75	69.875
450	25.65	37.9	44.0	53.9	62.7	68.75
500	24.0	38.4	44.1	55.5	64.6	68.95

Table 8. The weight of grain in the sampler-box expressed as per cent of the total weight of grain separated through the cone perforations.

Rotor speed (R.P.M.)	300	350	400	450	500
Per cent of total separated	12.2	13.375	13.825	11.77	11.55

Table 9. Per cent straw and chaff in the control sample for each combination of slot angle and speed.

Slot angle (degrees)	Rotor speed (R.P.M.) 300	350	400	450	500
15	37.3	34.96	34.41	34.05	25.20
30	38.0	18.0	26.5	25.00	18.00
37.5	26.8	28.5	30.8	20.00	10.50
45	16.0	13.75	16.2	15.00	14.00

Table 10. Per cent straw and chaff in the circle sample for each combination of slot angle and speed.

Slot angle (degrees)	Rotor speed (R.P.M.) 300	350	400	450	500
15	40.60	39.29	70.67	41.32	41.29
30	44.50	43.00	43.30	49.75	40.00
37.5	32.85	34.75	44.00	32.70	29.30
45	21.40	17.80	22.00	24.40	23.00

Table 11. Ratio of per cent straw and chaff in the circle sample to that in the control sample.

Slot angle (degrees)	Rotor speed (R.P.M.) 300	350	400	450	500
15	1.17	2.39	1.63	1.99	2.22
30	1.23	1.22	1.43	1.63	2.79
37.5	1.34	1.29	1.36	1.63	1.64
45	1.09	1.12	2.05	1.21	1.64