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12

GRAIN HARVESTING

INTRODUCTION

The purpose of grain harvesting is to recover grains from the field and separate them from the rest of the crop material in a timely manner with minimum grain loss while maintaining highest grain quality. The methods and equipment used for harvesting depend upon the type of grain crop, planting method, and climate. The major grain crops are rice, wheat, corn, soybeans, barley, oats, sorghum, and dry beans (navy beans, pinto beans, etc.). Many other grain crops, such as oil-seed crops, are harvested using the methods and equipment described in this chapter.

12.1 METHODS AND EQUIPMENT

The entire harvesting operation may be divided into cutting, threshing, separation, and cleaning functions. *Threshing* is breaking grain free from other plant material by applying mechanical force that creates a combination of impact, shear, and/or compression. It is important to avoid damaging grain during threshing–a challenging task under certain crop conditions. For example, at high moisture content it is harder to break grain away from the crop material but easier to damage grain. The operation of *separation* refers to separating threshed grains from bulk plant material such as straw. The *cleaning* operation uses air to separate fine crop material such as chaff from grain.

Depending upon the method employed for harvesting, these functions are performed by different machines, often with time allowed for windrowing or curing between the cutting and the threshing functions, or all the functions may be performed by one machine in a single pass over the field. The modern grain harvesters that combine all of these operations in one field-going machine are commonly called *combines*.

12.1.1 Direct harvesting

In the direct harvesting method, all functions, from cutting to cleaning, are performed by one machine called the combine (Figure 12.1). All major crops mentioned above can be harvested directly. There are two main kinds of combines, conventional types and rotary types. Either of these types may be self-propelled or pulled by a tractor and powered by the PTO drive as shown in Figure 12.2.

Figure 12.3 is a schematic diagram of a conventional combine showing the functional components. Different manufacturers have different designs but the functional components are similar. During combine operation the uncut standing crop is pushed

Figure 12.1 – A modern grain combine (courtesy of Ford/New-Holland).

Figure 12.2 – A typical pull-type combine drawn by a tractor
(reproduced by permission of Deere and Co. © 1991).

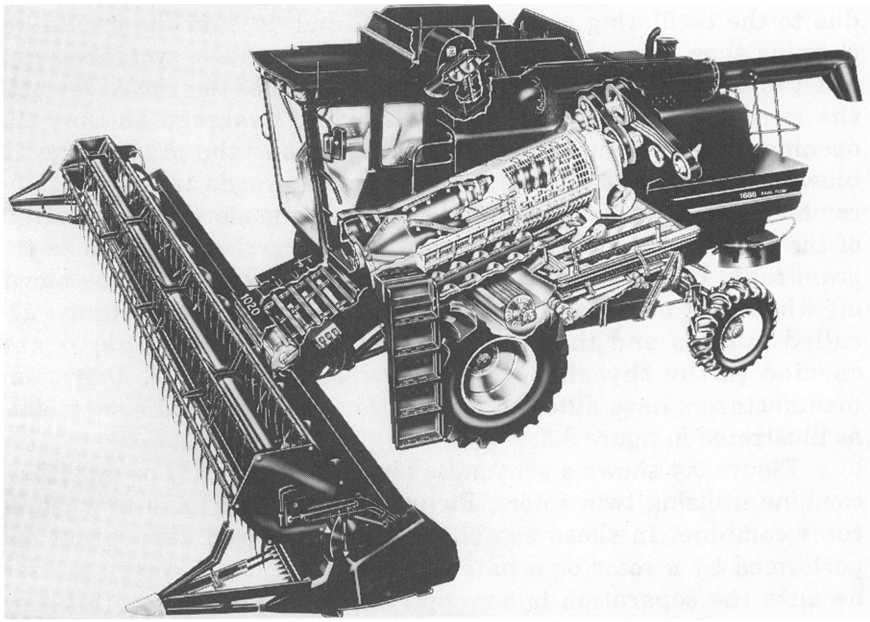


Figure 12.3 – Internal construction of a modern self-propelled grain combine (courtesy of Case-IH Co.).

by the *reel* against the *cutterbar* and onto the *platform*. The cut crop is conveyed towards the center of the platform from either side by the *platform auger* and conveyed to the threshing cylinder by the *feeder conveyer*. The crop is threshed by the *threshing cylinder*. The threshing cylinder rotates at a very high speed (about 30 m/s peripheral speed). About 80% of the grain, along with some chaff and small pieces of straw, is separated through the *grate*. The bulk of the straw, chaff, and the remaining grains pass through the concave-cylinder gap where the *beater* causes it to slow down. Then this material is delivered to a *separator*. In a conventional combine the separator is made of oscillating channel sections called the *straw walkers*. Since early 1970s separator design has changed to a rotary design. Rotary types of combines are discussed below. The separated material falls into the channels, moves towards the front of the combine, and is delivered on top of an oscillating *grain pan* where it is combined with the grain-chaff mixture separated at the cylinder-concave. This mixture of chaff and grain moves rearward due to the oscillating action of the pan and falls on the oscillating *cleaning shoe*. The cleaning shoe generally consists of two sieves and a fan to blow air upwards through the bottom of the sieves towards the rear of the combine. The top sieve is designed so that the openings may be adjusted. It is referred to as the *chaffer*. The air blows the chaff and the straw pieces off towards the rear of the combine while the clean grain falls through the sieves to the bottom of the cleaning shoe. The *clean-grain auger* carries the grain to the *grain tank*. Unthreshed grain heads that are too heavy to be blown off with chaff and too large to escape through sieve openings are called *tailings* and they are collected by the *tailings auger* and carried to the threshing cylinder for rethreshing.

In some combine designs multiple conventional threshing cylinders are used as shown in Figure 12.4. Each cylinder rotates faster successively to thresh out increasingly hard-to-thresh grains. Figure 12.5 shows yet another arrangement. A transversely mounted conventional threshing cylinder is used in conjunction with a rotary tine separator. This design is especially suited for crops such as rice that have tough straw.

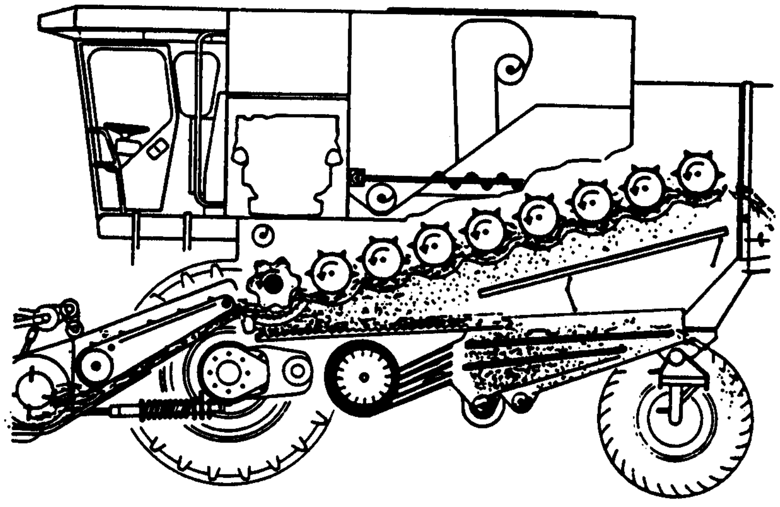


Figure 12.4 – A combine design utilizing a conventional threshing cylinder and multiple separation cylinders (courtesy of Prairie Agricultural Machinery Institute, Canada).

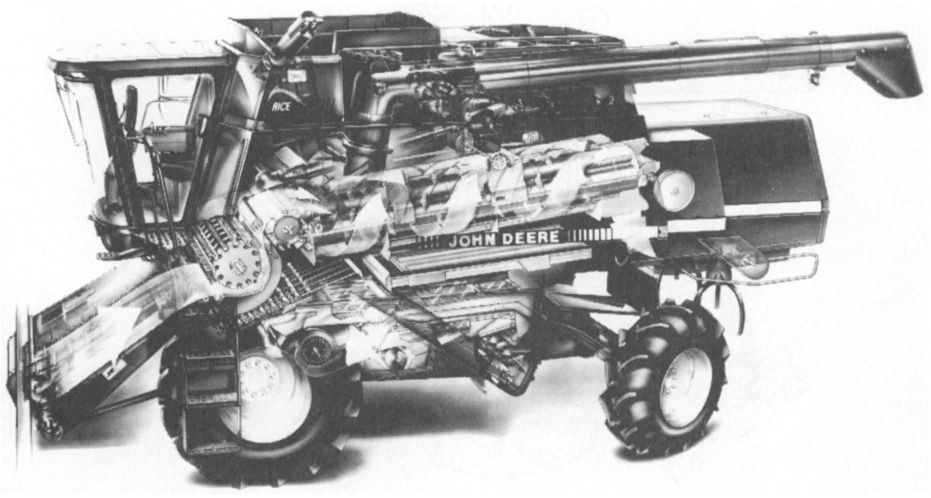


Figure 12.5 – A combine configuration utilizing a transversely mounted conventional threshing cylinder and a rotary tine separator (courtesy of Deere and Co.).

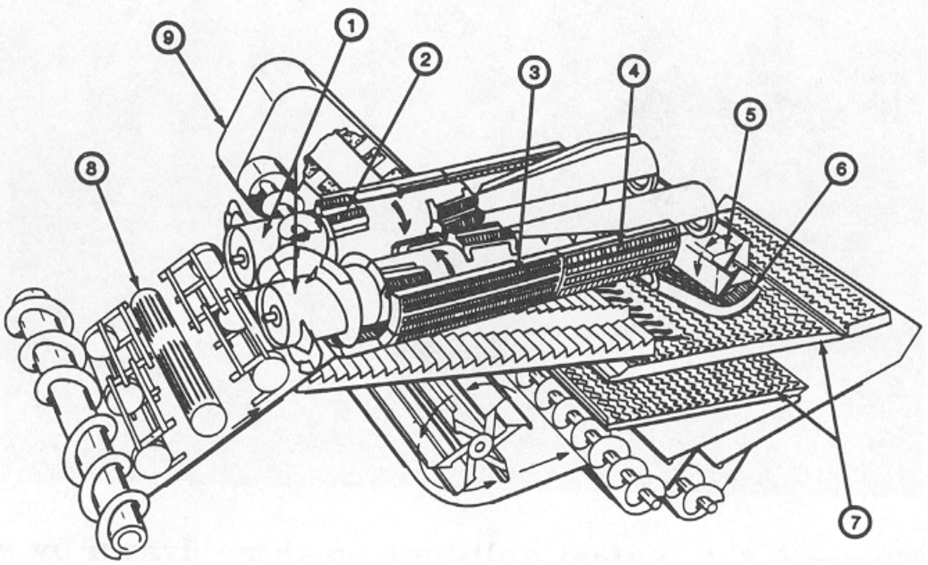


Figure 12.6 – An axial flow rotary combine utilizing twin rotors: (1) rotor, (2) rasp bars, (3) threshing concave, (4) separating concave, (5) discharge beater, (6) beater grate, (7) cleaning shoe, (8) feeder housings, (9) tailings auger (courtesy of Prairie Agricultural Machinery Institute, Canada).

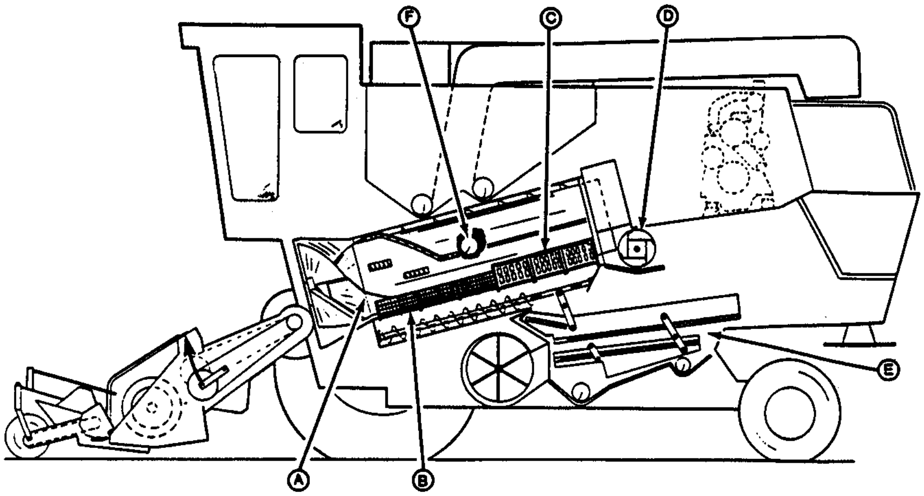


Figure 12.7 – An axial flow rotary combine utilizing a single rotor: (a) rotor, (b) threshing concave, (c) separating concave, (d) back beater, (e) cleaning shoe, (f) tailings return (courtesy of Prairie Agricultural Machinery Institute, Canada).

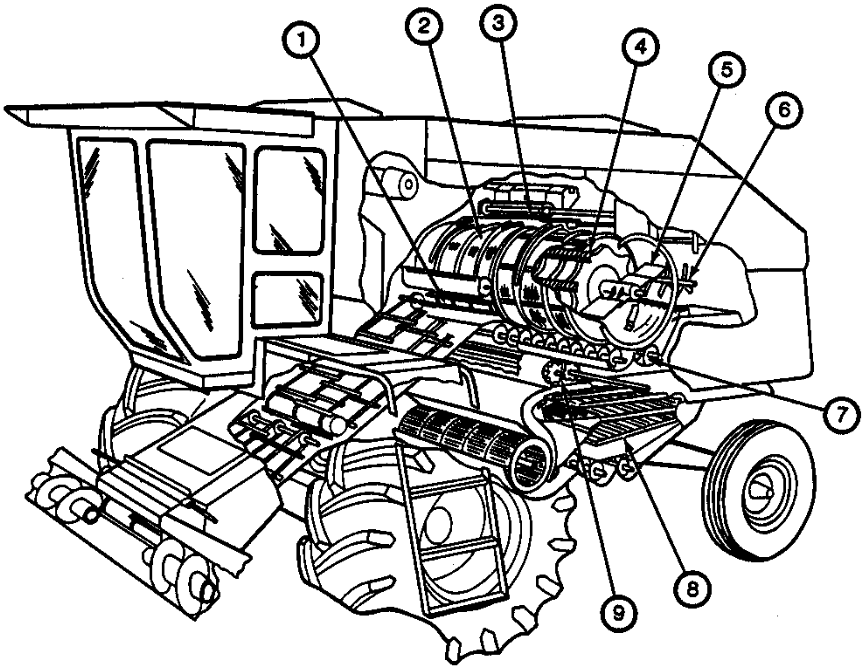


Figure 12.8 – A rotary combine utilizing a single transversely mounted rotor: (1) threshing concave, (2) cage, (3) cage sweeps, (4) rotor, (5) discharge paddles, (6) straw choppers, (7) distribution auger, (8) cleaning shoe, (9) accelerator rolls (courtesy of Prairie Agricultural Machinery Institute, Canada).

Combines that do not use the oscillating action of a straw walker use rotary action to accomplish threshing and separation, and are thus called *rotary combines*. Figure 12.6 is a diagram of a rotary or axial flow combine utilizing twin rotors. Figure 12.7 shows an axial flow single-rotor combine. In these combines, threshing and separation are performed by a rotor or a pair of rotors. The name *axial flow* is used because the axis of the rotor is parallel to the line of travel. The threshing cylinder is located transversely in some rotary combines, such as that shown in Figure 12.8, as well as in conventional combines.

12.1.2 Cutting and windrowing

Some crops that do not lend themselves to direct harvesting are better harvested by cutting and windrowing before threshing, separating, and cleaning. When the crop does not ripen evenly or (as in some northern climates) does not mature fully, cutting and windrowing allows for the crop to cure in the field before threshing. Some crops, such as edible beans, are cut below-ground and windrowed to avoid cutting bean pods.

Generally, cutting is accomplished by a cutterbar and windrowing is done by a draper. A draper is a flat horizontal belt that runs perpendicular to the line of travel. As the crop is cut by the cutterbar, it falls onto the draper and is carried to the side and

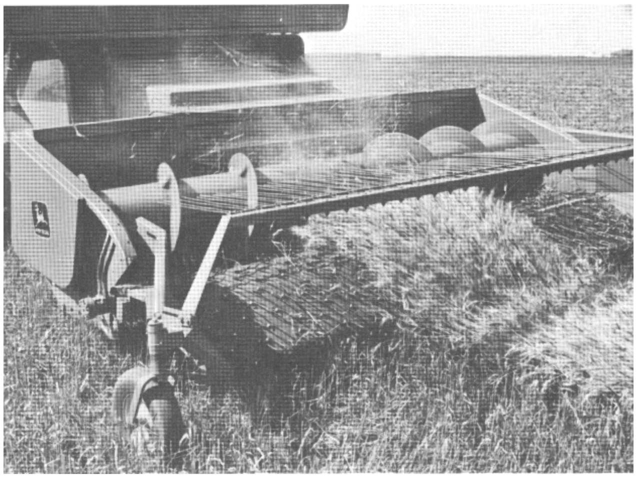


Figure 12.9 – A windrow pickup attachment and its operating principle (reproduced by permission of Deere and Co. © 1991).

dropped in a windrow. The crop material in a swath width is placed in a narrow windrow for the purpose of drying. If the crop was planted in rows, several rows are combined to form a windrow. The reel and cutterbar header is replaced by a pickup attachment in the combine as shown in Figure 12.9. The windrow is gently picked up by the pickup header and taken into the combine where the subsequent harvesting operations are completed.

12.2 FUNCTIONAL PROCESSES

A modern grain combine performs many functional processes. These are gathering and cutting (or in case of windrows, picking up), threshing, separation, and cleaning. Figure 12.10 shows a process diagram of a combine.

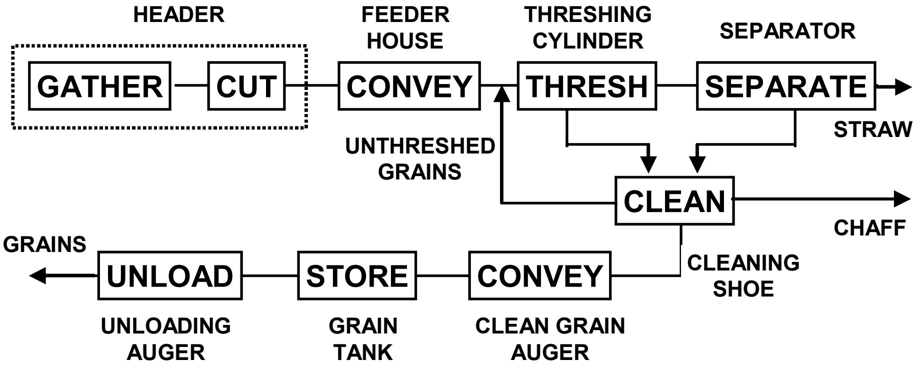
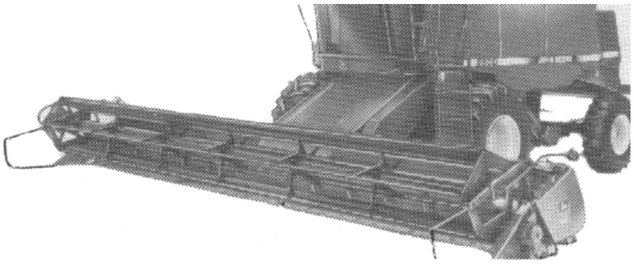
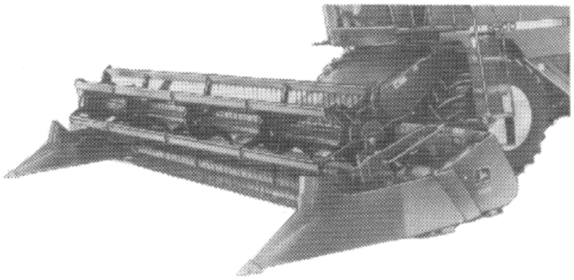


Figure 12.10 – Process diagram of a combine.



SLAT-TYPE REEL



PICKUP REEL

Figure 12.11 – Slat (or bat) and pickup reels (reproduced by permission of Deere and Co. © 1991).

12.2.1 Gathering, cutting, pickup, and feeding

12.2.1.1 Grain header

Mechanisms to gather and cut the crop are located in the *header*, which is also called the *cutting platform*. Slat-type (bat) and pickup reels, as shown in Figure 12.11, are commonly used for gathering most small grain crops. Pickup reels are used for lodged crops (crops that have fallen over due to heavy rains, winds, etc.), because they have fingers that reach into the lodged crops and help pick them up for cutting. The orientation of the fingers is controlled by either cam guides or a parallel bar mechanism.

Proper operation of the reel is critical to minimize header losses, which include shatter losses and cutterbar losses. Shatter losses are grain heads or pods that fall to the ground due to the action of the reel. Cutterbar losses are grain heads or pods that are cut by the cutterbar but fall to the ground. If the crop is windrowed, there are windrowing losses as well as combine gathering losses in the pickup and conveying operations. In direct-cut cases, all header losses are considered gathering losses.

Factors affecting header losses are (1) cutting height, (2) reel position with respect to the cutterbar, and (3) reel speed with respect to the forward speed.

For optimum combine operation the crop should be cut just below the grain heads. If the crop height is uneven or if the crop is lodged it may not be cut in some places, which will contribute to losses. Optimum reel position is determined by the crop height, amount of straw cut, and the condition of the straw. Normally, the reel should be set so the slats, when in their lowest position, will strike the straw 15 to 25 cm above and slightly ahead of the cutterbar. For lodged crops the reel should be set farther back. Proper reel speed is important to minimizing shattering and gathering losses. A reel turning too fast will result in excessive shatter loss, whereas too slow a speed will result in the cut grain head falling off the platform, a cutterbar loss.

It is recommended that the peripheral speed of the reel should be about 25% to 50% faster than the forward speed of the combine, or in other words, that the reel index be between 1.25 to 1.5. The reel index is defined as:

$$\text{Reel Index} = \frac{v_r}{v_c} \tag{12.1}$$

where v_r = peripheral speed of the reel

v_c = forward speed of combine

The reel is powered by either a V-belt drive or a hydraulic motor. Many manufacturers provide control of the reel speed from the operator's station. The position of the reel axis with respect to the cutterbar is adjustable and must be adjusted properly for satisfactory gathering operation. For example, in heavily lodged crops the reel is set well ahead of the cutterbar to improve lifting. Figure 12.12 shows the effect of reel position and reel index on cutterbar losses for slat and pickup type reels.

For most small grain crops the cutting is accomplished by a cutterbar consisting of oscillating knife sections that shear the crop stems. The cutterbar operation was discussed in detail in Chapter 11. To minimize cutterbar losses for crops with grains close to the ground a flexible cutterbar has been designed. The flexible cutterbar follows the ground profile across the width of cut for a uniform cutting height and minimum losses.

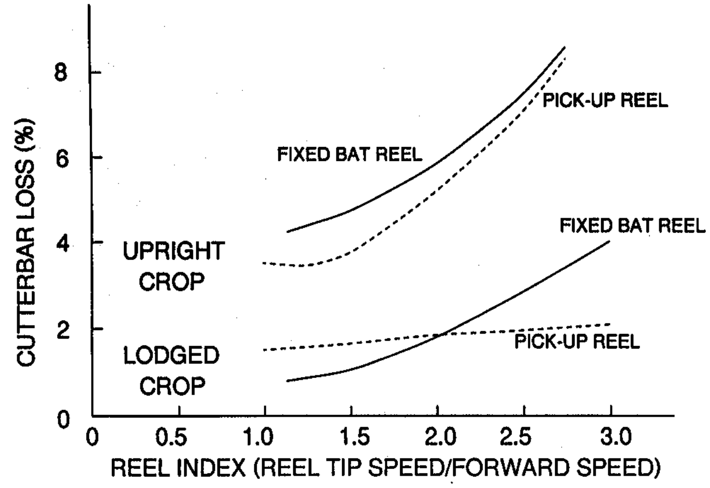


Figure 12.12 – Losses associated with reel adjustments (Wilkinson and Braumbeck, 1977).

12.2.1.2 Corn header

The gathering and cutting of seed corn is accomplished by a corn header, as shown in Figure 12.13. A corn header can harvest three to twelve rows at a time. The row spacing is designed to match the planter row spacing. During the operation, the gatherer points are positioned between the corn rows. The corn head on a combine primarily performs *gathering*, *snapping*, and *trash removal*. The gathering units are fitted with gathering chains equipped with finger links that assist in moving stalks into and through the snapping zone and prevent loose ears from sliding forward to be lost. When stalks are upright, the chain speed is adjusted to be approximately equal to the forward speed of travel.

The breaking of corn ears from stalks is called *snapping*. Snapping is performed by snapping rolls that grab the cornstalks and pull them between the snapping bars. The spacing between the snapping bars is such that the corn ears cannot go through. As corn ears reach the snapping bars they are snapped off and carried into the machine by the gathering chains, as shown in Figure 12.14. The entire cornstalk is pulled through, causing all ears to snap off.

One design of snapping rolls has fluted rollers (Figure 12.14). Straight-fluted rolls are more aggressive than spiral-ribbed rolls. Stripper plates located above the rolls prevent ears from contacting the rolls. Roll lengths of the fluted part are generally 40 to 60 cm and diameters are usually 9 to 12.5 cm. Because of their positive action, fluted rolls permit faster capacities and higher ground speeds.

Another design of snapping roll is referred to as a spiral-ribbed or spiral-lugged roll (Figure 12.15). As the name suggests, these rolls have spiral ribs on them. They are closer together than fluted snapping bars. The ears snap off as they reach the rolls and the spiral is such that the stalks move rearward. Roll lengths generally range from 1 to 1.25 m and the diameters from 7.5 to 10 cm.

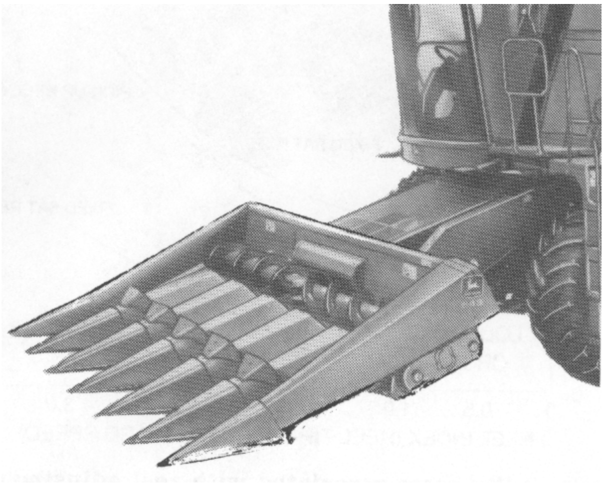


Figure 12.13 – A six-row corn header (reproduced by permission of Deere and Co. © 1991).

Peripheral speeds of snapping rolls are usually 180 m/min. Proper speed is important for adequate operation. Faster speeds result in shelling of cobs at the point of attachment to the stalk, while slower speeds result in stalk slippage and trash buildup on the rolls. It is also important to operate snapping rolls at a speed proportional to the forward speed of the combine. If the snapping rolls operate too slowly, the combine would run the stalks down before they are pulled through. Too high a velocity would cause the stalks to bounce off the snapping bars and fall to the ground. Roll spacing is also important to satisfactory roll operation. It is generally kept between 6 and 13 mm. Larger spacing may cause stalk slippage, and narrower spacing, stalk breakage.

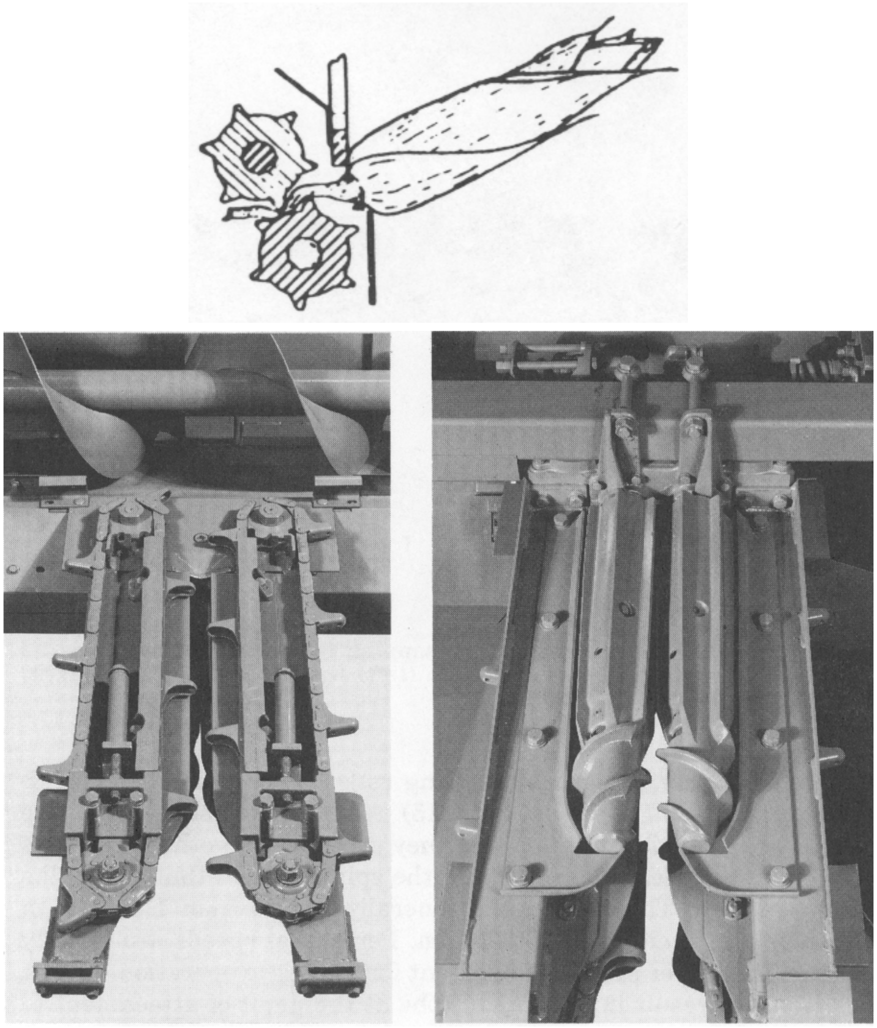


Figure 12.14 –Fluted snapping rolls of a corn header, showing operating principles. Top, reprinted from Wilkinson and Braumbeck (1977); bottom, from Kepner et al. (1978).

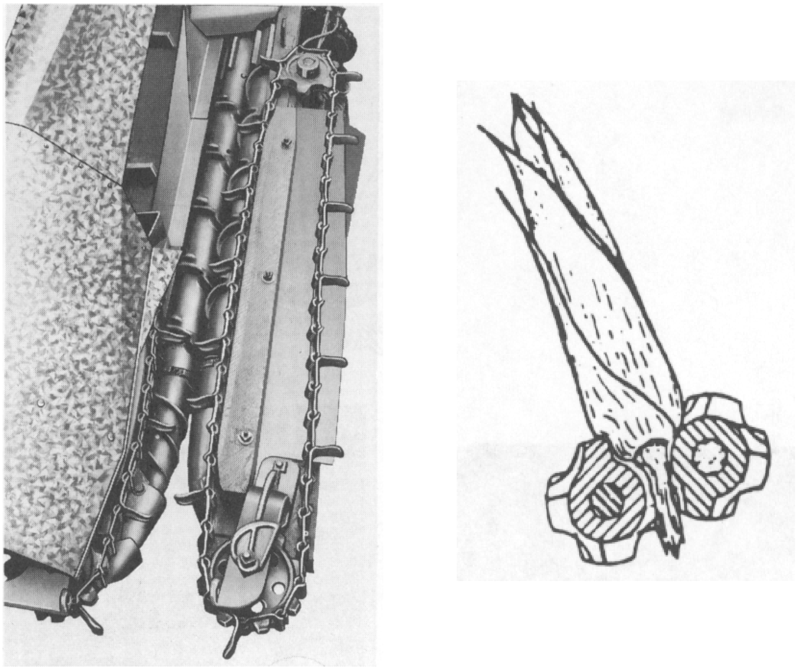


Figure 12.15 – Spiral-ribbed snapping rolls of a corn header, showing operating principles. Left, reprinted from Kepner et al. (1978); right from Wilkinson and Braumbeck (1977).

Special trash rolls are often provided on corn pickers to remove trash and broken stalks not expelled by spiral-ribbed snapping rolls. Fluted sections may be incorporated on the upper end of the snapping rolls as shown in Figure 12.16.

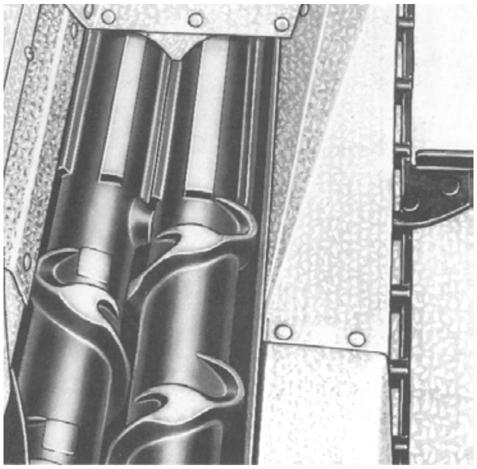


Figure 12.16 – Fluted trash rolls on the upper ends of snapping rolls (reprinted from Kepner et al., 1978).

12.2.2 Threshing

12.2.2.1 Threshing mechanisms

Threshing is accomplished by a rotating cylinder and a concave grate in both conventional and rotary combines. As the cylinder rotates, crop is forced through the gap between the concave and the cylinder and is subjected to impact and rubbing action that cause grains to be detached. In a rotary combine the crop flow is parallel to the axis of rotor, whereas in a conventional combine the crop flow is transverse to the axis of rotation.

In rotary (axial flow) combines, threshing cylinders are part of the separator. The front part of the rotor has helical rasp bars mounted at equal distance. The twin-rotor model has two helical bars mounted 180° apart (Figure 12.4). A single-rotor design has three helical bars with a staggered straight section between them (Figure 12.3). The rotor diameter for the twin-rotor is 43.2 cm; in the single-rotor design the diameter ranges from 61 to 76.2 cm. The crop takes a helical path while being threshed in a rotary combine. The rotor speed is less and the concave gap is higher than in conventional combines; that results in more thorough threshing with less damage under most harvesting conditions.

In conventional combines, there are three primary types of threshing cylinders and associated concaves: the rasp-bar cylinder and concave, the angle-bar cylinder and concave, and the spike-tooth cylinder and concave.

The *rasp-bar cylinder* consists of a number of steel bars that are mounted on several star-shaped hubs to form a cylinder. The hubs are mounted on a common shaft that is supported by bearings and driven by means of V-belts. The outer surfaces of the bars are corrugated. The concave is made of parallel bars that are held together by parallel curved bars as shown in Figure 12.17. As the cylinder rotates the crop is forced through the gap between the concave and the rasp bars, and is subjected to a combination of impact and rubbing action to accomplish threshing. The rasp-bar is most commonly used cylinder type because most crops can be threshed by the action it produces.

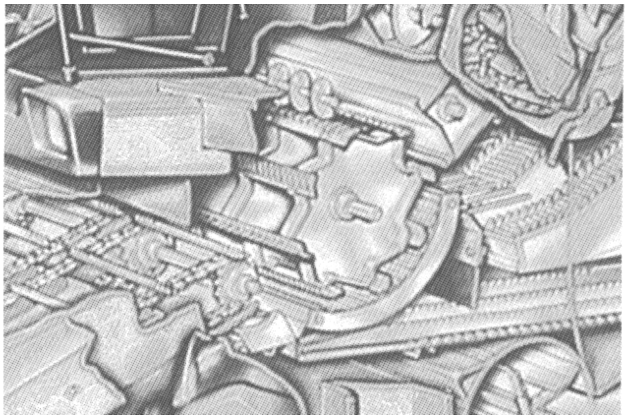


Figure 12.17 – Rasp-bar thresher
(reproduced by permission of Deere and Co. © 1991).

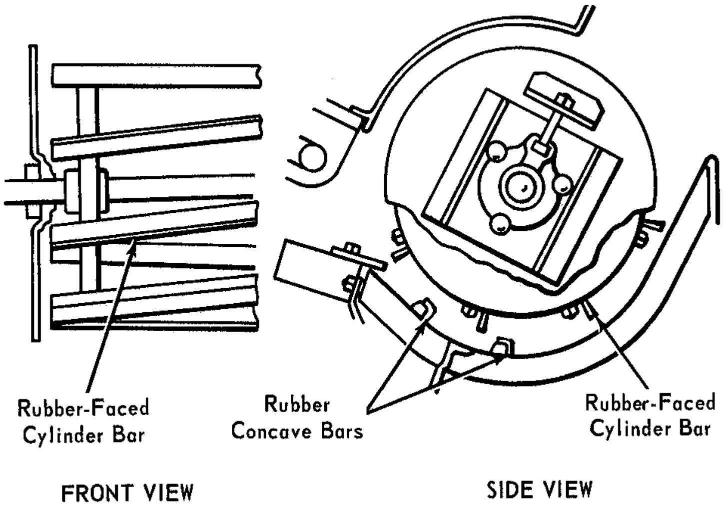


Figure 12.18 – An angle-bar threshing cylinder and concave (reproduced by permission of Deere and Co. © 1991).

The *angle-bar cylinder* is made of helical rubber-coated angle irons in place of rasp bars (Figure 12.18). The concave is also rubber-coated. The threshing action is primarily that of flailing that results in a gentler threshing action. The angle-bar design is commonly used for crops such as clover and alfalfa seed.

The *spike-tooth cylinder* has spikes on the bars in place of the rasps. The concave has matching spikes, as shown in Figure 12.19. The threshing action in this design is that of tearing and shredding. Compared to other cylinders, there is less damage to the grain. However, the tearing and shredding action has the undesirable effect of breaking up the straw that must be removed from the grain. Thus, the spike-tooth cylinder is used for rice, which has tough straw, and often for edible beans because beans are easily damaged.

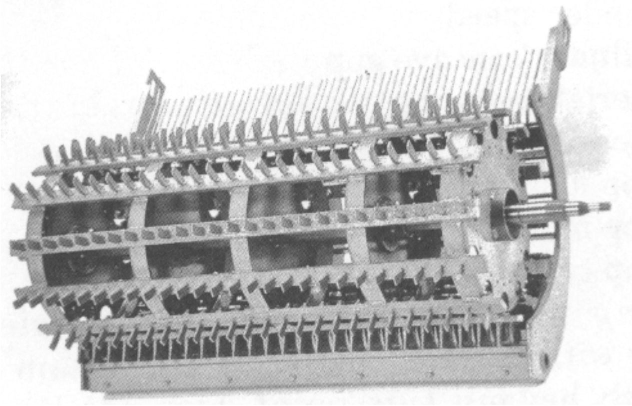


Figure 12.19 – A spike-tooth threshing cylinder and concave (reproduced by permission of Deere and Co. © 1991).

The threshing cylinders in conventional combines vary from 38 to 56 cm in diameter and rotate between 150 to 1500 rev/min. The cylinder speed is determined by the crop type and condition. Wet, hard-to-thresh conditions require higher speeds, but grain damage increases as cylinder speed is increased. Another factor affecting the quality of threshing is the cylinder-concave gap. If the gap is too large, the crop is not threshed completely. Too narrow a gap results in excessive power and grain damage. The length of the threshing cylinder is proportional to the width of the combine header. Multiple threshing cylinders arranged in series have been utilized to thresh edible beans and peanuts. Each successive cylinder rotates at a higher speed.

12.2.2.2 Threshing performance

The performance of threshing mechanisms is measured by threshing efficiency, separation efficiency, the amount of grain damage and the amount of straw breakup. Threshing performance parameters are affected by the following factors:

- Design factors: cylinder diameter, concave length, number of rasp bars;
- Operating parameters: cylinder speed, cylinder-concave gap, material feed rate;
- Crop condition: crop moisture content, crop maturity, crop type.

Threshing efficiency is the percentage of the threshed grains calculated on the basis of the total grains entering the threshing mechanism. It increases asymptotically with concave length up to a certain point. Increasing concave length beyond this point does not increase threshing efficiency and might even decrease it under certain conditions. However, experiments show that under easy threshing conditions there is little advantage of increasing the concave length beyond 33 cm (Arnold, 1964). Increasing the diameter of the conventional threshing cylinder increases threshing losses at a rate of about 0.9% for each 7.5 cm increase in the diameter. The number of rasp bars and their spacing do not seem to have any affect on the threshing efficiency. Cylinder speed is one of the most important variables affecting threshing losses. For hard-to-thresh crops and/or conditions, threshing losses can be significantly reduced by increasing the cylinder speed. In one set of experiments increasing the speed from 23 to 33 m/s reduced losses from 8% to 4%. The cylinder-concave gap affects threshing losses adversely. An increase of $^1/_8$ in. increased the unthreshed loss from 0.6% to 2.0%. Changing the concave clearance ratio (the ratio of the gap at the front to that at the rear of the cylinder) is done to facilitate crop feeding into the cylinder, but the effect of this variable on the threshing efficiency is not consistent.

Threshing losses increase with material feed rate, which is generally expressed in terms of tons/h of material-other-than-grain (MOG). The other ways of expressing material feed rate are grain feed rate and total feed rate. Threshing losses also increase with the MOG-to-grain ratio. Moisture content also affects threshing efficiency. Generally, the crop becomes hard to thresh at higher moisture content and as a result the threshing losses become higher. Also, if the crop is not fully mature and if there is a lot of green material in the crop, threshing becomes difficult and losses increase.

The *separation efficiency* of the threshing cylinder is defined as the percent of grains separated through the concave grate of a conventional combine, or at the threshing part of a rotary combine, to the total grain in the crop entering the threshing mechanism. A major portion of the total grain separation is done at the threshing

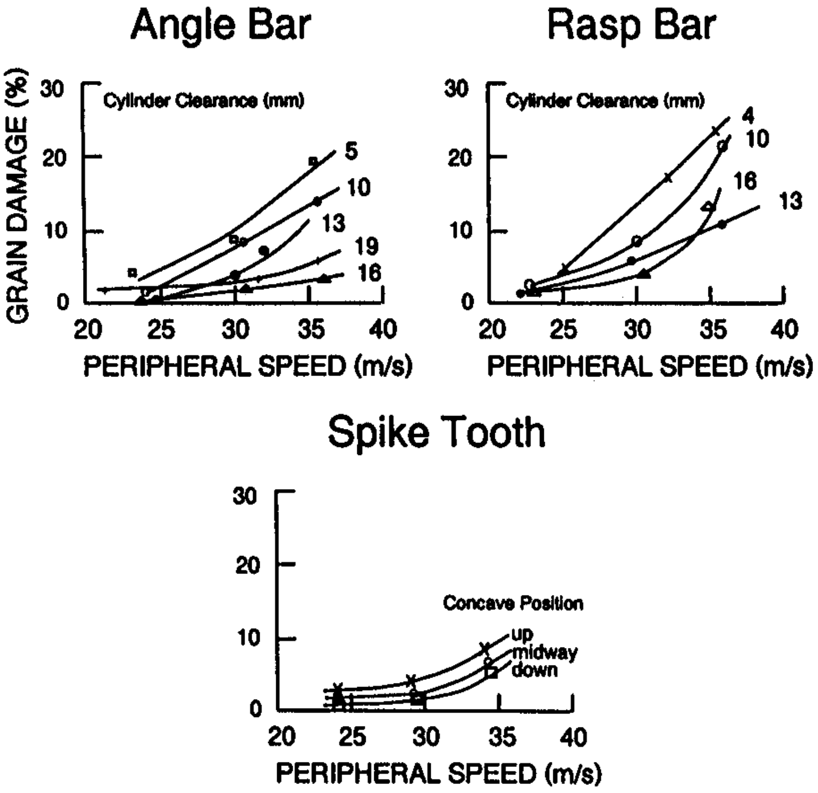


Figure 12.20 – Effect of cylinder speed and clearance on visible damage to barley having a moisture content of 12% to 15% (redrawn from Wilkinson and Braumbeck, 1977).

cylinder, and a high cylinder separation efficiency generally translates into higher separation and cleaning efficiencies of the combine. Cylinder separation efficiency varies from 60% to 90%. Increasing the concave length increases the separation efficiency but at a diminishing rate. Grain separation increases with cylinder speed. The number of rasp bars has little effect, while increasing the cylinder diameter or the cylinder-concave clearance tends to reduce the separation efficiency. Increasing the feed rate has a negative effect on the separation efficiency.

Grain damage refers to mechanical damage to grain during the process of threshing. It includes broken kernels, kernels with skin damage, and kernels with internal damage. Mechanical damage to grain results in poor germination, poor storability, and poor processing characteristics. There are many methods of measuring grain damage, including visual inspection of a sample of grain, sieving through a standard sieve, and germination testing. Cylinder speed has the most profound effect on grain damage during threshing, as increasing cylinder speed increases damage exponentially. Increasing concave length tends to increase grain damage slightly. Increasing cylinder diameter and cylinder concave gap reduces grain damage. Increasing feed rate provides more cushioning that may reduce grain damage. The effect of cylinder type, cylinder speed, and clearance on visible damage to barley is given in Figure 12.20. Increasing grain moisture increases grain damage, however at very low moisture content the kernels tend to crack and increase grain damage. For shelling corn the optimum moisture content was reported by Byg (1968) to be around 20%.

Excessive *straw breakup* during threshing results in an increased load on the cleaning shoe, which causes additional cleaning losses. Increased straw breakup also increases power requirements of the threshing cylinder.

Figure 12.21 shows the effect of the various factors, except for straw breakup, on threshing performance of a combine. Typical cylinder threshing speeds and concave clearances are given in Table 12.1.

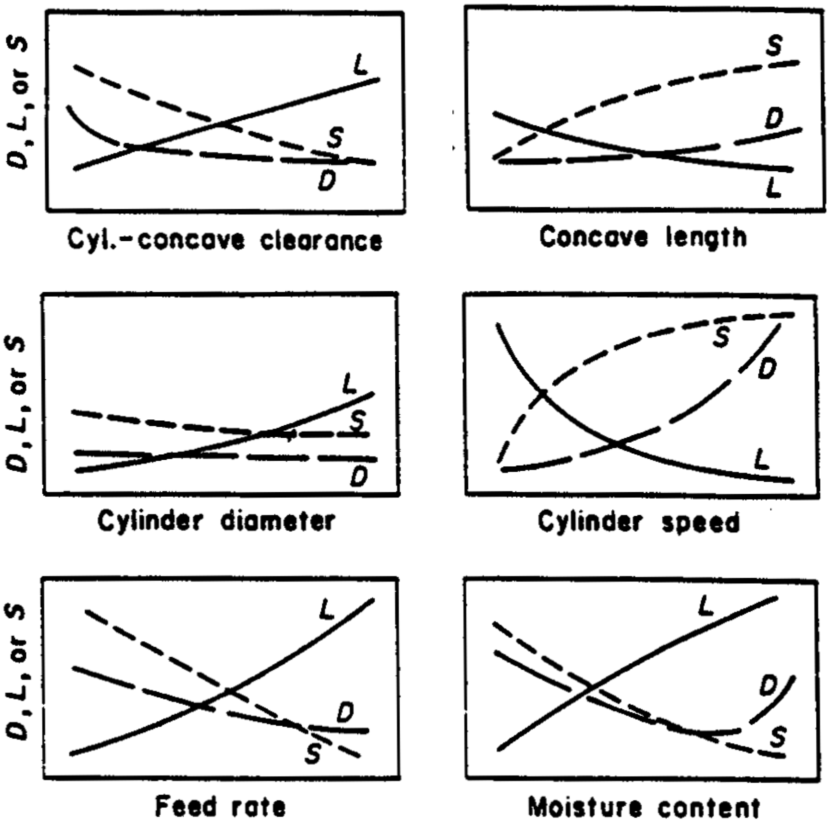


Figure 12.21 – Graphical characterization of some of the performance relations for a rasp-bar cylinder with an open-grate concave. L = cylinder loss; D = grain damage; and S = percent of grain separated through concave grate (Wieneke, 1964).

Table 12.1 Typical cylinder peripheral speeds and clearances for various crops (Kepner et al., 1978)

Crop	Peripheral Speed (rasp-bar or spike-tooth), m/s	Mean Clearance (rasp-bar cylinders), mm
Alfalfa	23–30	3±10
Barley	23–28	6–13
Edible beans	8–15	8–19
Beans for seed	5–8	8–19
Clovers	25–33	1.4–6
Corn	13–22	22–29
Flax	20–30	3–13
Grain sorghum	20–25	6–13
Oats	25–30	1.5–6
Peas	10–15	5–13
Rice	25–30	5–10
Rye	25–30	5–13
Soybeans	15–20	10–19
Wheat	25–30	5–13

12.2.3 Separation

12.2.3.1 Separation mechanisms

Grain separation in combines refers to the separation of grains from straw after threshing. A large percentage (70% to 90%) of grains are separated during the threshing process. Two types of grain separators are commonly used in combines: conventional combines use straw walkers and rotary combines use rotary separators.

Straw walkers consist of several long channel sections mounted on a crankshaft. As the shaft turns the channel sections follow an elliptical or circular path that causes the straw to bounce on top of the channels and move toward the rear of the combine due to the design of the sawtooth shape of the top of the channel sections. The oscillating action causes the grains and some chaff to be sifted down and be separated from the straw. There are three to eight sections in a combine depending upon its size. The sections are about 20 to 30 cm wide and the crank throw is about 5 cm. It rotates at approximately 200 rev/min. Figure 12.22 shows the straw walker movement. The crankshaft used to create the oscillatory action of the channel sections is shown in Figure 12.23.

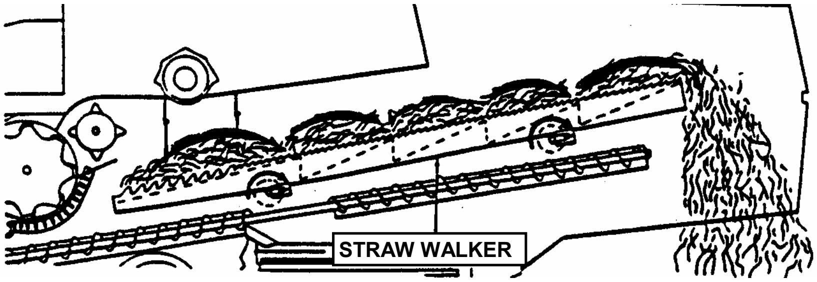


Figure 12.22 – Straw walker action in a conventional separator, side view (reproduced by permission of Deere and Co. © 1991).

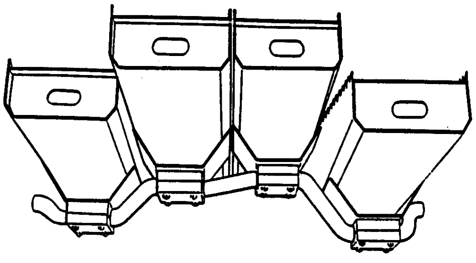


Figure 12.23 – Straw walkers and the driving crankshaft, end view (reproduced by permission of Deere and Co. © 1991).

Rotary separators. The main force causing the grain to move through a mat of straw is the centrifugal force caused by rotation of the straw mat by the rotor, as compared to the gravity force in the straw walkers. The rotor, which rotates inside of a stationary cylindrical screen, generates a centrifugal force field which is several times that of gravity. The paddles mounted on the rotor surface cause the crop to take a helical path in the annular space defined by the rotor and the screen. In rotary separators the crop motion is forced rather than induced (as in the case of straw walkers). This results in higher capacity per unit grate area, but requires higher power. Since the separation is not gravity dependent, irregularity of the ground surface has no effect on the separation process. Figure 12.24 shows a rotary separator that utilizes two rotors. The diameter of the front feed section of the rotor is 464 mm and the separator section is 502 mm providing a total separation area of 1.2 m^2. The rotors turn at 700 rev/min.

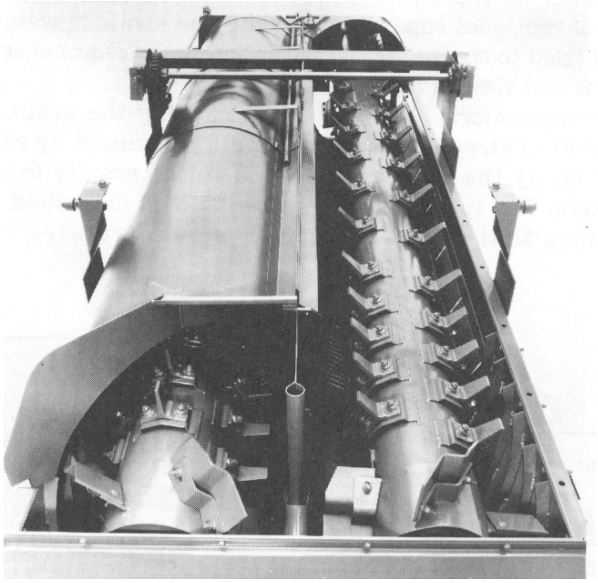


Figure 12.24 – A cylinder and tine rotary separator (courtesy of Deere and Co.).

12.2.3.2 Theory

The grain separation theory presented here is based on the research conducted by Gregory and Fedler (1987). They compared grain movement through a mat of straw with the process of diffusion to develop a separation model. The model, based on Fick's Law, is given as follows:

$$Q_g = -D\frac{A}{L_d}(C_2 - C_1) \tag{12.2}$$

where Q_g = volumetric grain flow rate, m^3/min
A = cross-sectional area, m^2
D = coefficient of diffusion, m^2/min
C_2 = concentration of grain on straw walkers
C_1 = concentration of grain below straw walkers
L_d = length through which diffusion is occurring, m

For the straw walker, the grain flow rate is defined as the change in grain volume with time. The grain concentration under the straw walker is zero. The above equation becomes:

$$\frac{dV_g}{dt} = -D\frac{A}{L_d}(C_2 - C_1) \tag{12.3}$$

where V_g = volume of grain on straw walker, m^3
t = time, s

The concentration of grain, C_2, on the straw walker is defined as the volume of grain divided by the total volume of material. Since the grain is contained in the volume of MOG, the total volume is equal to the volume of MOG. The area is defined in terms of the width and length of the straw walker. Equation 12.3 is then expressed as:

$$\frac{dV_g}{dt} = -D\frac{WL}{L_d}\left(\frac{V_g}{V_{MOG}}\right) \tag{12.4}$$

where W = width of separator area, m
L = length of separator area, m
V_{MOG} = volume of material-other-than-grain on the straw walker

The equation after rearranging and integrating becomes:

$$\ln\left(\frac{V_{gf}}{V_{gi}}\right) = -D\left[\frac{W\,L}{L_d V_{MOG}}\right]t \tag{12.5}$$

Taking the exponential of both sides of the above equation gives:

$$\frac{V_{gf}}{V_{gi}} = e^{-[DWL/(L_d V_{MOG})]t} \tag{12.6}$$

The grain volume can be replaced by grain mass divided by grain density. The above equation is rewritten in terms of grain masses as follows:

$$\frac{G_f}{G_i} = e^{-[DWL/(L_d V_{MOG})]t} \tag{12.7}$$

where G_f = final grain mass, kg
G_i = initial grain mass, kg

Replacing V_{MOG}/t by the MOG feed rate divided by MOG density:

$$\frac{G_f}{G_i} = e^{\left[DW\rho_{MOG}/\left(L_d \dot{m}\right)\right]L} \tag{12.8}$$

where ρ_{MOG} = bulk density of MOG, kg/m^3
$\dot{m}$ = MOG flow rate, kg/min

If all the variables, except for L, in the exponent on the right hand side of the above equation were held constant (= K_L) the resulting equation will be a decaying function of straw walker length as shown below. The values of K_L were found to be dependent on the MOG feed rate.

Reed et al. (1974) and Wang (1987) studied grain straw separation in conventional and rotary combines. They found that grain separation is an exponential function of the separator length as shown in Figures 12.25 and 12.26. Reed suggested the following relationship for grain loss in a conventional combine:

$$GL = e^{-bL} \tag{12.9}$$

where GL = grain loss
b = constant
L = straw walker length

Comparing Equation 12.8 with 12.9, we find that the two equations are identical and that K_L has the same meaning as b. Therefore, K_L may be determined using the data reported by Reed. The separator efficiency is determined by subtracting the grain loss from one and expressing the number in percentage. The walker length corresponding to 50% efficiency is determined as follows:

$$0.5 = e^{-bL_{0.5}}$$

or

$$\ln(0.5) = -bL_{0.5}$$

or

$$b = \frac{0.693}{L_{0.5}} \tag{12.10}$$

The value of b can be determined from the data given in Figure 12.25. It depends on the MOG feed rate and MOG/grain ratio. The following relationship was developed to estimate the value of b:

$$b = 648.4\,\dot{m}^{-1.296}\left(\frac{MOG}{Grain}\right)^{-0.662} \tag{12.11}$$

where $\dot{m}$ = MOG feed rate, kg/min
MOG/Grain = MOG-to-grain ratio in the crop

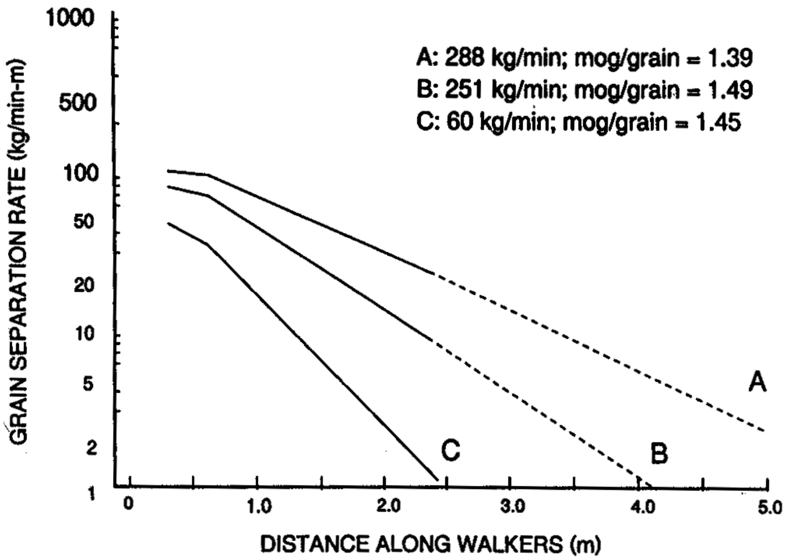


Figure 12.25 – Distribution of grain separated along straw walkers at three different feed rates. The number at each foot interval indicates the percentage of total separated at that foot of length (redrawn from Reed et al., 1974).

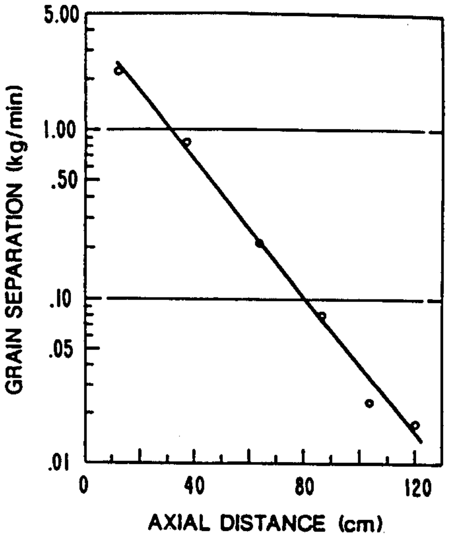


Figure 12.26 – Typical separation distribution along and beneath the central region of the threshing and separation concave of a rotary combine in wheat (Wang et al., 1987).

Example 12.1

A combine fitted with a 2.44 m long straw walker is harvesting wheat at a MOG feedrate of 9 t/h. The MOG/grain ratio is 0.8. Determine the expected grain loss from the separator. Assume that 75% of the grain was separated at the cylinder concave.

Solution

The grain loss is determined from Equation 12.9. Estimate the value of b from Equation 12.11 as follows:

$$b = 648.4\ (150)^{-1.296}\ (0.8)^{-0.662} = 1.137\ \text{m}^{-1}$$

Substituting in Equation 12.9 we get:

$$\text{grain loss} = e^{-1.137(2.44)} = 0.0624 \quad \text{or approximately } 6\%$$

Since only 25% of the total grain reaches the separator, 6% of which is lost, the grain loss on the total grain basis would be 0.25 × 0.06 = 0.015 or 1.5%. This is a reasonable amount for separation loss.

12.2.3.3 Separation performance

The performance of the separator is measured in two ways: *walker efficiency*, measured in percent grain loss, and *walker capacity*, measured in tons/h of MOG feed rate corresponding to a given grain loss (usually 1% to 2%). The *walker efficiency* is calculated by dividing the amount of grains separated by the amount of grains entering the separator and expressed as percentage. The amount of grain still in the straw as it leaves the combine is considered the separator loss. This method is preferred for comparing the separation performance of different combines.

The separation performance parameters for conventional combines are affected by the following factors:

- Design factors: walker length, crank throw and speed;
- Operating parameters: material feed rate, walker slope;
- Crop properties: grain-to-MOG ratio, crop physical and mechanical properties.

Effect of design factors. The effect of separator length on the performance has been presented earlier. The size and speed of straw walker crank are designed to obtain an optimum combination of the straw agitation and crop throughput rate. Increasing the crank throw would increase the agitation but at a higher power requirement. Increasing the speed would increase the throughput rate but may not allow all grains to sift out before the straw escapes through the rear of the combine.

Effect of operating parameters. Increasing the MOG feed rate of the crop increases grain loss exponentially. A reasonable balance between capacity and grain loss has to be maintained. Figure 12.27 shows the effect of uphill and downhill ground slope on the separator performance; downhill slope results in better performance. Hill

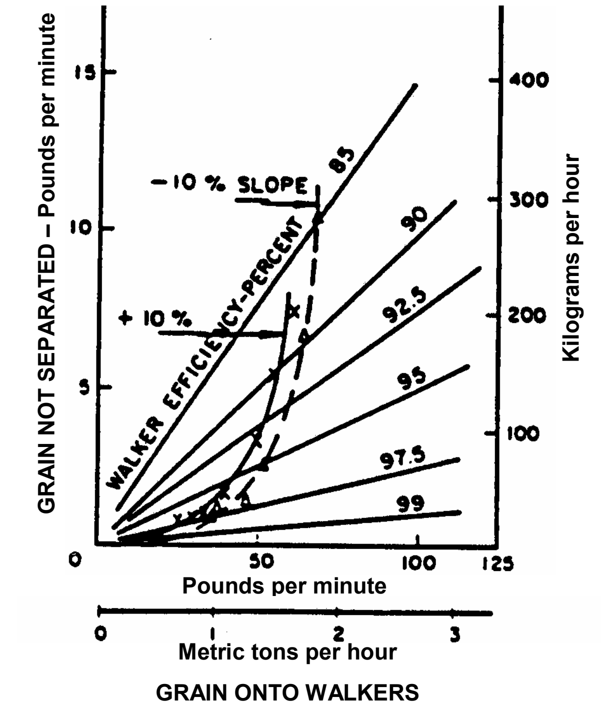


Figure 12.27 – The effect of 10% slope on walker efficiency (Reed et al., 1974).

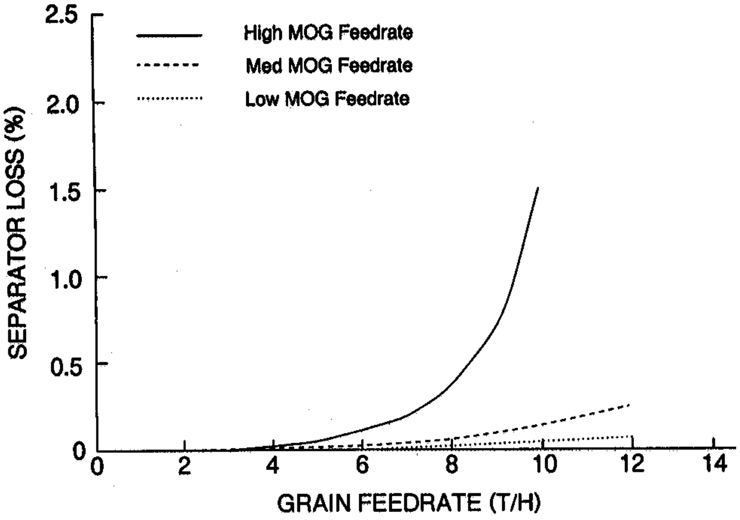


Figure 12.28 – Typical effect of MOG/G ratio on straw walker loss for wheat crop (redrawn from Hill and Frehlich, 1985).

and Frehlich (1985) reported that as the MOG/grain ratio increases, separator losses increase somewhat exponentially in wheat and barley as shown in Figure 12.28. In wheat, reducing the MOG/grain ratio from maximum (1.2) to medium (0.85) reduced the average straw walker losses from 0.73% to 0.48%. Reducing the MOG/grain ratio from 1.2 to 0.64 reduced losses to less than 0.3%. This suggests that an accurate header height control to cut the stalks just below the grain heads would improve separator performance.

Effect of crop properties. Srivastava (1990) reported that grain bulk density, grain angle of repose, and straw bulk density are related to separator performance while harvesting wheat and barley. Increasing grain density increases separator capacity while increasing the grain angle of repose has the opposite effect. Higher straw density reduces separator capacity.

12.2.4 Cleaning

Cleaning refers to the final separation of grain from other crop material, which consists mainly of chaff and broken straw pieces. The grain separated at the threshing cylinder and the separation unit is combined on an oscillating conveyor or a set of augers that feed the mixture of grain and chaff to the cleaner, often referred to as the *cleaning shoe*.

12.2.4.1 Cleaning mechanisms

A common cleaning shoe arrangement is shown in Figure 12.29. The separation is accomplished due to aerodynamic and mechanical actions. The cleaning shoe design consists of two or three oscillating adjustable-opening sieves and a paddle-type fan to blow air through the sieve openings. The crop is dropped on the top sieve *(chaffer sieve)* near the front of the shoe. The chaff gets blown off by the air and the grain falls through the openings onto the lower sieve *(cleaning sieve)*. The process is repeated once more as the clean grain passes through to the *clean grain auger* and conveyed to the *grain tank*. The separation occurs due to difference in the terminal velocities of grain and chaff material. For example, the terminal velocity of wheat, oat, and barley

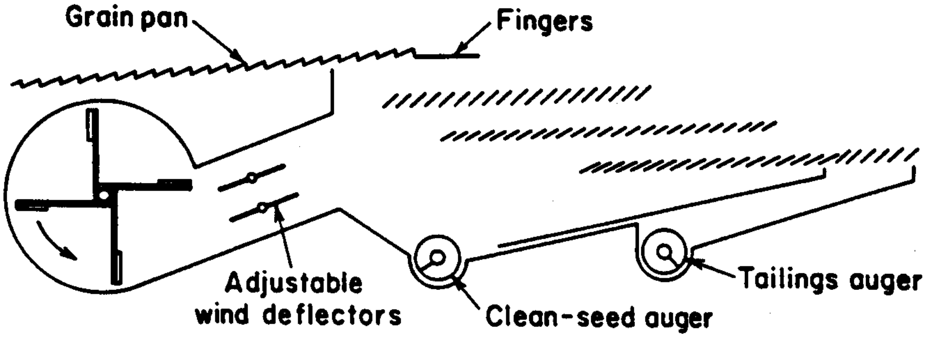


Figure 12.29 – A schematic diagram of a cleaning shoe showing an auger bed for feeding the grain-chaff mixture.
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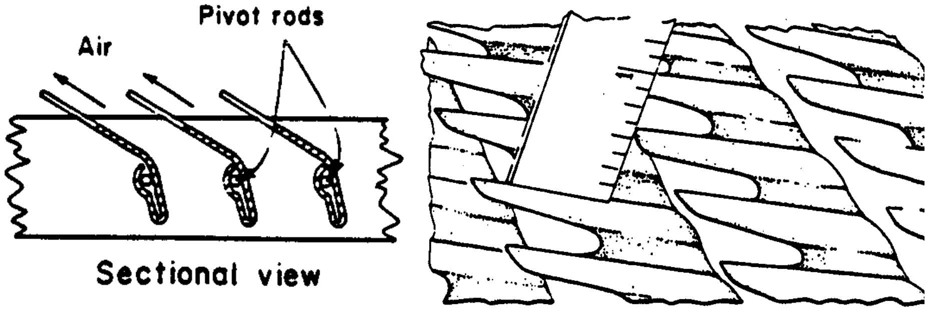

Figure 12.30 – An adjustable chaffer sieve (reprinted from Kepner et al., 1978).

grains range from 5 to 10 m/s whereas the terminal velocity for short pieces of straw is from 2 to 6 m/s and from 1.5 to 2.5 m/s for chaff.

The two sieves may oscillate in the same direction or opposite to each other for better balance. The rate of oscillation varies from 250 to 325 cycles per minute. The sieve area depends on the width of the threshing cylinder. Generally, the chaffer sieve area varies from 114 to 147 cm^2 per cm of the cylinder width for models having two sieves. Figure 12.30 shows the adjustable opening sieve design. The lips rotate to open or close the openings. The bottom sieve has smaller openings. For small grain the bottom sieve is replaced by round-hole sieve. The unthreshed grain that is too small to go through the sieves and too heavy to be blown off by the fan is commonly referred to as the *tailings*. The tailings travel on top of the chaffer towards the rear of the combine due to the oscillations and are collected by an auger and conveyed to the threshing cylinder for rethreshing.

Rotary combines utilize the same cleaning shoe design as conventional combines. There are augers placed longitudinally under the rotor to carry the grain-chaff mixture to an oscillating grain pan that feeds the mixture to the cleaning shoe. Some rotary designs create air flow through the rotor to remove chaff. This may be considered a form of pre-cleaning.

12.2.4.2 Theory

To understand the theory that applies to the cleaning shoe it would be worthwhile to examine what happens to the crop material during the process of cleaning. The mixture of grain, chaff, and small pieces of straw falls from the oscillating grain pan or an auger bed on to the front part of the chaffer sieve. As the mixture falls, a blast of air is directed at about a 45° angle towards the rear of the combine. The air velocity is such that it carries most of the chaff with it while the grain and some chaff fall on the chaffer sieve. The remaining mixture of crop material is subjected to air movement as well as mechanical oscillations. The mat of crop material moves towards the rear of the combine on the chaffer sieve due to the oscillations. The air moving through the mat causes the mat to lose chaff as it is carried by the air stream while the grain sifts down through the mat of chaff and small pieces of straw due to gravity and passes through the openings in the chaffer. The grain and a small fraction of chaff fall on the cleaning sieve where the process is repeated.

Thus, the theoretical principles applicable to the cleaning process are (1) aerodynamic separation based on the terminal velocities, (2) movement of the crop material on the chaffer, (3) movement of the grain through the mat, and (4) escape of the grain through the openings in the chaffer. *Aerodynamic separation* is based on the pneumatic conveying of chaff and straw which in turn depends upon the terminal velocities and the drag coefficients of the different components in the crop mixture. The crop movement on the chaffer is based on the theory of oscillating conveyors. Grain motion through the chaff and straw mat is due to gravity and the resistive force caused by the straw mat. The escape of grain through the sieve opening is based on the theory of sieving which is based on the theory of probability.

Aerodynamic model. The *aerodynamic model*, based on the research reported by Rumble and Lee (1970) on aerodynamic separation, is presented here. This model applies to the separation process that occurs as the crop falls from the grain pan and is subjected to an air blast and as it moves over the upper screen. The following assumptions apply:

1. The drag coefficient is independent of the air velocity.
2. The particles are accelerated as free bodies and not as a mat.
3. The velocity of air through the upper screen is constant.
4. Air flow above the upper screen is streamlined parallel to the orientation of the chaffer lips.

Summing forces acting on the particles in the vertical direction we get:

$$m\,a = F_g - F_d \tag{12.12}$$

where m = particle mass, kg
a = particle acceleration, m/s^2
F_g = force of gravity acting on the particle, N
F_d = aerodynamic drag acting on the particle, N

The aerodynamic drag force is expressed as:

$$F_d = C_d v_y^2 \tag{12.13}$$

where C_d = drag coefficient
v_y = relative velocity between the particles and air in the vertical direction, m/s

At terminal velocity the drag force equals the weight of the particles, or:

$$F_d = m\,g = C_d v_t^2 \tag{12.14}$$

where v_t = terminal velocity of the particle.

From the previous two equations the drag force can be computed as follows:

$$F_d = m\,g\left(\frac{v_y}{v_t}\right)^2 \tag{12.15}$$

Substituting Equation (12.15) in (12.12) the following equation is obtained:

$$\frac{d^2y}{dt^2} = g - g\left(\frac{v_y}{v_t}\right)^2 \qquad (12.16)$$

Acceleration in the horizontal direction is given by:

$$\frac{d^2x}{dt^2} = g\left(\frac{v_x}{v_t}\right)^2 \qquad (12.17)$$

where v_x = velocity of the particles relative to the air in the horizontal direction. Note that v_x and v_y are $dx/dt - v_{ax}$ and $dy/dt - v_{ay}$, respectively, where v_{ax} and v_{ay} are the horizontal and the vertical components of the air velocity.

The above two equations are non-linear and require numerical solution. The equations were solved using an analog computer by Rumble and Lee (1970). The solution was obtained in two parts. The first part was related to the free fall of the particles from the grain pan and the second part consisted of the particle motion on the chaffer. The vertical motion would come to a stop when the particles reached the chaffer sieve. After the particles fall 17.78 cm (7 in.), the second condition applies. It was considered, based on the experimental studies, that excessive loss would occur if the grain travelled 7.62 cm (3 in.) towards the rear of the combine without landing on the chaffer. Using this as the criterion, they developed the results as shown in Figure 12.31. The horizontal axis is the initial downward velocity of the grain. If the initial downward velocity is too low grain would travel farther toward the rear and will end up in grain loss. Very high values would result in excessive chaff landing on the screen which will also result in the grain loss. An optimum zone is shown in the figure.

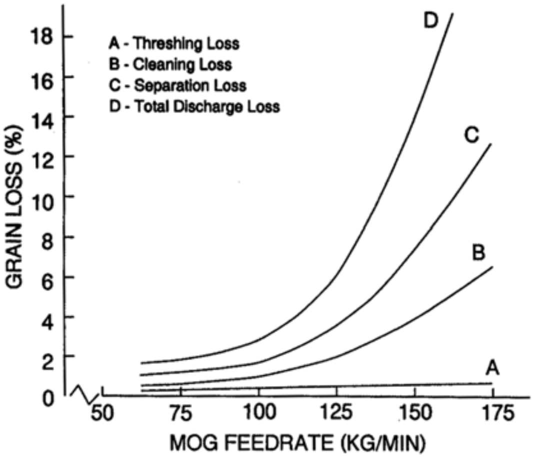

Figure 12.31 – Computer-simulated results of a cleaning shoe showing the combination of grain and air velocity for acceptable performance (redrawn from Rumble and Lee, 1970).

12.2.4.3 Cleaning performance

The performance of a cleaning shoe is expressed in terms of (1) grain loss or cleaning efficiency, (2) cleaner capacity, and (3) grain dockage. *Grain loss* is calculated by determining the percentage of lost grain on the basis of the total grain entering the cleaning shoe. The *cleaning efficiency* is the percentage of grain recovered by the shoe. The *cleaner capacity* is determined by first plotting a curve of grain loss against the material other than grain (cleaner MOG) feed rate passing through the cleaning shoe. A curve is fitted to the data, usually an exponential function, and the capacity of the cleaning shoe is determined corresponding to a given grain loss level. *Grain dockage* is the amount of chaff that is separated with grain. It is determined by taking a sample of grain from the grain tank of the combine and cleaning the sample to determine the percentage of chaff in the sample.

The cleaning shoe performance is affected by the following factors:

- Design factors such as sieve size, oscillation amplitude and frequency.
- Operating conditions including material feed rate, cleaning shoe slope, air flow, and chaffer openings.
- Crop properties including grain to MOG ratio, chaff and grain properties.

Design factors. Longer sieves would allow longer dwell time for more complete separation of grain. However, physical considerations limit the size of the cleaning shoe. Studies have indicated that the initial sieve length does not contribute much to the cleaning action. A cascade arrangement permits a more complete cleaning while keeping the length of the sieves short. The frequency and the amplitude determine the level of acceleration imparted on the crop. This determines the level of agitation necessary to provide the least resistance to grain separation. The material flow rate is also determined by these parameters. German and Lee (1969) reported on the effects of the frequency of oscillation on the shoe performance. The range of frequencies used were 260 to 460 cpm. Increasing the frequency of oscillation at 90 kg/min input rate reduced the grain loss significantly. However, they did not recommend increasing the frequency because of the increased mechanical vibrations.

Operating conditions. German and Lee (1969) also studied the effect of air volume on cleaning performance. The air volume has to be matched with the feed rate. They developed a relationship between the air volume and the debris found in the grain sample as follows:

$$Z = 2 - 50\times10^{-6}V + 0.4\times10^{-9}V^2 \tag{12.18}$$

where Z = amount of debris, kg/min

V = air flow rate, m^3/min

Bottinger and Kutzbach (1987) reported on the effect of fan speed and feed rate. Their results are shown in Figure 12.32. As shown in the figure, the grain loss increases somewhat exponentially with the fan speed and feed rate. Nyborg et al. (1969) found that the cleaning losses increase with MOG feed rate and with grain/straw ratio. The results are shown in Figure 12.33. As shown in the figure, the effect of feed rate becomes more significant at high grain/straw ratios and vice versa. Increasing the lip angle from 30° to 36° reduced grain loss according to a study reported by Lee and Winfield (1969). The lip angle effect is highly dependent on other factors such as the material feed rate.

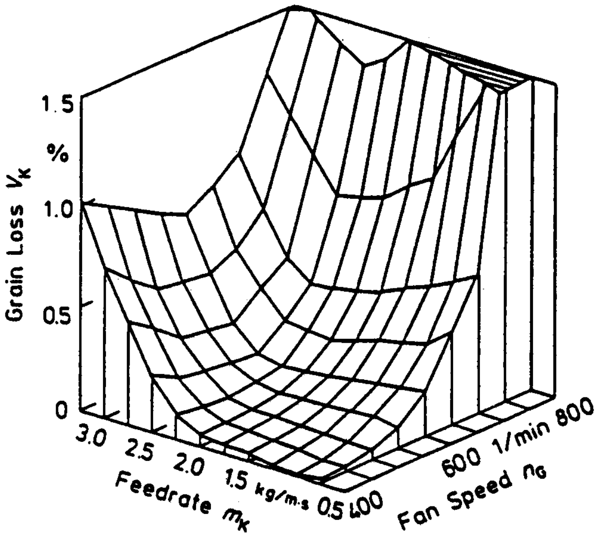

Figure 12.32 – Performance characteristics of a cleaning shoe (Bottinger and Kutzbach, 1987).

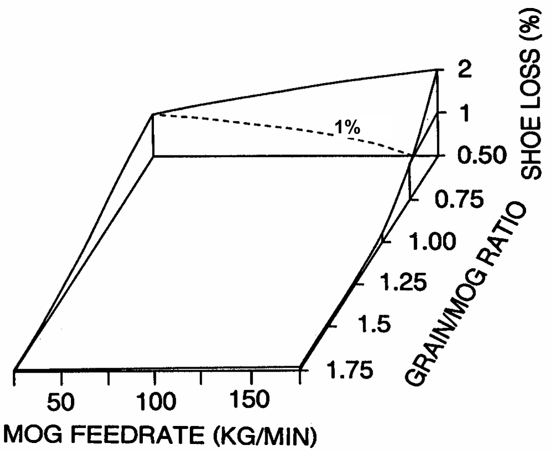

Figure 12.33 – Shoe-loss surface for a standard combine in wheat (Nyborg et al., 1969).

Crop properties. Srivastava et al. (1990) studied the effect of chaff and grain properties of wheat and barley on the capacity of the cleaning shoe. They found that the grain angle of repose had a negative effect on the cleaner capacity. Increasing the chaff friction also decreased the capacity. Increasing grain density increased the cleaner capacity. Increasing chaff mean length tended to reduce the cleaner capacity. Both grain and chaff moisture tended to decrease the cleaner capacity. Increasing grain-to-MOG ratio decreased cleaner capacity.

12.2.5 Power requirements

Rotz et al. (1991) reported a simplified method for estimating rotary power requirements for agricultural machines by the following equation:

$$P_r = a + c\,F \tag{12.19}$$

where P_r = rotary power required, kW
F = material throughput rate, t/h
a, c = machine-specific parameters

Use a = 20 kW and c = 3.6 kWh/t for small grain self-propelled combines. The material flow rate is based on MOG flow rate. To estimate power for grain corn use a = 35 kw and c = 1.6 kWh/t. The throughput rate for corn is based on grain flow rate. For PTO-driven combines the value of parameter a should be reduced by 10 kW. A variation of as much as 50% can be expected in the value of b depending on the crop and the harvesting conditions.

If F is set equal to zero, Equation 12.19 can be used to estimate no-load or propulsion power. The cylinder generally accounts for a large portion of the total power. Power requirements for the separation and cleaning units are small and relatively independent of material flow rate. Short-time peak power requirements for the cylinder may be two to three times as great as the average requirement.

12.3 COMBINE TESTING

Combine testing is performed in the field as well as in the laboratory. Laboratory testing has the advantage of uniform crop and better control on test conditions. However, the crop has to be stored and that may cause changes in its properties, which affect the performance characteristics of the component being tested. The test engineer has to be aware of this.

The objectives of combine testing are to determine the performance characteristics of its functional components, power requirements, and durability. Only functional testing is discussed in this book. The objective of functional testing is to determine grain losses and capacity. Grain losses are expressed as percentages of total grain entering the combine. The capacity of a functional component is expressed as the MOG feed rate (t/h) through that component at a certain grain loss level.

Combine losses are divided into (1) header losses, (2) threshing losses, (3) separation losses, and (4) cleaning losses.

Header losses include lodging, shatter, and cutterbar loss. Lodged crop not cut by the cutterbar is considered lodging loss. Shatter loss is the grain that falls to the ground as the grain head is shattered due to the impact by the reel. Cutterbar loss is the cut grain heads that fail to land on the platform. The header losses may be expressed as kg/ha or as percentage of the crop yield. To determine the header losses, the combine is driven in the field and when the steady state operation is achieved, the combine is stopped. The combine is backed up a distance less than or equal to the longitudinal distance between the cutterbar and the discharge chute at the rear of the combine. A sample area is marked off in front of the combine and the losses collected from that area. Uncut grain heads still on the crop are considered lodging losses. Loose grain is considered shatter losses and the cut grain heads are considered cutterbar losses.

Threshing or cylinder losses are those unthreshed grain heads that escape the combine at the rear with straw and are expressed as the percentage of total grain entering the combine.

Separation losses, also called walker losses in conventional combines, are lost grain with straw expressed as the percentage of total grain entering the combine.

Cleaning losses, also called shoe losses, are the grain lost with chaff expressed as the percentage of the total grain entering the combine.

Discharge losses are the sum of threshing, separation, and cleaning losses. These losses are affected by the material-other-than-grain (MOG) flow rate through the machine. The plot of these losses at different MOG feed rates is referred to as the *machine performance curve*. The capacity of a functional component is the MOG feed rate at a certain loss level. This loss level is 1% to 2% for the separator capacity and 0.5% to 1% for the cleaner capacity.

To determine the discharge losses in field material, discharges from the separator and the cleaner are collected separately. A simple method of collecting the sample is to hang a canvas bag at the appropriate discharge chute at the rear of the combine. The combine is run in the field and when the steady state operation is reached the bag is opened to collect the material. At the same time, grain coming out of the clean grain auger is collected at the grain tank. When the bag is full it is closed and the sampling time is recorded. The material is weighed and the MOG flow rate is established. The grains are separated from the collected MOG and their percentage is computed. The procedure is repeated several times at different combine forward speeds and a curve is plotted as in Figure 12.34. To determine threshing losses the MOG collected from the separator is re-threshed in a stationary thresher after determining separator losses. Re-threshed grains are then separated to find cylinder losses. The separator and cleaner losses are often plotted against their own MOG feed rate rather than the total machine MOG feed rate. In this case it is necessary identify it as the separator MOG (primarily straw) and the cleaner MOG (primarily chaff). Various manufacturers have developed automated methods that save time and increase accuracy in developing loss curves.

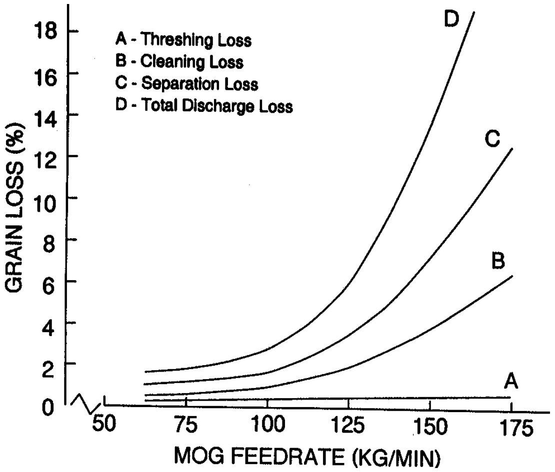

Figure 12.34 – Typical combine performance curves.

PROBLEMS

12.1 The following data were collected in a field test while harvesting barley with a 4-m self-propelled combine:

total material over walkers = 9.4 kg
total material over shoe = 4.4 kg
free seed over walkers = 76 g
free seed over shoe = 289 g
unthreshed seed over walkers = 60 g
unthreshed seed over shoe = 81 g
total seed collected at grain tank = 17.6 kg

The length of test = 12 m, the time = 21.3 s, and the average gathering loss = $10.2 g/m^2$. Calculate (a) cylinder, walker, shoe, and total processing losses as percentage of total grain feed rate; (b) gross yield, gathering loss, and processing losses in kg/ha; (c) gathering loss as percentage of gross yield; and (d) walker, shoe, and total MOG feed rate in t/h.

12.2 For the case as described in Example 12.1, what would be the separator length if the separation loss was to be under 1%? Is it practical? What other means do you have at your disposal to reduce the losses if the same separator length was used?

12.3 List possible causes and cures for each of the following combining losses: (a) excessive header loss, (b) excessive amount of unthreshed seed, (c) broken kernels of grain, (d) excessive seed loss over the separator, (e) excessive amount of chaff in the grain tank, and (f) excessive cleaner seed loss.

12.4 Suppose you are the test engineer in charge of comparative functional performance testing of a new combine against a reference combine. Develop a detailed testing program that you would follow.