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Combine harvesters for soybean research

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COMBINE HARVESTERS FOR SOYBEAN RESEARCH

by

Graeme Ross Quick

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
the Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Agricultural Engineering

Approved:

In Charge of Major Work

Head of Major Department

Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa
1970
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INTRODUCTION

The soybean is destined for a leading position in the nutrition of a burgeoning world population. The crop already plays an important role in world commodity trade and although it began humbly as the oriental "meat of the field", it has now joined the exclusive "billion dollar export club" of the United States.

The harvest from 1 in every 3 acres of U.S. soybeans goes abroad, 3/4 as sales and the remaining 1/4 as foreign aid (30). A bushel of soybeans (60 lbs.) will yield 10.8 lbs. of oil, 2/5 of the value of the raw product, and 47.5 lbs. of meal, used largely as livestock feed. End product uses range from such extremes as explosives to confections.

Soybeans provide the cheapest source of protein among processed human foods. Protein deficiency is the most critical dietary deficiency in the world, affecting some 2 billion people (8). Soybean protein, complemented nutritionally by cereal protein, is one of the finest human foods, and new commercial developments such as soymilk (13), spun fibers and textured soy foods have vast potential (21).

The introduction of soybeans into the U.S. began in earnest around 1898 when W. J. Morse brought over 7,000 introductions from the Orient to provide the germ plasm for subsequent breeding work (22).
With the successful application of the combine harvester, and adoption of varieties suitable for machine harvesting, over the last 46 years there has been an increase of over 100% in the national average yield. The first combine was used in a soybean field by the Garwood Brothers of Illinois in 1924. Since then U.S. production has increased twelvefold (29).

It was through the unrelenting efforts of the biologists and plant breeders that these spectacular results have been achieved. No investment has returned so high a dividend as has the art and science of producing improved seed varieties. Successful plant breeding programs involve the genetic adjustment of plants to provide the primary ingredient of the agricultural industry.

The statistical tools of replication, randomization and local control are employed in the plant breeder's study of gene action and genotype-environment interaction. Progress in the science of breeding depends in fact, upon the correct estimation of experimental error. The need for replication and the magnitude of the task means that much labor is involved in a multitude of operations at every phase in the breeding program, from pot culture through nursery plots, to seed increase strips.

The number of field experiments a researcher can conduct in any given season is limited by the number of plots he can
harvest. Specialized combines are needed for harvesting experimental plots as commercial field combines are neither small enough nor streamlined well enough inside for the specific requirements of the plant breeder.

Here is a challenge for the Agricultural Engineer, which has been practically unaccepted by this profession. Why?

1. Until recent years, sufficient cheap labor has been found to just cope with the breeding programs.

2. The potential demand for machines has not been sufficient to attract the larger manufacturer who would have the research facilities to persevere with machine development.

3. The plant breeder tends to distrust any device which might risk contamination of his seed due to malfunction or poor design, and which might raise the coefficient of variation of his data, for example, by incomplete pickup of tangled or lodged soybeans.

4. Since the harvesting machines which are envisaged would tend to be smaller and would appear somewhat less sophisticated, they do not attract the general interest of aspiring engineers.

The rising cost and scarcity of labor, the development of standardized rapid plot planting methods and the need to
evaluate machine harvestability of soybeans have now thrown into bold relief the lack of specialized combine harvesting equipment for soybean research.

If suitable plot combine designs can be produced, the breeding program itself could be modified. Full mechanization would enable the researcher to handle a greater number of variables, possibly reduce coefficients of variation, and raise the degree of confidence which can be attached to his results.

This one development may indeed be the key to the next major advance in soybean research.
OBJECTIVES

The primary objective of this work was to determine the design parameters, and to build and evaluate harvesters to meet the immediate and projected needs of soybean research workers.

Single plant and bundle threshers have been successfully developed; the immediate problem was to produce an acceptable field plot combine design.

The design criteria for any combine harvester are maximum seed recovery with minimum loss or damage. To these are added a third for the plant breeder: ease of cleanout, or immediate self cleanout after each plot.

No seed intermingling can be tolerated at critical stages in the breeding program. In certain other research work and in yield trials this latter requirement may be relaxed, with obvious effects on the design of the machine.

Further objectives pursued in this work were the evaluation of novel machine principles of interest to the harvesting engineer and the encouragement of the plant breeder to move the machine-harvestability character of a soybean variety further up the scale of values. The plot combine should provide the means for evaluating the machine-variety interaction by enabling lodging and shattering propensities to be readily exhibited.
REVIEW OF LITERATURE AND STATE OF THE ART

There are three groups of potential users of plot harvesting equipment:
1. the plant breeders
2. the seed producers
3. the botanists, agronomists, biologists, engineers and other researchers initiating soybean field trials on yield, weed, insect and disease control, fertilizer response, tillage effects, etc.

The most rigorous design requirements for the plot combine are those of the plant breeder, namely, no seed carryover from plot to plot, self-cleanout, and maximum maneuverability. Once these requirements are met, the design can be simplified, enlarged or otherwise modified, to satisfy the other groups of users.

Plant breeding

The plant breeder is primarily a biologist (4), and his craft may be broadly defined as the art and science of improving the genetic pattern of plants in relation to their economic use (11). He aims to produce varieties which give higher yields than the existing varieties. By "yield" is meant the amount of useful plant products harvested by man. General productivity may or may not be related to specific
characters, but once the breeder has the ideal variety in mind he is ready to initiate the developmental program (19).

**Soybean breeding**

The soybean, Glycine Max (L) Merrill, is an erect bushy leguminous annual with woody upright stem (22). The purple or white flowers appear first around the fourth node, then proliferate up and down the stem and branches. The fruiting pods appear in clusters and carry from 2 to 5 elliptical or round seeds. A full grown specimen of the plant at maturity has shed its leaves, and is a mass of pods ranged in tiers from ground level to stem tip. Heights range from 1 to 5 feet and there is usually some branching, which is a function of row width, spacing, variety and environment.

Since the self-pollinating flowers are tiny, with the male and female parts enclosed together, hybridization of soybeans, i.e. the production of off-spring from two unlike parents, is a difficult manual task, impractical for the commercial production of F₁ hybrid varieties (10). The breeder then hand-crosses pure lines with the desired characteristics in the hope of eventually selecting a progeny with the combination of desired traits of both parents.

The first hybrid seed (F₁) is obtained for pot or field culture in the next season. In the following year, seed from the F₁ plants will be grown space-planted in nursery field plots. The technique most widely used is known as the
"Pedigree Method" and is outlined in Table 1. In the F₂ generation hundreds of genetically different soybean plants are found for each cross made, and from these the breeder selects those which possess most intensely the characteristics he desires in the proposed variety. Single plant threshers may be used on the F₂ to F₅ generations.

Usually from the F₆ to the F₁₀ generations planting is in single or multiple row yield tests. Multiple row plots often consist of three rows each with the outer two rows as protective borders. If a successful plot combine were available the breeder might change to four rows and harvest the middle two, thereby sacrificing seed from 2/4 of the rows instead of 2/3. In this respect alone a substantial saving in highly valuable seed could be credited to the plot combine.

Varieties for release which surpass those existing might be selected as early as the F₆ to F₈ generations. Plots of certified seed are sown which may be harvested with a larger plot combine or a commercial combine modified for easier cleanout.

Many soybean varieties are responsive to narrow row spacing, even down to 7" or "solid" seeding, however the breeder must also be mindful of the farmers' current cultural practices. Many plots are planted with conventional row spacings of 36" to 42" in Iowa.
Table 1. Diagram of pedigree method, typically used in the development of a new variety

<table>
<thead>
<tr>
<th>Generation</th>
<th>Description</th>
<th>Number of Plants</th>
<th>Number of Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$</td>
<td>Space-planted for hand selection</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$F_2$</td>
<td>Single plant thresher and hand selection</td>
<td>5,000</td>
<td>250</td>
</tr>
<tr>
<td>$F_3$</td>
<td>Single-row plot harvester</td>
<td>250</td>
<td>125</td>
</tr>
<tr>
<td>$F_4$</td>
<td></td>
<td>125</td>
<td>90</td>
</tr>
<tr>
<td>$F_5$</td>
<td></td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>$F_6$</td>
<td></td>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td>$F_7$</td>
<td>Replicated tests</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>$F_8$ to $F_{10}$</td>
<td>Several replicated tests</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Dots indicate populations grown as single plants; the joined dots represent families or varieties examined as single plants; rectangles are selections grown in bulk; arrows show the route of materials from one year to the next; and asterisks are the number of varieties or families giving selected plants. [Adapted from Figure 11.3, page 141, Briggs and Knowles (4).]
The plot planting process has been substantially mechanized and planting rates as high as 1,000 nursery plots per hour have been achieved. At the present rates of between 8 to 40 plots per man hour, the harvesting chore is by far the most time consuming operation.

Current field plot practice differs little from the steps outlined in Table 2, with the exception of statistical analysis which is now computer-aided, so that the relative times spent on the various tasks as shown are still fairly representative.

The plant breeders' work does not end with the successful release of a new variety (19). The breeders, seedsmen and other researchers then work on ways to control weeds, diseases and insects, investigate fertilizers, study nodulation and many other husbandry aspects. They also have to publicize the new variety to encourage farmers to use it.

**Mechanizing the harvest of research plots**

In the review which follows, and in the accompanying illustrations, will be shown those machines which have been of greatest influence in plot harvesting, or which might embody ideas which could be incorporated into the design of soybean plot combines.

It is understandable that among the first to mechanize the harvest of plots have been mechanically-inclined plant breeders, and especially notable work has been done by
Table 2. Man-hour estimates for measuring yield of 1088 soybean plots of 3 different sizes, adapted from Weber and Horner (34)

<table>
<thead>
<tr>
<th>Operation and Description</th>
<th>Plot Size: Number of Basic Units in a Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Planting Plan - Randomize. Write.</td>
<td>13</td>
</tr>
<tr>
<td>Seed Preparation - Screen. Label. Pack. Randomize. Check.</td>
<td>41</td>
</tr>
<tr>
<td>Planting - Lay Out Seed Envelopes. Plant. Check.</td>
<td>21</td>
</tr>
<tr>
<td>Care of Plots - Weed. Trim.</td>
<td>32</td>
</tr>
<tr>
<td>Notes - Maturity. Height. Lodging. Tagging. Checking.</td>
<td>31</td>
</tr>
<tr>
<td>Harvesting - Cut. Carry. Thresh. (Dry). Weigh. Record.</td>
<td>142</td>
</tr>
<tr>
<td>Sampling - Label Envelopes. Records. Measure. Picking.</td>
<td>42</td>
</tr>
<tr>
<td>Statistical Analysis - Conversions. Transpose. Analyze. Check.</td>
<td>55</td>
</tr>
<tr>
<td><strong>Total Hours for Yield from 1088 Plots</strong></td>
<td>382</td>
</tr>
</tbody>
</table>

Man-Hours Per Plot (Basic Unit Size - 8' x 24" Row Width) 0.351 0.786 1.396
Orville A. Vogel of Washington State University. The earliest reference to be found on the subject bears his name, and followed the development of the self-propelled combine by only a few years (32).

The plot harvesting procedure most widely used at present is illustrated in Figure 1 and has been called "two step combining" by Øyjord (24).

The gathering operation

Being harnessed to the power scythe shown in Figure 1, right, is hard labor and in addition this tool has occasionally been responsible for harvesting a finger or two of the operator doing the bundling and carrying.

It was a logical next step to mount the power scythe on drive wheels and attach a collecting tray and shield to the frame as in Figures 2 and 3.

Hergert (14) reports on several plot binders built or modified by the Canadians, one of which, the Italian Motofalciatrici of Figure 3, deposited the untied bundle back on the stubble from which it was cut.

The Ottawa single-row harvester, Figure 4, was developed for standing or lodged cereal plots (15). Lodged stems are picked up by a pair of oblique-head finger bar assemblies inclined at 30 degrees. As the straw is straightened it is gripped by a pair of elevating belts, cut at 6" height and elevated to the bundling platform. Two 18 ft. rows can be
Figure 1. Harvesting rod-row plots at Iowa State, 1969 season

Figure 2. Power scythes for single row plots. Hand-carried scythette (left) and portable scythe with bundling attachment (right)
Figure 3. Plot bundling and binding machines - "Hoffco" two-row bundling unit and modified Italian reaper and binder

Figure 4. Ottawa single-row plot binder (courtesy Engineering Research Service, Research Branch, Canada Department of Agriculture)
collected by two men in 1 minute. The unit has been tried in soybeans, but with poor results as threshing occurred in the gathering belts.\footnote{Hergert, G. B. Ottawa, Canada. Single row crop pick-up mechanism. Private Communication. Sept. 25, 1967.}

Plot binders and bundling machines will not be entirely replaced by combines as long as some soybean plants need to be dried and stored in bundles.

The threshing and cleaning operation

When the crop is dry enough, the collected sheaves are carried directly to a stationary trailer-mounted unit for threshing. Vogel's 30 year old stationary thresher design, Figure 6, has been sold by at least two manufacturers and has evidently been so successful that little deviation from the original sketch (33) is evident in the latest designs. An 8-second cleanout is a feature which enhances the popularity of this screenless machine (33).

A variety of more sophisticated and compact stationary threshers with higher capacity are now available, Figure 5.

The Canadian oil-seed thresher (18) of Figure 7, and the Allan Machine Company's rasping-bar thresher both use punched-hole screens as a straw rack and have substantially lower feed aprons than the Vogel unit. The Vogel and Allan designs, and that of Owen and Magee (23), use overshot
Figure 5. Stationary threshing equipment. Folkerts and Kramer's rolling concave type in field operation (left), two Allan Machine Company overshot raspbar units in use on stored and dried crop bundles (right).

Figure 6. Orville Vogel's overshot spike-tooth cylinder screenless thresher - a standard in the industry over thirty years. Original design (right)
cylinders to avoid any possible trapping of grain in the concave. Edge-mounted angle irons are fastened behind the rasp-bars to prevent seed collecting there on the Allan unit.

Perhaps the first belt-thresher to have been made commercially available is the Curl unit made in Idaho, Figure 8. Where damage to seed is critical, as in the garden and legume seed business, the belt-thresher is favored.¹

A different approach using rubberized components was reported by Bainer and Winters (2) in which a series of rubber rolls was used to effectively thresh lima beans. Hamblin et al. (12) reported a tractor front-mounted combine using a 5 ft. wide rubberized belt with bonded rubber-moulded rasp-bars beating over an inclined stationary concave. Threshing and separation were obtained in one pass and the combine was easy to clean.

Self-propelled plot combines - modified commercial units

Hunter and Johnson (16) reported on the modification of an Allis-Chalmers model 40 All Crop harvester which was stripped of frame, tailings elevator, return system and clean grain elevator, and remounted on an automotive type ground drive. The engine and operator were mounted on top and the insides were streamlined similarly to the machines

Figure 7. Canadian oil seed thresher (courtesy Engineering Research Service, Research Branch, Canada Department of Agriculture)

Figure 8. Curl belt thresher with low speed peg-tooth cylinder as a pre-thresher and feeding means for edible bean seeds
shown in Figure 9. Complete self-clean was not achieved with these machines, although seed carry-over was minimal.

Øyjord (24), after a study tour in England and Europe, reports that Allis-Chalmers, Munktell and Massey-Ferguson commercial combines were rebuilt and used to harvest plot sizes from 220 to 1300 sq. ft. The necessary idle time between plots for unloading varied between 1/2 to 2 minutes. Even when strategically located compressed air nozzles were used, cleanout was not absolute. None of the Institutions visited by Øyjord used these rebuilt combines in plant breeding because of the risk of mingled seed. The Danish side-mounted harvester of Figure 10 represents a very practical alternative for research requiring larger plot sizes.

Activity in plot mechanization has progressed rapidly in Europe since the formation in 1964 of the International Association on Mechanization of Field Experiments (IAMFE) of which Egil Øyjord is the President. Quadrennial conferences are held and a directory (17) and bibliography (20) of plot equipment have been published.

Self-propelled plot combines for research plots

The earliest attempts by Agronomists to make self-propelled plot combines involved building a header to feed the crop into a Vogel-type thresher. Some ungainly looking machines emerged, but a job was done. The Michigan machine,
Figure 9. The adaptation of commercial harvesters. Modified Allis-Chalmers 140, Maryland (left) and IHC 4-foot cut Ohio agronomist's design (right)

Figure 10. The side-mounted Danish-JF-Fabriken harvester offers an interesting alternative for seed increase plot trials
Figure 11, by Wolfe and Grafius, and a later model by Goering in Missouri, utilized an air nozzle behind the cutterbar to blow the crop up the feed trough.

An operator with a broom would walk alongside the header in lieu of a reel, to insure that the row was all gathered and to help the crop over the cutterbar-nozzle obstructions. ¹

Vogel himself is still actively engaged in designing plot equipment and has built a prototype combine with the "Vogel thresher" mounted alongside a New Idea Uni-system chassis, Figure 12 right. The header has a number of lever-directable compressed air nozzles for clearing the cutterbar and auger zones. The cross-auger feeds between a pair of press-belts which run at the same speed and direction to convey the crop to the overshot peg-drum and concave.

A striking feature of this 10 ft. machine, which testifies to Vogel's ingenuity, is that it can be used on single row plots. The machine is driven up at right angles to the 8 ft. row, the reel is raised practically to the vertical and then two men with a push-bar bend the heads over the cutterbar for heading and threshing by the machine. Over $20,000 has been spent on the development of this prototype.

Figure 11. Michigan cereal combine lacks reel, man with broom forces crop up trough to an air conveyor which feeds the Vogel-type thresher.

Figure 12. World Seeds, North Dakota, seed company's combine built around Vogel thresher (left). Washington State Agronomist Calvin Konzak beside Orville Vogel's 1969 prototype, built onto Uni-tractor chassis (right).
The average farm size in Japan is around 3 acres and equipment developed there is sometimes useful in plot mechanization. From the Suzue rice harvester of Figure 13 comes the idea of using side air jets in the dividers to force the crop over a pair of rotary disc cutters. Air is used behind the crop thresher also for conveying and cleaning (15).

Fans are also used extensively in the Austrian 63" PAM 150 combine of Figure 14. The venturi principle is used for feeding the high volume pneumatic conveyer illustrated on the right of Figure 14.

The German 49" Hege 125, Figure 15, differs from the PAM 150 in that it has a straw rack and short cleaning sieve but does not have a reel. Viewing doors provide access to the cleaning section and an oversize fan is used to blow the separating area clean at the end of each plot. Overall width is 51", length 12.8 ft., and a 32.8 ft. long plot can be cut in 1 minute, including time for cleanout (15).

The model SP50 Chain Machine Company self-propelled plot combine of Figure 16, left, has a fixed position bat reel with spiral strips, which wipe the cutterbar and deliver to a central 27" feeding conveyer. This cereal plot combine has a 17.5 HP Wisconsin engine and sells for around $4,000.

The machine on the right hand side of Figure 16 is the Farmers Forage Research 42" FFR soybean plot combine, custom built by seedsmen for yield trials. The seed is vacuum
Figure 13. Japanese Suzue rice harvester used in cereals. Walk-behind machine utilizes rotary knife, air feeding and two-stage threshing.

Figure 14. Austrian Walter and Wintersteiger PAM 150 cereal plot combine has venturi and pneumatic conveyance for the cleaned seed.
Figure 15. German Hege 125 cereal plot combine achieves effective self-cleanout without using air, by means of belt conveyors.

Figure 16. Chain Machine Company, Kansas, 50" cereal combine (left) and Farmers Forage Research Cooperative, Indiana, 42" soybean plot combine (right). Custom built units for individual research programs.
conveyed through 3" plastic tube and bagged from the cyclone above the operator's platform.¹

Figure 17 shows a small seeds combine which utilizes a differential speed belt thresher. The designer L. M. Klein, reports that an important reduction in damage to garden bean seeds is achieved with a 9.5:1 speed ratio, the actual belt speeds being 95 and 900 f.p.m. for lower and upper belts, respectively. Klein's experience indicated that 98% threshing can be attained, but if the belts were set so that 85-90% threshing was accomplished in one pass, capacity could be increased 50%. An unthreshed-heads return system is used accordingly.

The vertical vibratory-centrifugal sieve provides the greatest screening capacity per unit volume and is self-cleaning without air, and is not affected by side-slopes.²

From Allison, Iowa, comes the 18" IVR single row soybean plot combine of Figure 18. With 24" between divider points, 18" cutterbar and overall width 42", this machine has been tested with power auger dividers to separate rows and feed.


Figure 17. U.S.D.A. Corvallis small seed combine uses belt thresher with returns system and has vertical vibratory-centrifugal screen cleaning.

Figure 18. 18" single-row soybean combine under development in Iowa by Folkerts and Kramer. 1969 modifications resulted in removal of auger dividers and replacement of pickup reel with disc-enclosed 6-bat type reel.
a 12" wide front canvas draper. Due to the extremely narrow width of the header, however, some tendency to snarling and wrapping of branches was experienced. The crop is fed between a pair of peg-tooth cylinders by a feeder-beater. The lower cylinder or "rolling concave" rotates at about 1/15 the speed of the upper cylinder and is self-cleaning.

The crop straw feeds onto a series of six 4-vane beaters rotating in the same direction at speeds diminishing toward the rear. Beneath the beaters is a conventional aspirated screen cleaning section. Clean grain falling through the screen is conveyed by a small cross-feed belt to a bagging chute. The machine is "practically" self-cleaning and three men can harvest a 10 ft. single row in 30-40 seconds. A number of changes on the header are proposed before the next season's harvest trials.¹

Assessment

No universal combine has been produced which can effectively meet all the requirements of the plant breeder for harvesting soybean research plots.

Work is intensifying in this field, as is the degree of anticipation among the breeders themselves, who are looking for a way to alleviate the harvest bottleneck of plot work.

Modified combines, or the use of cereal plot combines, are not acceptable alternatives for soybeans. Some promising ideas have emerged from this review. The next section will be addressed to the development of an integrated plot combine design.
DESIGN

Machine size

Plot size was the first consideration in determining the overall dimensions of a plot harvester. The primary plot dimensions regulating machine size are row spacing and number of rows.

In the midwestern part of the United States, soybeans have been secondary to the corn crop, and corn cultivation practices and equipment have dictated the row spacing for soybeans. Soybeans are yield responsive to narrower rows but the ideal row spacing for a variety varies, depending on environmental factors.

In 1969 the soybean physiology team of the Agronomy Department at Iowa State University planted 2,500 plots which could be harvested by plot combine as follows:

1. 300 plots on 7" row spacing, 12 rows per plot
2. 300 plots on 20" row spacing, 6 rows per plot
3. 1,900 plots on 40" row spacing, single and 3 row plots

The rows were cultivated and ends trimmed to a length of one rod (16-1/2 ft.). An additional 6,500 machine harvestable plots, mostly on 40" and 30" spacings were sown to soybeans by other I.S.U. research workers in 1969.
Regarding plot length, Brim and Mason (5) indicate that plots longer than 18 ft. are questionable from the labor-cost standpoint.

Van Bogaert (31) states that plots should be:
1. harvested in one action, i.e. usable plot width should not exceed that of the harvester,
2. rectangular in shape, this shape is more manageable and usually has lower experimental errors than square plots,
3. of sufficient size to minimize the influence of individual plant deviations, and yet allow for a sufficiently accurate measurement of yield.

A single row on 30" spacing one rod in length in a 35 bushel/acre crop requires a yield measurement to 2/100 lb. to be within a 1% weighing error.

These and other researchers further indicate that:
4. the choice of an appropriate experimental design on the arrangement of the plots may improve the reliability of the data more than the enlargement of plot size,
5. on a given surface more replications are preferred over greater plot area.

Of passing interest at this juncture is the hill-drop plot design. The plot consists of a group of seeds planted in a hill on a square grid pattern of 20-50" intervals. This
effects a considerable saving in land and seed and enables more replications. The building of a combine for continuously harvesting hill-drop plots is beyond the scope of the present work. Such a machine would be feasible, however, if it had ultra-fast cleanout and automation of the seed packaging and tagging operations.

A row-plot combine traveling at 2 mph will harvest 10 to 20 ft. long plots in 4 to 6 seconds. To minimize headland area the machine should be compact, responsive and maneuverable.

**Header selection**

On cereal combines the limiting factor on field capacity is the separating section. But in soybean harvesting the capacity limiting component is the gathering head, or header. The average farmer leaves 10% or more of his crop in the field when combining soybeans. Gathering losses account for around 84% of the total losses, according to Buchele and Johnson (6). Even higher header losses and lodging problems are to be expected in research plots with the diversity of varieties to be harvested.

The promoters of row-crop gathering attachments advertise that significant reductions in soybean gathering losses can be obtained. A row-crop gathering device is definitely indicated when the plot combine will be used exclusively on single rows, but when variable row spacings and multiple rows
are encountered, the "open front" header would be necessary. The idea of a variable width row crop attachment, as used in corn, is not entirely practicable for soybeans. Any tendency to displace the stems, which bear their pods almost to ground level, will increase losses. There will be increased cutterbar stripping and pod slicing, or the stem will be cut too high and stubble losses would increase.

In Table 3 matching widths for cutterbar and dividers on the open front header are suggested. Two header sizes, of 30" and 40" cutterbar width, appear to match most of the plot combinations likely to be encountered at I.S.U.
Table 3. Influence of field plot layout on header design

<table>
<thead>
<tr>
<th>Row Spacing</th>
<th>Rows Planted</th>
<th>Rows Harvested</th>
<th>Plot Width In.(^a)</th>
<th>Machine Width In.(^b)</th>
<th>Width Cutter-Bar In.(^c)</th>
<th>Gather Width In.(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40&quot;</td>
<td>1</td>
<td>1</td>
<td>40</td>
<td>40</td>
<td>16-40</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>120</td>
<td>65</td>
<td>16-40</td>
<td>40</td>
</tr>
<tr>
<td>30&quot;</td>
<td>1</td>
<td>1</td>
<td>30</td>
<td>30</td>
<td>16-30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>90</td>
<td>48</td>
<td>16-30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>120</td>
<td>78</td>
<td>42-60</td>
<td>60</td>
</tr>
<tr>
<td>20&quot;</td>
<td>1</td>
<td>1</td>
<td>20</td>
<td>20</td>
<td>16-20</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>60</td>
<td>32</td>
<td>16-20</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>80</td>
<td>48</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>15&quot;</td>
<td>1</td>
<td>1</td>
<td>15</td>
<td>24</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>45</td>
<td>24</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>60</td>
<td>40</td>
<td>27</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3</td>
<td>75</td>
<td>54</td>
<td>42</td>
<td>45</td>
</tr>
<tr>
<td>10&quot;</td>
<td>3</td>
<td>1</td>
<td>30</td>
<td>16</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>40</td>
<td>26</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3</td>
<td>50</td>
<td>36</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>7&quot;</td>
<td>6</td>
<td>4</td>
<td>42</td>
<td>32</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4</td>
<td>56</td>
<td>40</td>
<td>28</td>
<td>28</td>
</tr>
</tbody>
</table>

\(^a\) Assuming no buffer space between varieties.

\(^b\) Rule of thumb: overall machine width = (rows harvested \times row width) + 0.6 \times row width

\(^c\) Assumes row center divergence ideally not more than 6".

\(^d\) Equals rows harvested \times row width.
Execution of design

It was originally intended in this project to build a basic self-propelling chassis, adaptable to carry the various header and body configurations and other plot equipment.

The 30" harvester and chassis were built and tested first. Such was the difference between it and the 40" header and thresher requirements that another chassis was built. Both machines could then be tested independently.

Brief specifications of the SB 1 and SB 2 plot combines are outlined in Table 4. The "SB" designates "soybean", and the "1" and "2" indicate the number of 30" rows the respective header units can handle.

In Figures 20 and 24 schematic layouts of the SB 1 and SB 2 plot combines are seen, and in the sections which follow the design rationale of the various components is presented.

The SB 1 multiple-use chassis design

Hydrostatic transmissions provide the greatest design freedom on mobile equipment applications. This method of power transmission was fully exploited on the SB 1 chassis (Figure 23).

The pump stroke control was connected by cable to a rocking foot pedal so that stepless speed regulation as well as reverse/forward motion were all contained in the one control.
Table 4. Comparative specification, SB 1 and SB 2 plot combines for soybean research

<table>
<thead>
<tr>
<th>Machine Model</th>
<th>SB 1</th>
<th>SB 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of Cutterbar</td>
<td>29&quot;</td>
<td>39&quot;</td>
</tr>
<tr>
<td>Width Between Dividers</td>
<td>30&quot;</td>
<td>50&quot;</td>
</tr>
<tr>
<td>Without Extensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Combine Width</td>
<td>48&quot;</td>
<td>65&quot;</td>
</tr>
<tr>
<td>Overall Length</td>
<td>160&quot;</td>
<td>216&quot;</td>
</tr>
<tr>
<td>Weight, on Front Axle</td>
<td>1440 lbs.</td>
<td>Est. Total 3500 lbs.</td>
</tr>
<tr>
<td>Weight, on Rear Axle</td>
<td>820 lbs.</td>
<td></td>
</tr>
<tr>
<td>Power Unit</td>
<td>Wisconsin SI2D</td>
<td>Wisconsin VH4D</td>
</tr>
<tr>
<td></td>
<td>12 hp @ 3400 rpm</td>
<td>30 hp @ 2800 rpm</td>
</tr>
<tr>
<td>Ground drive</td>
<td>Wheel Motor Fully</td>
<td>2 Speed Gear</td>
</tr>
<tr>
<td>Transmission</td>
<td>Hydrostatic</td>
<td>Hydrostatic &amp;/Hydrostatic</td>
</tr>
<tr>
<td>Front Tire Size</td>
<td>23/8.50-12</td>
<td>8.00-16</td>
</tr>
<tr>
<td>Rear Tire Size</td>
<td>4.00-12</td>
<td>4.00-15</td>
</tr>
<tr>
<td>Ground Underframe Clearance</td>
<td>8&quot;</td>
<td>8&quot;</td>
</tr>
<tr>
<td>Cutterbar Design</td>
<td>1-1/2&quot; Str. Dou-</td>
<td>3&quot; Str. Conven-</td>
</tr>
<tr>
<td>Double Sickle</td>
<td>ble Sickle</td>
<td>tional</td>
</tr>
<tr>
<td>Reel</td>
<td>12x30 Cross-Flow</td>
<td>Hume Pickup, 6</td>
</tr>
<tr>
<td>Vortex Fan Reel</td>
<td>Tapering Duct,</td>
<td>Bar, Feathering</td>
</tr>
<tr>
<td></td>
<td>Air Conveying</td>
<td></td>
</tr>
<tr>
<td>Elevator</td>
<td>36&quot; Rubberized</td>
<td>1 Ply Belt 3/4&quot;</td>
</tr>
<tr>
<td></td>
<td>1 Ply Belt 3/4&quot;</td>
<td>Lugs on 6&quot; crs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threshing System</td>
<td>Spike Tooth</td>
<td>Differential Speed</td>
</tr>
<tr>
<td></td>
<td>Cyl. &amp; Concave</td>
<td>Inclined Belt</td>
</tr>
<tr>
<td>Thresher Dimensions</td>
<td>20&quot; Wide, 18&quot;</td>
<td>36&quot; Wide, 54&quot; Effec-</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>tive Length</td>
</tr>
<tr>
<td>Separating System and Width</td>
<td>Raised Lip Screen, 18&quot;</td>
<td>Punched Hole Screen, 34&quot; Wide</td>
</tr>
<tr>
<td>Cleaning System</td>
<td>Oscillating</td>
<td>Cascade/Pneumatic</td>
</tr>
<tr>
<td></td>
<td>Sieve &amp; Fan</td>
<td></td>
</tr>
<tr>
<td>Cross-Flow Fan</td>
<td>6&quot; Dia. x 18&quot;</td>
<td>9&quot; Dia. x 36&quot;</td>
</tr>
<tr>
<td>Seed Presentation</td>
<td>Slide Tray</td>
<td>Side Bucket or Elev.</td>
</tr>
<tr>
<td></td>
<td>18 x 6 x 8</td>
<td></td>
</tr>
<tr>
<td>Cleanout Time</td>
<td>5 Minutes</td>
<td>12-18 Seconds</td>
</tr>
</tbody>
</table>
Figure 19. SBl prototype 30" soybean plot combine. A 12" x 30" cross-flow fan reel forces crop over cutterbar and elevates material to threshing cylinder.

Figure 20. SBl prototype single-row plot combine built at Iowa State University. Schematic diagram 1:32 scale.
Figure 21. U.S. patent disclosures. Vortex fan means for a crop gathering apparatus (left). Cross-flow combine cleaning blower (right).
Figure 22. SBl single-row plot combine hydraulic system - U.S.A.S.I. standard circuit symbols

1 PROPELLING PUMP - VARIABLE DISPL., LEVER OPERATED OVER CENTER
2 DUAL RELIEF VALVE - 2500 PSI
3 TOWING VALVE
4 WHEEL MOTOR, LH, 5 PISTON RADIAL
5 WHEEL MOTOR, RH, 5 PISTON RADIAL
6 CUTTERBAR DRIVE MOTOR
7 LIFT CYLINDER, DOUBLE ACTING
8 DRAIN LINES
9 TANK FILLER AND BREATHER
10 LIFT CYLINDER VALVE
11 PRECHARGE VALVE - 65 PSI
12 MAIN FILTER - 10 MICRON
13 LIFT RELIEF, 2000 PSI
14 DUAL PUMP, 4-1/2 and 1 GPM
15 SYSTEM STRAINER AND MAGNET
16 RESERVOIR - 15 GALLONS
17 ADJUSTABLE FLOW CONTROL AND RELIEF, 2000 PSI
18 PRECHARGE AND NON-RETURN VALVE - 5 PSI, GROUND DRIVE

Figure 23. SBl self-propelling chassis, basic low profile hydrostatic drive unit is adaptable to carry other plot equipment
Figure 24. SB2 self-cleaning 50" soybean plot combine developed at Iowa State University. Schematic diagram 1:30 scale
By this means, an extremely responsive system was obtained, to the point of being too sensitive and even unsafe to operate.

In the sizing of the hydraulic components for the ground drive, the following criteria were used (bracketed figures indicate field results):

- Overall weight, with operator: 1,600 lb. (2260)
- Weight on drive axle: 1,000 lb. (1440)
- Weight on rear axle: 600 lb. (820)
- Max. traction on solid ground: 800 lb. (750)
- Typical operating speed required: 2 mph
- Maximum forward speed required: 7.5 mph (6.5)
- Wheel radius, for calculations: 1 ft. (11")

Suitable tire size 23/8.50-12; Terra tire on 12-4 rim

Estimated maximum wheel torque $T_m = 400$ lb. ft.

Using this value to find specific displacement of motor $D_m$, at 3,000 psi, a direct coupled wheel motor displacement of 10.5 cu. in./rev. was required, since

$$D_m = \frac{24\pi T_m}{\Delta p}$$

Houdaille fixed shaft hydraulic wheel motors (size 17A, 10.3 cu. in./rev.) were selected to fit directly into the wheel hubs.

Maximum pump capacity = $2D_m \left(\frac{88 \times 7.5}{231 \times 2}\right) = 9.6$ gpm.

In the initial design of SB 1, independent hydraulic control of the drive wheels for pivotal steering was proposed.
for maximum maneuverability. The extra expense of the compact wheel mounted motors was felt to be justified because of their minimal oil flow requirement (smaller pump required), fast response for hydrostatic steering, and high efficiency (95% at 100 rpm and 100 lb. ft.).

The independent hydraulic control of the drive wheels was achieved by splitting the flow through a 50/50 pressure-compensated flow dividing valve, and then metering the oil in each leg of the circuit by directional steering valves.

After persevering with several valve combinations, the hydrostatic steering attempt was abandoned for these reasons:

1. Hydrostatic skid steering was highly inefficient, the pressure drops across the steering valves during turns was wasted energy and heated the oil.

2. No reasonably cheap alternative, or high precision flow dividing valve could be obtained, so that the machine tended to steer itself according to the magnitude of the resistance encountered by the individual drive wheels.

3. Castor wheels had to be used on the rear axle and these introduced further lack of control over the steering direction, especially when starting.

4. There was no mechanical "feel" of the direction the machine would go, the steering valves were detent centered for neutral, but valve position
did not accurately define the direction the machine was steering. With the steering valves in opposed positions, extremely tight (pivotal) turns were possible.

The machine was changed to conventional mechanical steering by replacing the castoring rear axle with Ackerman linkage controlled steering wheels. The drive wheel hydraulic circuit was changed to parallel flow with the elimination of the flow divider and steering valves (Figure 22).

**SB 2 chassis and operator station**

The combined hydrostatic two-speed geared rear axle of a Case 190 tractor was used as the ground drive mechanism for the SB 2 combine. Separately mounted stub axles with a chain drive reduction to the wheels were utilized to take the weight of the combine off the 12 hp garden tractor transmission housing. The 2" rotor Char-Lynn Orbit motor is driven through a directional valve and open center circuit by a fixed displacement gear pump.

Horsepower requirement for both of the combines was assessed on the basis of header size by interpolation of the data of Tables 14 and 15. [See Appendix.]

The SB 2 is a "straight through" harvester design, of 40" body width, with the operator station above the thresher for maximum visibility. The SB 1 body width was reduced to
20" so that the operator station could be placed alongside the thresher for ease of access.

**Crop dividers**

The dividers should extend beyond the reel sufficiently to penetrate and firmly separate adjacent rows of soybeans, thereby lifting plants before they can entangle supports or sides of the reel mechanism. Adjustable dividers, lifters, and divider extensions would be desirable attachments for varying row spacings and crop conditions. Square sockets for such attachments were provided at the tips of the fixed dividers on both machines.

**Cutterbar**

The 3" spacing of guards and knife sections on the conventional cutterbar design might well be questioned: Can shatter and cutterbar loss in soybeans be reduced by using a closer guard and knife spacing? To answer this question, comparative field tests of a 1-1/2" sickle were conducted on Case field combines. Reductions in header losses in favor of the closer guard spacing were found. For further comparisons, a double knife cutterbar was installed on the SB 1. This cutterbar has 3" conventional knife sections reciprocating through 3" pressed steel double guards. Both knifebar and fingerbar reciprocate counter to each other on a 1-1/2"
stroke. Field tests have not been concluded on this balanced knife design.

The energy required to release soybeans from the pod (typically about 0.02 in. lb.) is so small compared with the energy required to physically impress plants into the header against the advancing cutterbar that reel design merits careful consideration.

The SB 1 gathering and threshing system

The possibility of using a directed air blast was considered as an alternative to the mechanical reel and elevator. Bowman (3) reports on the successful use of the Phillips wind reel in soybeans. A series of low-mounted nozzles was set ahead of the cutterbar and supplied with air by a high volume centrifugal fan. This device, and the Suzue air feed system (Figure 13), prompted the idea of using a cross-flow fan as a "vortex reel and air elevator".

The replacement of the reel with a cross-flow fan, Figures 19 and 21, was the subject of the patent disclosure, Quick (27). The following claims have been made for the device:

1. Reduced shatter losses.
2. Elimination of the need for a feed conveyor on plot combines, since the wind would bend the plants over the cutterbar, then blow them up the feed trough to the cylinder.
3. Air blast cleaning of the cutting zone between plots.

This cross-flow fan is a newcomer to the grain harvesting equipment field and offers some important advantages over the side-inlet paddle wheel blower:

1. A single rotor can be made of any length, consistent with structural rigidity.
2. For the same discharge and speed a smaller housing and rotor diameter can be used.
3. The air has no axial velocity component, air sweeps through 180 degrees in passing from inlet to outlet and passes twice through the rotor. There are no side inlets, and air inlet and outlet openings are both rectangular.
4. There is a more uniform velocity distribution across the width of the rotor, with peak velocity in the center instead of at the ends.

The housing design is critical however, a factor which has previously hindered its acceptance. The criteria for housing design and rotor selection for this and the cleaning blower application on the shoe were outlined by Quick (26).

An air stream velocity of around 4,000 f.p.m. at the fan outlet was necessary in laboratory tests for the vortex reel to effectively bend the plants over the cutterbar. Velocity of air needed in the trough for conveying the severed plants
up the incline was around 3,500 f.p.m. For this air flow the 12" diameter, 30" wide shaftless rotor equipped with 43 blades was driven at 580 rpm, and required 1.2 hp.

Another anticipated advantage of the vortex reel and air elevator was that the air blast would blow grain out of the closed concave on its passage through the threshing slit. The results proved otherwise on the SB 1 combine. The threshing cylinder originally tested was a Massey-Ferguson 35 raspbar type operated conventionally over a closed and streamlined raspbar concave.

The parasitic windage created by this cylinder was considerable, and there was a positive pressure and draft out of the throat of the thresher. When the two opposing air-streams met, a component of the resultant air stream moved vertically upward and carried out some of the crop with it. Several attempts were made to rectify the problem by cylinder and housing modifications. Among the cylinder-concave modifications tested was a reversed M-F raspbar cylinder, a 12-blade cross-flow cylinder, a variable pitch 6-blade cylinder, and a spike tooth cylinder with two rows of spikes spaced 3" apart in the concave, see Table 5.

The following observations were noted on SB 1 laboratory threshing cylinder tests with air feeding:

1. All the threshing cylinders were operated at 580± 20 f.p.m. Combine operator manuals recommend cylinder
Table 5. Comparison of airflow through different threshing cylinders in SBl combine

<table>
<thead>
<tr>
<th>Cylinder 17-1/2-18&quot; Dia. 580±20 rpm</th>
<th>Bar or Spike</th>
<th>Typical Air Velocity Without Reel f.p.m.</th>
<th>Typical Air Velocity With Reel f.p.m.</th>
<th>Crop Feeding - Subj. Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Bar MF35 Conv.</td>
<td></td>
<td>1000</td>
<td>2000</td>
<td>6</td>
</tr>
<tr>
<td>8 Bar MF35 Rev.</td>
<td></td>
<td>1100</td>
<td>2300</td>
<td>5</td>
</tr>
<tr>
<td>12 Bar Cross-Flow</td>
<td></td>
<td>1600</td>
<td>3500</td>
<td>4</td>
</tr>
<tr>
<td>6 Blade Variable Radial</td>
<td></td>
<td>1500</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>6 Blade Forward-Curved</td>
<td></td>
<td>1300</td>
<td>2700</td>
<td>2</td>
</tr>
<tr>
<td>8 Rows Spike Tooth</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
speeds of 2,500-3,500 f.p.m. and clearances 5/16-7/8" in soybeans.

2. With the relative positions of inlet and outlet fixed, it was practically impossible to eliminate back pressure at the throat by changing cylinder or blade design. Cylinder windage - a parasitic drag - is considerable, increasing with number of beaters, bar width and speed.

3. Beater bar design exerts only a moderate influence on the air moving capacity of the cylinder, but can significantly alter the degree of obstruction to passage of air through the threshing slit when a 3,000 f.p.m. air blast is directed at the throat.

4. Only the spike tooth cylinder and concave arrangement would accept most of the crop with the air stream.

5. Even with a spike tooth cylinder, which has an aggressive feeding ability, there was a substantial amount of spitting-back of the beans. This could not be prevented without seriously obstructing the air flow from the elevator.

The spike tooth configuration was used in the SB 1 when the machine was field tested in 1969. In spite of power transmission problems, the following observations were of value:
1. Any lodged stems or intertwined branches between rows proved incapable of pickup using the vortex reel.

2. Any plants bridging across the feed trough or entangling on the cutterbar would clog the header. This would not normally be a problem with a mechanical reel and feed conveyor.

In view of these difficulties and the further aggravation of the turbulent air at the cylinder, work was discontinued on air feeding of the cylinder in soybeans. The principle might prove useful in cereal crops where lighter straw and higher cutting would enable the air to be more horizontally inclined and directed to the cylinder through an improved feed trough shape.

A problem which must be faced in plot combine design is the need to attain a high threshing level in just one pass through the threshing zone. The unthreshed crop return system from sieve to cylinder, as used on commercial combines, is not acceptable on plot harvesters because of their rapid self-cleaning requirement. Young reports that in Amsoy beans at 10% m.c. and normal cylinder settings, 89.3-94.3% of the crop is threshed at the concave in one pass with a Case 600 combine without return system.

One way of increasing the threshing at the concave, without the deleterious effects of higher cylinder speed, is to increase the angle of wrap of the concave around the cylinder. This is achieved very simply by using an overshot cylinder feed, and at the same time the risk of having the seed trapped in the concave is avoided.

There are disadvantages in using an over-shot cylinder:
1. The crop has to be raised considerably higher to obtain the best feed orientation to the threshing throat.
2. The crop will be discharged at an awkward angle, for example, vertically down or forward, increasing the height of the machine still further.
3. Increasing the arc of the concave increases the tendency to straw wrapping. There is also an increase in straw breakage which increases the load on the cleaning section.

Among the alternatives considered were the rotating concave, vibratory threshers, and belt threshing. The rotating concave design (Figure 18) was judged to have insufficient angle of contact for tough threshing conditions, unless a series of cylinders was used. The vibratory threshing principle using either multiple beaters or vibrating counter member is still under investigation and was not evaluated sufficiently for field testing.
The differential speed belt thresher was finally selected for the SB 2 combine.

The SB 2 header and belt thresher

A conventional Hume pickup reel was cut down in width for the SB 2 plot combine. The use of parts of a header of an Allis Chalmers model 40 combine, which had a 39" wide conventional 3" section knife design and 36" draper width, expedited the construction of the SB 2 header (Figure 25). A 36" wide single ply rubberized conveyor with 3/4" high molded lugs on 6" centers was found superior to the A-C canvas and slat draper construction. The over-shot draper feed belt unloads onto the lower threshing belt which travels faster than the upper threshing belt. Both upper belt and draper belt were chain driven at similar surface speeds, approximately 5/4 of the forward speed of the machine.

The most readily obtainable threshing belts, 36" wide, were 3 ply rough-top container conveyor belting, 5/16" nominal thickness, with a raised knob pattern on the threshing surface.

Feeding angle on the upper threshing belt was 30 degrees to the lower belt. This angle of feed gently crowded the crop into the threshing slit (see Figure 26, right). Both belts were sloped 26 degrees to the rear to raise them over the engine and transmission and the sides were left exposed for self-cleaning and observation.
Figure 25. Left- and right-hand front views of SB2 50" soybean plot combine

Figure 26. SB2 belt clearance and pressure adjustment (left). Normal feeding of crop into threshing belts (right)
Separating systems

Several methods of separating grain from straw have proved successful on plot harvesters. The rotary beater and comb first used on SB 1 and the rotary rack of the IVR plot combine (Figure 18) both have one drawback: They may be hazardous to the operator attempting to remove any stems which might have speared through or wrapped on the rotating separator.

A punched-hole screen rack was used on the SB 2 combine. Optimal speed was approximately 200-240 cpm and stroke of the shaker 1-1/2". There was some indication that the rack length of 40" should be extended for reduced rack losses. A rotary beater behind the threshing belts was found necessary to intercept ejected beans and slow the crop material over the separator.

Grain cleaning and presentation

Pneumatic cascade cleaning, Figures 6 and 24, is one of the simplest and most direct cleaning systems practicable. The air blast needed for grain cleaning is dependent upon the aerodynamic behavior of the foreign material not wanted in the grain sample. Soybean stem pieces broken by the thresher and escaping from the rack cannot be separated by cascade cleaning alone, and if these cannot be tolerated in the grain sample then a vibrating cleaning screen must be used.
Magnitude of the cleaning section grain losses will be largely governed by the effectiveness of the rack, and length of the cleaning screen.

European plot machines favor the use of the Graepel raised triangular lip type fixed screens. Adjustable chaffers tend to suffer from straw spearing through the slots. A Hart-Carter no. 9 raised lip screen was used on SB 1 since Graepel screens were not available. The cross-flow fan is ideally matched to the cleaning shoe application (25) and air blast control is maintained by varying fan speed on both machines.

Grain sample cleanliness is not a requirement of a plot combine. The breeder will usually want to evaluate the sample in the laboratory and the cleaning operation can be done more thoroughly there.

A rod row soybean plot will produce up to 4 lbs. seed per row, depending on yield and other factors. A metal container of minimum capacity 200 cu. in. is required which does not spill and which can be easily handled. The seed is tipped into labeled sacks, and the possibility of using a sackholder directly under the combine spout should be considered among future machine refinements.

For the larger plots, provision was made on SB 2 for a lugged rubber elevator to convey the seed to a weighing station behind the operator. This equipment has not been
installed, but a 7 bushel bin which would be unloaded by a 3" wide oscillating conveyor was located behind the operator's station.
ANALYSIS OF DATA

Much time was expended on SB 1 in trying to overcome the problems recited in the previous section, and as a consequence, the SB 2 combine was not ready for field testing before snowfalls ended field work for the 1969 crop season.

Most of the information and performance testing which follows was therefore conducted under controlled indoor test conditions using stored soybean plant bundles. Laboratory testing of a combine provides for control over the environment, enables more replications, and modifications can be effected more rapidly in working towards the optimum configuration. The header and transmission components, which are of more orthodox design, were shown to be functional. It remains to be seen whether field trials will verify the findings from the laboratory test program on the rest of the machine.

Characteristics of the differential speed belt thresher

There is a dearth of information in the literature on the performance of belt threshers. In order to find the best operational settings for the belts in soybeans the following pertinent variables were considered:

(i) Threshing level, defined as ratio of total threshed beans/net potential seed yield. Total threshed = net potential yield - unthreshed seed.
(ii) Damage intensity, defined as ratio of split and visibly damaged beans/net potential seed yield.

Net potential seed yield is the bin yield plus all losses collected in the laboratory test. For a given variety, these are functions of:

(iii) lower belt speed, $S_1$ f.p.m.

(iv) upper belt speed, $S_2$ f.p.m.

(v) belt surface characteristic $r$, ribbing height/belt thickness

(vi) feeder belt speed, $S_3$ f.p.m.

(vii) slope of belts $\alpha$

(viii) threshing slit clearance $x$, ft.

(ix) threshing length $L$, ft.

(x) pressure on belts, exerted by plates $p$, lb./sq. ft.

(xi) gravitational constant $g$, ft./min.$^2$

(xii) crop moisture $m\%$ wet basis

(xiii) crop throughput rate $q$, lbs./min., assuming no losses from sides of thresher

Using the principles of dimensional analysis and the Buckingham Pi theorem, with 12 quantities and 3 dimensions $(F, L, T)$ involved, there are 9 Pi terms in each equation. Two possible sets of Pi terms yield the following equations:

\[
\text{Threshing} = f_1\left(\frac{S_1}{S_2}, r, \frac{S_2}{S_3}, \frac{S_2^2}{gx}, \alpha, \frac{q}{ps_2L}, \frac{x}{L}, m\right)
\]

= (100 x threshing level)
and

\[ \% \text{Damage} = f_2(s_1/s_2, r, s_2/s_3, s_2^2/gx, \alpha, q/ps_2L, x/L, m) \]

(100 x damage intensity)

A number of the physical characteristics of the thresher were fixed by practical and functional requirements. This threshing study was limited to the following Pi terms:

- Threshing level
- Damage level
- Threshing belt speed ratio \( s_1/s_2 \)
- Thresher clearance to length ratio \( x/L, \text{ or } x'/l.0368x10^{-4} \)

where \( x' \) was clearance in sixteenths inch, and \( L \) was 4-1/2 ft, and crop moisture \( m \).

**Effect of belt speed ratio and clearance**

Amsoy bean bundles which were collected and bound during the 1969 season and stored indoors were used in the laboratory tests. Moisture content was measured on a wet basis by Delmhorst moisture meter and checked periodically by forced-draft oven drying at 103°C for 72 hours. Bean moisture at the two levels in the first test series was 14.5±1% w.b. and 10.2±0.6% w.b.

The plants were fed heads first by hand onto the draper belt at a feed rate of approximately 10-12 lbs. of plants per minute. This rate of feed is equivalent to about 1 mph in a single row plot on 30" row spacing with 5 plants per foot.
The threshing slit clearance was parallel along the 54" threshing length, although it appeared later that there might be advantages in having a diminishing clearance along the threshing length. All tests were run with the press plates spring loaded. As far as possible the lower belt speed was held at 900 f.p.m. for this test sequence. The data are tabulated in the Appendix and are plotted in Figure 27. Conclusions drawn from these data were:

1. The variation from the predetermined lower belt speed of 900 f.p.m. was primarily due to belt slippage under load. At clearances below 3/16" and at the lower belt speed ratios, the loaded thresher could stall the engine.

2. Belt drag affected upper belt speed considerably. As the crop entered the threshing zone, the upper belt would be speeded up, altering the actual speed ratio. This effect became more pronounced as nominal speed ratio was increased.

3. Maximum damage level, as measured by splits and visibly damaged beans, was below 2.2% at the 14.5% moisture level and below 4.8% at the 10.2% moisture level. Damage was highest at the 7.28:1 nominal belt speed ratio.

4. Threshing level increased markedly as belt clearance decreased. Changes in clearance of as little as
Figure 27. Belt speed ratio and clearance effects on belt thresher performance at two moisture levels
1/16" were found critical, as shown in Figure 27.
5. Threshing level normally improved as belt speed ratio was increased.
6. At the higher belt speed ratios, the tendency of the lower belt to overdrive the upper increased even with "tight" belts.
7. The optimum belt speed ratio was about 4:1.

Effect of manner of feeding

Even if plants were fed into the thresher at an angle, the configuration of the belts was such that the crop tended to be pulled into the threshing slit parallel to the direction of travel of the belts.

It was of interest therefore to see what effect feeding at right angles to the direction of belt travel (cross feeding) would have upon the threshing.

It is evident from Figure 28 that normal feeding was the "line of least resistance" of the crop passing through the belt thresher. At all speed ratios, for 1/2" clearance, the threshing level was considerably improved by cross feeding. Regardless of manner of feeding, the crop stems were discharged practically intact from the belt thresher. With cross feeding it was evident that the stems had been rolled over and over, as any threshed pods which had remained attached were shredded and wrapped tightly around the stems.
Figure 28. Effect of varying belt speed ratio on belt threshing with normal and cross-feeding. Constant lower belt speed and clearance, 14.5% m.c.
Damage levels were slightly higher with cross feeding, but at 1/2" clearance, damage was negligible.

Cross feeding the belts would not be practicable with the present combine design, but a machine might be worth developing to take advantage of this method of feeding.

**Effect of belt speed deviation**

The tendency of the lower belt to overdrive the upper belt was examined during the second phase of the threshing study.

Upper belt speed deviations as high as twice the nominal setting were observed, Figure 29. This occurred despite the rubber lagging on the 7" drive rollers and the fact that belt speed ratio was maintained at 4.95:1. The Corvallis combine of Figure 17 has both front and rear power driven rollers to provide more positive belt speed control.

**Effect of moisture content**

It is doubtful whether the data represented in Figure 30 could be accurately repeated in the field, since pod and straw moisture content of the stored crop bundles varied considerably during a day's testing. The 19.6% beans were plants collected from standing crop kept over winter in the field, and were in poor condition. Nevertheless the typical tendency of threshers to increase damage at both ends of the range of moisture was evident.
Figure 29. Belt speed deviation at 4.07:1 setting.

Figure 30. Effect of moisture content on belt threshing characteristics.
Minimum damage was sustained around 14% moisture content.

As could be expected, the higher moisture beans were tougher to thresh. There are several practicable ways of improving the threshing performance of the belt thresher if high moisture (over 16%) beans have to be harvested by the plot combine:

1. Use cross feeding.
2. Fix the pressure plates, by blocking out the springs (see Table 10).
3. Use an unthreshed material return system.
4. Use different belt surfaces.
5. Use secondary beater threshers under the belt.
6. Use a vibrating concave design under the upper belt.

**Effect of overall speed changes on threshing performance**

Some difficulties are met in accounting for the behavior of the thresher when both belts are speeded up at a given belt speed ratio (Figure 31).

Hawkeye beans at 14.5% m.c. were used, clearance set at 3/8", and belts geared for a 4.05:1 speed ratio. By using the primary drive belt speed variator and an array of sprockets, the thresher was progressively speeded up to a maximum lower belt speed of 1915 f.p.m.

Threshing performance improved with increased speed, and approached the 100% threshing level asymptotically. Visible
Figure 31. Effect of overall speed variation on belt threshing performance. Log and double-reciprocal plots.
grain damage levels (similar in magnitude to those for variety Amsoy) were not influenced as markedly by increasing speed.

These interesting phenomena will be considered in more detail.

**Contribution to the development of a threshing equation**

Threshing, i.e. the action of pod opening and release of beans, has been shown by the cross feeding experiment to be markedly improved by increasing the plant-machine component interactions.

If the velocity differential of the crop between threshing throat and discharge end is increased, then more energy is put into the plants, according to the relation

\[
E = \frac{a}{2g} (s_5^2 - s_4^2),
\]

where \( s_4 \) = average crop inlet velocity, f.p.m.,

and \( s_5 \) = average crop outlet velocity, f.p.m.

In this test the draper belt was also speeded up, but the contribution by \( s_5^2 \) should predominate, since \( s_5^2 \) could be as much as 16 times as large as \( s_4^2 \).

By the further consideration of the general impulse relation, \( \text{Impulse} = \int_{0}^{t} F \, dt = \frac{a}{g} (S_5 - S_4) \), per unit time, then higher velocity differentials will result in a larger change in momentum of the crop. If inlet velocity, \( S_4 \), were held constant while the threshing belts were speeded up, then,
to some extent, the higher threshing with higher belt speeds would be explained by impulsive conditions at the throat.

This explanation does not adequately account for the situation here where the inlet velocity was increased at the same rate as the thresher velocity. Impulsive conditions at the throat do not therefore account for the results shown in Figure 31.

Arnold (1) has developed an exponential relationship for rasp bar thresher performance. A double reciprocal relationship would also fulfill the limiting conditions, namely, as crop outlet velocity $S_5$ increased, threshing level approached 100%; and as velocity decreased, threshing level declined rapidly. The following empirical relations for threshing level $Y$ were considered:

- Exponential: $Y = Ae^{-b/S}$, or $\ln Y = \ln A - \frac{b}{S}$
- Double reciprocal: $Y = \frac{S}{CS+d}$, or $\frac{1}{Y} = C + d \frac{1}{S}$

where $S$ = lower belt speed, and $A, b, C, d$ are constants.

In lieu of a theory to explain exactly the action within the threshing belts, there was one practical consideration which would tend to support the use of the second empirical relationship over the first; namely, no matter how poor the operation, there would always tend to be some threshing whenever soybean plants interacted with a machine. There would be a value for the intercept on the Y axis (threshing level)
even when belt speed approached zero, due to normal compressive forces between the belts.

In order to find the constants in the linearized threshing equations, the data in Table 12 was analyzed by computer. An Omnitab least squares regression program, with tests for goodness of fit, was used.

The results indicated a very slight improvement in fit in favor of the double reciprocal model. Further testing is necessary before any strong claims are made in favor of the double reciprocal method of representing threshing performance rather than the generally accepted logarithmic threshing equation.

**Threshing damage comparisons**

Larger seeded soybeans, such as Magna, Prize, Disoy, etc. are more prone to damage during threshing. One of the reasons for selecting the belt thresher was to take advantage of the supposed advantages of belts in reducing damage.

According to Arnold (1) a change in the design of the threshing mechanism is necessary to reduce

"...damage originating when the grain was impacted by the beater bar, or once accelerated, was suddenly arrested by the concave or some structural member. The severity of all such impacts could be reduced by employing
lower cylinder speeds. The evidence suggested that this could be completely effective within optimum moisture ranges, but outside these, because of the speeds necessary to maintain efficiency and output, some damage was inevitable.... Cylinder speeds used in commercial practice were frequently in excess of those necessary to achieve complete threshing. The extent by which they could be reduced, especially at higher moisture levels, without serious loss in efficiency, and whether this would reduce damage to a completely acceptable level was open to question."

Soybean damage may be conveniently divided into two categories:

1. **Visible damage** - splits and ruptured seed coat, and
2. **Cryptic damage** - indicated by reduced seed germinability, seedling abnormalities and reduced seedling vigor (5).

Generally a high percentage of splits and visibly damaged beans is indicative of severe hidden damage, and removal of the splits, or even cracked seed, from the sample does not eliminate the damage.
Amsoy variety, as used in these comparisons, was not a large-seeded soybean, nevertheless there was a distinct reduction in damage due to the use of the belt thresher \(^1\) (Table 6).

**Durability of the threshing belts**

The 3 ply industrial conveyor threshing belts used on SB 2 were considered expensive, the O.E.M. price being about $400 for 21 ft. of 36" wide belting. Wear on the upper belt after an estimated 15 hours of use was 0.01" and on lower belt 0.035". The predicted useful life for the lower belt is approximately 70 hours.

The belts are vulnerable, especially at the joiners, and are prone to ride against the sides of the thresher housing when flat drive rolls are used.

Alternative belt surfaces, such as small raised-lug patterns and materials of higher Duro scale (SB 2 belt surface: 50 Duro A scale) offer possibilities for reducing the overall size of the thresher as well as extending belt life.

The use of an open weave metal belting for threshing, and the use of a single belt over an oscillating counter

---

<table>
<thead>
<tr>
<th>Method of Threshing</th>
<th>Moisture Content (w.b.)</th>
<th>Visible Damage Splits, etc.</th>
<th>Cryptic Damage (measured on cleaned sample)</th>
<th>Germination</th>
<th>Abnormal Seedlings&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Threshed</td>
<td>13.5%</td>
<td>Trace</td>
<td>96.25%&lt;sup&gt;a&lt;/sup&gt; (94-98.5%)</td>
<td>1-1/2%&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Belt Thresher (900 &amp; 150-200 fpm)</td>
<td>14.5%</td>
<td>0.85%</td>
<td>93%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.0%&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Rasp-Bar Cylinder</td>
<td>10.2%</td>
<td>0.04%</td>
<td>98.3%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.6%&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Almaco Plot Thresher (2200 fpm)</td>
<td>15.3%</td>
<td>0.81%</td>
<td>92.6%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.38%&lt;sup&gt;a&lt;/sup&gt;</td>
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</tr>
<tr>
<td>Case 600 Combine</td>
<td>11.5%</td>
<td>1.56%</td>
<td>96%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.0%&lt;sup&gt;a&lt;/sup&gt;</td>
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</tr>
<tr>
<td>Rasp-Bar Cylinder, with Returns System</td>
<td>12.5%</td>
<td>3.3% at 2830 fpm</td>
<td></td>
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</tr>
<tr>
<td>Random Samples, 20 Certified Seed Growers. Field Combine Harvested 1969.</td>
<td>Not Available</td>
<td>Not Available</td>
<td>95%</td>
<td>Not Available</td>
<td>88-98%</td>
</tr>
</tbody>
</table>

<sup>a</sup> Some hail damage noted.

<sup>b</sup> Abnormal seedling: less than half cotyledon attached, radical damage, roots detached, hypocotyl abnormalities, etc.
member, as illustrated in Figure 32, are novel principles which might be considered.

Estimated man-hour reduction possible with SB 2 plot combine

The SB 2 plot unit was substantially a self-cleaning machine and emptied within a 12-18 second overrun period. Occasionally a stem would spear through the punched hole screen and in case the stem might carry an unthreshed pod, the machine should be checked after each run.

It was noticed incidentally, that very little material ever came out the sides of the threshing slit in level-land operation, even when stems were fed in reasonably close to the sides of the header.

Cleaning loss without a screen with the cascade cleaner was around 1% free seed. It was evident from this and from the fact that unbroken straw was discharged from the belt thresher that there was a considerably reduced load on the cleaning section compared with cylinder type threshing machines. Faster cleanout occurs without a cleaning screen.

The term "best production rate" will be used for the comparison of plot harvesting methods. Best production rate is defined as maximum rate of harvesting plots of one rod - row length, when the machine is operated continuously over a prescribed period of time. This time should be sufficient for not less than 3 plots and includes cleanout between plots and grain sample collection. Such time does not include turn
Figure 32. SB3 plot combine proposal with improved header and vibrating concave-belt thresher assembly
around, breakdown or operator time delays. The unit selected for best production rate is plots per man-hour.

1. Plots harvested completely by hand, without machine tools. A team working without the aid of mechanization might manage to harvest a sample of beans at 0.8 plots per man-hour.

2. "Two step combining". In the 1969 I.S.U. varietal improvement trials, 3 men, using shoulder harnessed scythes and an Almaco thresher harvested 350 single row plots in 6 hours, i.e. 19.5 plots per man-hour.

3. Using the bundling unit of Figure 2. Two men operating the Merry-tiller sickle-bundler and carrying bundles to 2 men on the Folkerts and Kramer IVR stationary thresher of Figure 5, could harvest 120 - 10' rows in 75 minutes, a rate of approximately 22 rod-row plots per man-hour.

4. The IVR single row plot combine of Figure 18 was operated at approximately 1/2 mph and required 3 men. With a 15 sec. cleanout, a rate of 40 plots per man-hour was achieved.

5. With the SB 2 plot combine in the laboratory, 2 men have been able to simulate field production rates of 60 plots per man-hour, at an effective forward speed of 1 mph and with 15 sec. cleanout time.
The use of plot combines could potentially double the amount of field experimentation of the research worker who is at present limited by the time required to harvest the plots.
CONCLUSIONS AND RECOMMENDATIONS

Genetic improvements in soybeans have resulted in new varieties which have improved seed quality and size, reduced lodging and shattering, raised disease resistance, and increased oil content. The potential return to Iowa farmers from using new soybean varieties over old, has been estimated as an additional income of $7 to $13 per acre (19).

A basic contribution to plant breeding and agronomic research has been, and continues to be made through the mechanization of field plot work.

The rate of advance of field plot mechanization has been rapid. After viewing the exhibits at the 2nd International Conference on Mechanization of Field Experiments in July 1968, Buchele wrote: "In 1964 the designs looked like 1850 machines. This year the designs looked like 1920 machines. If all goes well, the 1972 designs will look like 1972 machines. That's moving ahead 122 years in 8 years."¹

The plot harvesting bottleneck can be avoided by the use of a suitable plot combine and such a design has been proposed in this work. Design objectives have been realized and an integrated unit developed.

Increases in productivity of 50% over the best known methods are predicted using the SB 2 plot combine.

It is recommended that:

1. The SB 2 unit be thoroughly field tested at the earliest opportunity.

2. A new harvester, SB 3, be built onto the SB 1 mobile chassis, and several of the suggestions made in this work be incorporated, for example, the use of the metal belt and vibrating counter member.

3. The idea of cross feeding a differential speed belt thresher be investigated.

4. The development of a generalized threshing equation be further pursued.

5. As funds become available, automatic header height controls and hydraulic reel speed controls be fitted to the plot combines.

6. Closer guard spacing and novel crop lifters and dividers on the header be further tested.

7. Methods of handling the seed at the ends of the plot, so that seed sacking and tagging can be done mechanically, should be investigated. If this can be automated, then hill-drop plots might even be amenable to plot combine harvesting.
SUMMARY

Plant breeders have made noteworthy contributions to the productivity of world agriculture. Further developments in this science are contingent upon the full mechanization of field methods, and especially of harvesting. Plant breeding methods in soybeans were considered. An extensive illustrated review of plot harvest equipment was presented. The steps leading to the design of an integrated field plot combine have been enumerated.

A number of novel machine principles, some fruitful and others not so productive, have been explored. A differential speed belt thresher, the cross-flow fan and narrower cutterbar guard designs have been shown to have effective application on plot combines.

New data from a belt threshing study was presented and threshing equations suggested.

Productivity figures for various plot harvesting methods were compared, to show how the field productivity of plant breeders can be increased.
LITERATURE CITED


The author wishes to record his sincere appreciation for the help of the following individuals:

Dr. C. W. Bockhop, Head, Department of Agricultural Engineering, for providing financial support and the facilities for the pursuance of this work.

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My wife, Marlene, above all for her devotion, godly influence in the family, and partnership in this work.
### Table 7. SB 2 belt thresher loss as affected by operating variables

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<th>Speed</th>
<th>Clearance</th>
<th>Threshing Loss %</th>
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<td>0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The SB 2 belt thresher was tested under the following conditions:

Variety Amsoy, stored crop bundles.
Date January 30 - February 4, 1970
Lower belt speed held to 900±57 f.p.m.
Manner of feeding - normal, i.e. parallel to belt direction. Plants fed in heads first at 10-12 lbs./min. equivalent feed rate.
Each threshing loss figure represents weighted means from three runs (approximately 1 lb. seed) at each setting.
Moistures 1 = 14.5% w.b.
2 = 10.2% w.b.
Speed ratios 1 = 1.645:1
2 = 2.86:1
3 = 4.95:1
4 = 7.28:1
Clearances 1 = 1/2"
2 = 3/8"
3 = 5/16"
4 = 1/4"
5 = 1/8"

Threshing loss = % unthreshed

\[
\text{Threshing loss} = \frac{\text{wt. unthreshed beans in bin and over back}}{\text{total wt. beans collected} + \text{wt. unthreshed beans}}
\]

Effect of varying belt speed ratio and clearance on threshing losses (Figure 27)
Table 8. Effect of varying belt speed ratio and manner of feeding on belt thresher performance. SB 2 plot combine (Figure 28)

<table>
<thead>
<tr>
<th>Nominal Belt Speed Ratio</th>
<th>% Threshed, or Threshing Level</th>
<th>Normal Feed</th>
<th>Cross Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.645:1</td>
<td>72.38</td>
<td>83.22</td>
<td></td>
</tr>
<tr>
<td>2.86:1</td>
<td>81.10</td>
<td>92.60</td>
<td></td>
</tr>
<tr>
<td>4.95:1</td>
<td>83.15</td>
<td>93.36</td>
<td></td>
</tr>
<tr>
<td>7.28:1</td>
<td>85.90</td>
<td>93.60</td>
<td></td>
</tr>
<tr>
<td>Upper Belt Held Stationary</td>
<td>99.0</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

Variety Amsoy, stored crop bundles.
Date January 30 - February 4, 1970
Crop moisture content - beans 14.5%, pods 13.1%, stems 12.4% (moisture determinations on wet basis from forced draft oven drying at 103°C for 72 hours)
Parallel belt clearance 1/2"
Lower belt speed 900± 10% f.p.m.
"Normal feed" refers to crop fed heads first onto draper belt with stems parallel to belt direction.
"Cross feed" refers to crop fed onto draper belt at right angles to direction of belt motion.
Table 9. Effect of crop moisture variation on belt thresher performance (Figure 30)

<table>
<thead>
<tr>
<th>Bean Moisture Content % w.b.</th>
<th>Threshing Loss %</th>
<th>Threshing Damage Level %</th>
<th>Damage Level, Splits and Visibly Damaged, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.6\textsuperscript{a}</td>
<td>2.45</td>
<td>97.55</td>
<td>1.05</td>
</tr>
<tr>
<td>14.5</td>
<td>1.89</td>
<td>98.11</td>
<td>0.62</td>
</tr>
<tr>
<td>13</td>
<td>0.78</td>
<td>99.22</td>
<td>0.89</td>
</tr>
<tr>
<td>10.2</td>
<td>0.45</td>
<td>99.55</td>
<td>1.27</td>
</tr>
<tr>
<td>8.5</td>
<td>0.0</td>
<td>100</td>
<td>1.88</td>
</tr>
</tbody>
</table>

\textsuperscript{a}19.6\% m.c. beans were crop left standing in field over winter until test date.

Variety Amsoy, stored crop bundles.

Date February 2-12, 1970

Parallel belt clearance 3/8"

Belt speed ratio 4.95:1

Belt speed ratio 4.95:1

Lower belt speed 900+ 10\% f.p.m.

Results are weighted means from several runs. Machine hand fed, heads first, normal feeding.
Table 10. Effect of lower press plates mounting method on belt threshing performance

<table>
<thead>
<tr>
<th>Lower Press Plates Mounted for</th>
<th>Threshing Loss %</th>
<th>Threshing Level %</th>
<th>Damage Level, Splits and Visibly Damaged %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Pressure</td>
<td>1.79</td>
<td>98.21</td>
<td>1.06</td>
</tr>
<tr>
<td>Constant Clearance</td>
<td>0.70</td>
<td>99.30</td>
<td>1.41</td>
</tr>
</tbody>
</table>

All machine settings as in Table 9. Amsoy beans, moisture content 14% w.b. Lower pressure plates are normally spring loaded to provide a constant pressure between the upper and lower belts over the threshing zone. To provide a constant clearance comparison, wooden blocks were used to rigidly maintain the 3/8" clearance between the belts.
Table 11. Belt speed deviation from predetermined value (Figure 29)

<table>
<thead>
<tr>
<th>Measured Lower Belt Speed f.p.m.</th>
<th>Theoretical Upper Belt Speed at 4.07:1 Speed Ratio, f.p.m.</th>
<th>Actual Upper Belt Speed f.p.m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>320</td>
<td>78.5</td>
<td>78</td>
</tr>
<tr>
<td>410</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td>468</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>506</td>
<td>124.5</td>
<td>122</td>
</tr>
<tr>
<td>558</td>
<td>137</td>
<td>137</td>
</tr>
<tr>
<td>687</td>
<td>169</td>
<td>163</td>
</tr>
<tr>
<td>1020</td>
<td>250</td>
<td>400</td>
</tr>
<tr>
<td>1172</td>
<td>288</td>
<td>520</td>
</tr>
<tr>
<td>1346</td>
<td>330</td>
<td>600</td>
</tr>
<tr>
<td>1650</td>
<td>405</td>
<td>750</td>
</tr>
<tr>
<td>1915</td>
<td>470</td>
<td>900</td>
</tr>
</tbody>
</table>

*Measured with Zero-Max ME 1000 electrical tachometer directly indicating 0-1000 f.p.m., least scale division 10 f.p.m.*

Variety Hawkeye, stored crop bundles.
Date February 5 & 6, 1970
Moisture contents (w.b.) - beans 14.5%, pods 12.0%, stems 12.4%
Belt speed ratio set at 4.07:1 by sprocket combinations
Parallel belt clearance 3/8", lower press plates spring loaded
Feed rate 2-4 lb./min., plants hand fed onto draper in normal direction with heads first.
Table 12. SB 2 belt thresher performance characteristics: Effect of belt speed on threshing level at a given clearance and speed ratio (Figure 29)

<table>
<thead>
<tr>
<th>Measured Lower Belt Speed f.p.m.</th>
<th>Threshing Level %</th>
<th>Damage Level Splits and Visible %</th>
</tr>
</thead>
<tbody>
<tr>
<td>320</td>
<td>93.57</td>
<td>0.58</td>
</tr>
<tr>
<td>410</td>
<td>97.13</td>
<td>0.59</td>
</tr>
<tr>
<td>468</td>
<td>95.08</td>
<td>0.67</td>
</tr>
<tr>
<td>506</td>
<td>95.50</td>
<td>0.56</td>
</tr>
<tr>
<td>558</td>
<td>95.49</td>
<td>0.39</td>
</tr>
<tr>
<td>687</td>
<td>96.04</td>
<td>0.30</td>
</tr>
<tr>
<td>1020</td>
<td>98.87</td>
<td>0.58</td>
</tr>
<tr>
<td>1172</td>
<td>99.17</td>
<td>0.77</td>
</tr>
<tr>
<td>1346</td>
<td>99.34</td>
<td>0.24</td>
</tr>
<tr>
<td>1650</td>
<td>99.28</td>
<td>0.92</td>
</tr>
<tr>
<td>1915</td>
<td>99.33</td>
<td>1.43</td>
</tr>
</tbody>
</table>

aMachine settings and Hawkeye crop conditions as for Table 11.
bData analyzed on Omnitab computer program for least squares regression and goodness of fit for the following mathematical models:

(i) Exponential relationship: \( Y = Ae^{-b/S} \)

Linearized relationship: \( \ln Y = \ln A - b \frac{1}{S} \)

and

(ii) Double reciprocal relationship: \( Y = \frac{S}{CS+d} \)

Linearized relationship: \( \frac{1}{Y} = \frac{C+d}{S} \)

where \( Y \) = threshing level, %
\( S \) = lower belt speed, f.p.m.
\( A, b, C, d \) are constants

Data was machine plotted, then traced and reduced for reproduction in Figure 29. Results are weighted means of three runs at each setting.
Table 13. Tests for fit of threshing equation models (Figure 31)

<table>
<thead>
<tr>
<th>Mathematical Model</th>
<th>Standard Deviation in Y from Predicted Curvea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log Relationship $Y = Ae^{-b/S}$</td>
<td>0.8693%</td>
</tr>
<tr>
<td>Double Reciprocal $Y = \frac{S}{CS+d}$</td>
<td>0.8644%</td>
</tr>
</tbody>
</table>

aStandard deviation in threshing level $Y = \sqrt{\frac{1}{n} (\bar{Y} - \dot{Y})^2}$

where $Y_i =$ predicted value from model equation for a given
$\dot{Y}_i =$ actual data point for given
$i = 1,2,3...n$
$n = 11 =$ number of data points

Table 14. SB 2 belt thresher torque measurements

<table>
<thead>
<tr>
<th>Belt Speed Ratio</th>
<th>Belt Clearance</th>
<th>Torque lb.-ft.a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.645:1</td>
<td>1/2</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>5/16</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>1/4</td>
<td>65</td>
</tr>
<tr>
<td>4.95:1</td>
<td>1/2</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>3/8</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>1/4</td>
<td>115</td>
</tr>
</tbody>
</table>

aMeasured by hand-crank and balance while slowly turning over lower belt drive roll shaft. Includes all harvester drives except cutterbar and reel.
Table 15. Combine power requirements for threshing soybeans, adapted from Burroughs (7)

<table>
<thead>
<tr>
<th>Component</th>
<th>Power, hp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Header, Draper, Reel and Cutterbar</td>
<td>1.6 - average</td>
</tr>
<tr>
<td>Cylinder</td>
<td>4 - average</td>
</tr>
<tr>
<td></td>
<td>1.3 - unloaded</td>
</tr>
<tr>
<td></td>
<td>15 - overloaded condition</td>
</tr>
<tr>
<td>All Machine Components</td>
<td>8.6 - average</td>
</tr>
<tr>
<td>Traction Power in Rowed Soybeans</td>
<td>10 - average</td>
</tr>
</tbody>
</table>

For combine with 7' header and 5' cylinder, operated at 2 mph with straw throughput of 40 lb./min., machine weighing 6,600 lb., with 5,000:1600 weight distribution.