Development of a rethresher for combine tailings returns

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Development of a rethresher for combine tailings returns

by

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Signatures have been redacted for privacy
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CHAPTER 1. INTRODUCTION

The modern combine is a highly versatile and expensive machine. Combines must be able to harvest a wide range of crops in greatly varying conditions. The capability to handle a wide range of crops and conditions poses many challenges for engineers contemplating new designs or improvements. The cleaning system of these combines must adapt to seed sizes that encompass greater than a five thousand-fold size range. (Quick and Buchele, 1978.)

The cleaning system of most modern combines has not changed appreciably in its principle of operation for over a century. Today, though, the same cleaning system may have to separate timothy, a legume with 1.2 million seeds per pound or without modification clean corn that has 800. The cleaning system sorts by density and size, ideally segregating only clean grain for transport to the grain bin.

Probably the most difficult process is dealing with material entering the cleaning system that is not properly threshed. Grain that is incompletely threshed and still attached to plant material has size and aerodynamic principles much different than threshed grain and is more difficult to sort out. Material that enters the cleaning system after overthreshing contains many unwanted plant particles of similar size and density to properly threshed grain. These particles add greatly to the load on the cleaning system and the threshed grain is difficult to remove from them. In either of these conditions, it is advantageous to have a recycling system built into the cleaning system to provide another opportunity to save this grain instead of discharging it with the chaff back onto the field.

The tailings return system is essentially such a recycling system. ASAE standards define returns as “the material from the grain cleaning mechanism which is recirculated for reprocessing.” Tailings return systems have been utilized on cleaning systems of stationary threshing machines for well in excess of one hundred years. Not all cleaning systems on early machines used returns systems. Some evidence suggests that the returns system is predominately a North American influence on combine harvester design. Early North American threshers were built for high throughputs and minimum labor requirements. They typically used spike tooth cylinders that were very aggressive and
sometimes severed heads from the grain stems without threshing them. (Cooper, 1966.)

In such circumstances, reprocessing this material had great benefits in grain savings.

Figure 1.1 and the following explanation detail the combine cleaning and tailings return systems.

![Diagram of combine cleaning shoe]

**Figure 1.1 Combine cleaning shoe**

The following are the major working parts of the simplest and most common combine cleaning system or "shoe" shown in Figure 1.1.

**Grain pan:** The grain pan is a vibrating conveyor or a series of augers that deliver threshed and partially separated grain to the cleaning shoe. Any material on the grain pan has come from the rotor or the threshing cylinder and separator.

**Fan:** The fan in most combines is either a centrifugal fan or a transverse flow fan. It delivers air to the chaffer and sieve to aid the cleaning process.

**Chaffer:** The initial cleaning process takes place on the chaffer, or top sieve. The chaffer has adjustable perforations to allow grain to penetrate. It oscillates to convey the material toward the rear of the machine. The air blast from the fan levitates the mat of material and blows away the light chaff.

**Sieve:** The lower sieve is very similar to the chaffer, but the openings are usually adjusted smaller. It also oscillates and uses an air blast from the fan to separate grain from chaff. Any material that passes through the sieve should be clean grain and will be
delivered directly to the combine’s grain bin. Any material that passes through the
chaffer but not the sieve will go into the tailings return.

**Chaffer extension:** The chaffer extension is the rear section of the chaffer. It is
adjustable independent from the chaffer. In most conditions the chaffer extension is set
to be slightly more open than the chaffer. Any material that passes through the chaffer
extension goes directly to the tailings return.

**Tailings:** The “tailings” or “returns” is the material that passes through the chaffer but
not the sieve, or through the chaffer extension. Tailings often include clean grain,
damaged grain, small pieces of chaff, and grain heads or pods that are not completely
threshed. In most crops, the tailings are recycled through the machine to be threshed,
separated, and cleaned again.

**Tailings auger:** The tailings auger delivers the tailings to the tailings return system. The
tailings return system is the mechanism that delivers the tailings back to the threshing
cylinder or an auxiliary threshing cylinder where they are reprocessed to and prepared for
rethreshing. Without a returns system, the tailings would be discharged out the back of
the combine and all the grain in them would be lost.

The grain enters the cleaning system after it has been threshed from the plant
head, pod, or cob and has been through a first stage of separation. It flows off the grain
pan onto the chaffer. There is often a vertical drop from the grain pan to the chaffer, and
some machines introduce a horizontal air stream across this vertical drop to winnow
some of the lighter material before it gets to the chaffer. The chaffer is a variable
opening sieve that sifts the small dense grain particles out of the chaff. It uses airflow to
levitate the mat of material on top of it, and it oscillates to convey the material toward the
rear of the combine. It completes the first step of the cleaning process.

The back section of the chaffer is adjustable independently of the front section.
This short back section is commonly referred to as the chaffer extension. The chaffer
extension is usually more open than the chaffer to allow unthreshed grain heads to
penetrate and fall into the tailings return.

The sieve is located directly below the chaffer and performs a very similar
function. The second and final “fine” cleaning of the grain occurs on the sieve.
Anything that passes through the sieve goes directly to the grain bin of the combine. All
material that is small and dense enough to penetrate the chaffer but not the sieve goes into
the tailings return.
The constituents of the tailings depend very much on the crop type and conditions and the performance of the threshing and separating systems of the machine. Tailings generally include clean grain, damaged grain, under-threshed grain, and chaff and over-threshed plant material. The volumes and weights of these constituents vary dramatically.

There are several options for reprocessing these tailings. The most often used method is returning them to the main threshing cylinder. There the tailings enter the main cylinder with the incoming crop and repeat the entire trip through the combine.

A second less common option is the use of an auxiliary rethreshing cylinder. In some machines the tailings are rethreshed in a small threshing cylinder dedicated only to tailings. From there they are generally returned to the grain pan to be presented to the cleaning shoe again.

Another option on some machines eliminates the rethreshing process entirely. The tailings are returned only to the separation or cleaning system of the combine. They are not exposed to the threshing process a second time in an effort to prevent undue grain damage. All of these approaches have been incorporated in modern harvesting machines, and all have been successful in different crops and conditions. Each option is advantageous in certain conditions.

This thesis will explore the second two possibilities in greater detail. The purpose is to develop an improved system to replace the traditional tailings return of a modern combine harvester.

This thesis includes data and graphs from numerous field studies taken in the harvest seasons of 1999 and 2000. All of the graphs include the date of the study, the crop harvested, and the machine used for the study in the graph title. The graphs taken in different crops are scattered throughout the thesis; this is a deliberate effort to illustrate how many of the fundamental operating characteristics of a combine do not change in changing crops.

The date is expressed in the title of each graph as YYMMDD. In the year position, 99 corresponds to 1999 and MM corresponds to 2000. MM and DD are the month and day respectively.
Appendix A contains many other graphs of data from the field studies. Nearly all of the graphs shown in the body of the thesis display trends that can be shown in similar graphs taken in different crops. These similar graphs are included in Appendix A and referenced from the body of the thesis. Many of the graphs display trend lines to help the reader visualize the trends apparent in the graph. In a few of the graphs, trend lines do not fit well or make the graph more difficult to read and are therefore not included.

Four different machines were used for the field studies. In the graph titles, JD 45 corresponds to a John Deere 45 combine, JD 4420 corresponds to a John Deere 4420 combine, JD 9750 STS corresponds to a John Deere 9750 STS combine, and Case IH 2388 corresponds to a Case-International 2388 combine. Details of the studies and the machines are included in Appendix B.

Appendix B also contains descriptions and definitions of several terms that clarify the meaning of the graphs for the reader. The important clarifications are as follows:

The term “throughput” always refers to grain only throughput of the combine measured in the grain bin unless otherwise noted.

In several of the graphs, grain “damage” is displayed. A 100-gram sub-sample was taken from each bin sample for damage determination. In corn, any kernel that displayed a defect that exposed the starch was considered to be damage. The corn was sieved with a 12/64 sieve before sorting. “Total damage” refers to the damaged grain and the material removed by sieving. “Visible damage” refers only to the hand sorted damaged particles after sieving. In soybeans, any soybean that was not whole was taken to be damaged. The damage percent was calculated as the weight of damaged grains in the sub-sample divided by the total weight of the sub-sample.

The term “mog” in any context refers to material other than grain. Mog may include light chaff, stalks, pods, cobs, and any other plant or non-plant material in the combine.

The term “tailings” is used in several different contexts. “Tailings” in general refers to the material flowing in the tailings returns system of the combine. As displayed in graphs, “tailings” refers only to the grain flowing in the tailings returns. “Total tailings” refers to grain and mog flowing in the tailings returns system. “Tailings
percent” refers to the tailings returns flow rate as a percentage of the clean grain flow rate into the combine grain tank.

All other relevant terms and test descriptions are included in Appendix B. The analysis of several of the studies included an analysis of variance performed with SAS statistical software. The ANOVA tables from SAS and a brief description of each is included in Appendix C.
CHAPTER 2. OBJECTIVES

1. Observe the composition and flow rate of tailings as affected by crops, conditions, and machine settings.

2. Establish relationships between tailings and combine performance.

3. Develop a rethresher for combine tailings.

4. Provide insights to reduce the cost and/or complexity of modern combines.

5. Provide useful information to direct further studies on tailings returns.

6. Review the history of the tailings return systems on present combines.

7. Evaluate the utility of a tailings rethresher as opposed to a tailings return system.

These objectives of this thesis will be attained in the literature review and the seven chapters following. Each of the seven chapters begins with an original objective hypothesis, and then presents the gathered evidence to support or disprove the hypothesis. The seven hypothesis for the seven chapters are as follows:

1. Tailings returns are influenced primarily by threshing performance and sieve settings and will be somewhat indifferent to machine throughput.

2. The tailings return system is designed to handle under-threshed grain, therefore threshing performance will have strong influences on the tailings return system.

3. An increase in tailings will increase damage in the grain bin. Not returning the tailings to the main cylinder will cause a reduction in grain damage.

4. Low throughput and high damage cause elevated losses.

5. The tailings studies data shows that information about tailings is an indicator of combine performance and may help locate the optimum operating conditions.

6. The tailings return system and general combine cleaning shoe performance could be improved if the cleaning shoe was load sensitive.

7. A tailings returns rethresher is a useful alternative to a conventional tailings returns system.
CHAPTER 3. REVIEW OF LITERATURE

The tailings return is one section of a combine that is potentially easy to ignore. It seems to be a nuisance, an added cost and a complexity on a modern machine. To some it may seem of questionable utility. If a combine performed all functions perfectly in the first pass, there would be no use for a tailings return system. However, in the world of grain harvesting only one thing can be said with complete certainty: conditions will never be identical. Because of this tremendous variability, even the most modern machines contain the age-old nuisance of the grain that did not make it to the right place the first time. For much more than one hundred years, grain threshing machines have used tailings return systems, and for just as long there have been inventors seeking to improve or replace the return systems.

One focus of this thesis is replacing the common tailings return system with an auxiliary rethreshing cylinder. Retreshers have been used with varying amounts of success, but they are not used on very many modern production machines. The idea of a rethresher is not at all a new one, though.

Patent art is a powerful indicator of historical developments and progress in farm machinery. Whenever there were bursts of rapid farm mechanization there were a large number of short-lived equipment manufacturers. Information on these manufacturers and their products is at best scarce, and often not available at all. Patents, on the other hand, are precise records, traceable to a specific location, time and inventor or firm. U.S. patents on tailings rethreshers are numerous. The first such example is a patent issued to Frank F. Landis of Waynesborough, Pennsylvania in 1895.

Landis's invention was a simple tailings rethresher that doubled as a tailings conveyor that returned tailings to the cleaning shoe of a stationery threshing machine. It was a relatively simple and ingenious device that mounted directly on the end of the tailings auger. The tailings entered the cylinder radially from the center of the auger S. As the material moved forward and radially outward, it passed across a conical threshing disk D and a corresponding adjustable clearance stationary threshing ring I. The threshing disk D was attached to a conical hub that was spring g loaded on the axis of the shaft d. If the rethresher encountered large pieces of material or excessive flow rates, the
spring g would be forced back and the concave clearance would expand to allow the object or slug of material to pass through. After the tailings passed the threshing ring, they were forced into a centrifugal impeller F that acted as a slinger to carry them back to the shoe of the threshing machine via pipe C'.

Shortly after Landis’s patent, another patent for a tailings rethresher was issued to Crawford D. Chalfant of Thornport, Ohio. It was a secondary spike tooth cylinder that was fed by the existing tailings elevator of a threshing machine. From the patent it is evident that Chalfant intended the cylinder to be readily adaptable as an attachment to various makes of threshing machines. The expressed purpose of the device was to rethresh unthreshed grain in the tailings without intermixing it with incoming straw. Chalfant’s claimed advantage was reduced loss and increased capacity from the thresher as the rethreshed tailings were easier to separate if they were handled independently of the incoming straw and crop material.

The cylinder D was designed to be mounted directly below the tailings elevator C discharge A with its shaft perpendicular to the driveshaft of the elevator. The cylinder discharged into a centrifugal impeller E directly below. The impeller E was to distribute the rethreshed tailings back onto the grain pan of the thresher.

Martin T. White of Maury City, Tennessee received a patent in 1901 for a pea thresher that included a rethreshing cylinder 4. On this machine, the rethreshing cylinder 4 was also fed with a tailings elevator 7. It was to run at a peripheral speed of
approximately 20 percent faster than the primary threshing cylinder C and utilize a smaller clearance. White claimed that the addition of this secondary threshing cylinder 4 could reduce pea losses by 20 percent by extracting remaining unthreshed peas. After being rethreshed, the peas would pass through a spout 8 back to the separating pan F of the thresher.

Figure 3.2 Rethresher by C.D. Chalfant, 1899

Figure 3.3 Pea thresher with rethreshing cylinder by M.T. White, 1901
Also in 1901, Martin S. Bowers of Zanesville, Ohio received a patent for a "machine for rethreshing the tailings in threshers." This rethresher, like the one patented by Landis, was mounted directly on the end of the tailings auger shaft 16. It was of notably small diameter, essentially the same size as the auger it attached to. It relied on the interaction of fingers 17 protruding from the auger shaft 16 and offset fingers 18 protruding from a concave 19 to rethresh the tailings. After passing through the threshing fingers 17, 18, the tailings were discharged into a centrifugal impeller 24 much like the impeller in Landis's patent. This time the tailings entered the impeller 24 at one place on the periphery and were accelerated and thrown up a pipe 13 to be discharged back onto the separating pan of the thresher. Like Landis’s invention, this rethresher was intended to be readily adapted to currently available threshing machines.
Frank Landis seems to have been a prolific inventor in the era of stationary threshing machines. He was issued another patent in 1908, this time for a threshing machine that included a tailings rethresher C. The rethresher appears to have carried some ideas from his 1895 patent. This patent does not give much detail on the rethresher itself. Interestingly, this machine used more than just a rethresher; it used a completely separate separation and cleaning system for the tailings. Landis claimed that this system was advantageous because tailings could not be caught in a loop and recirculated. Some particles, especially unripe grain heads, are too large and heavy to be blown out by the cleaning fan. They tend to fall into the tailings and get recirculated. If they are not threshed or broken into smaller pieces by the rethresher, they recirculate again. Recirculating tailings, he claimed, would build up inside the returns system until the rethresher became overtaxed. If the green heads were to be threshed eventually, they would contaminate and degrade the clean, dry grain. In this system, the tailings would be sorted by shaking grain pans and air after rethreshing. There was no path for them to
enter the tailings a second time, so the tailings material had to go into the clean grain conveyor or out of the machine as chaff.

In 1922, John C. Junkin, an inventor from Minneapolis, Minnesota obtained a patent on a tailings rethresher assigned to the Minneapolis Steel & Machinery Company. This rethresher, like several before it, was fed by the tailings elevator 33. It was mounted adjacent to the main threshing cylinder 5 and driven directly off the main cylinder shaft 6. In this way Junkin eliminated an extra drive, and the rethresher had the aid of inertia from the main cylinder 5 for tough conditions. This rethreshing cylinder 16 used interacting knives 20,24 on the cylinder 16 and concave 23. The knives 20 were staggered about the

Figure 3.6 Tailings Thrasher for Thrashing Machines J.C. Junkin, 1922.
periphery of the cylinder, presumably to make the rethresher operate more smoothly. The rethreshed tailings were discharged through a spout 29 below the cylinder onto the grain pan 30 below the main threshing cylinder 5. The concave 23 for the rethresher also warrants a claim in Junkin’s patent. It was designed so that it would be forced open if the rethresher encountered a hard object that would otherwise damage the cylinder 16 and concave 23.

Herman Fank of Alden, Iowa received a patent in 1940 for an attachment to rethresh tailings on a combine or threshing machine. Fank intended this invention only to be a temporary addition to a threshing machine or combine for use cleaning clover and alfalfa. This invention was intended to increase capacity and decrease unthreshed grain loss in combines or threshing machines used for clover or alfalfa. This rethreshing cylinder 33 mounted directly below the discharge 46 of the tailings elevator 38. The tailings entered the top front of the cylinder 33 and were threshed against a closed concave 37 for over 180 degrees of revolution before exiting near the top rear of the cylinder. This cylinder also utilized a wiper 53 similar to a beater on a conventional combine to ensure that the tailings were not carried over and rethreshed

Figure 3.7 Clover and alfalfa hulling attachment for threshing machines or combines H. Fank, 1940.
again. After rethreshing, the wiper 53 pushed the tailings into an auger 58 that fed a spout 64 to the grain pan of the threshing machine.

Melfred Makin of Ontario, Oregon invented a tailings rethresher and was granted a patent on it in 1943. The objective of Makin’s invention was not only to rethresh grain in the tailings, but also to provide a mechanism more effective for handling damp seeds. Makin claimed that losses of seed in damp clover and alfalfa could be reduced by 50-75% with this rethresher attachment. He also claimed that this machine, by virtue of reduced recirculation and use of a less aggressive concave, could maintain better straw quality for better separation and lower power requirements.

Figure 3.8 Re-thresher attachments for threshers M. Makin, 1943.
This rethresher 21 offered a feature not evident in the prior art; its use was optional even if it was installed on the machine. The tailings auger trough had gates 12 on the bottom that could be opened to allow flow to the rethresher 21 or closed to just use the conventional tailings return auger 6. If the gates were open, tailings were drawn into the rethreshing cylinder 21 by the airflow it developed. The tailings fed into the cylinder 21 from the center and accelerated outward radially where they were carried through the outlet 26 of the cylinder housing with the exiting airflow. The rethreshed tailings could be directed through a spout 36 in the top of the machine body 1 to the draper behind the cylinder beater or directly back into the main cylinder. This is also the first rethresher in the patent art that allows the rethreshed tailings to be directed back to the main threshing cylinder.

Figure 3.9 Auxiliary threshing and conveying unit  J. Belkowski, 1959.

In 1959, Massey-Ferguson Inc. patented a tailings rethresher invented by Jerzy Belkowski and Walter Stanley Hockey, both of England. Belkowski and Hockey designed this machine with the intentions of replacing the tailings elevator and reducing load and subsequent losses of the primary threshing cylinder.

This rethresher was an integral part of the tailings conveyor auger 42. A portion of the flighting 47 of the tailings conveyor auger 42 was replaced by a set of 12 adjustable pitch paddles 48. The paddles 48 would determine the amount of rethreshing by their pitch. If pitched forward, they would convey the tailings relatively quickly and
spend little time rethreshing. If the fingers were set with no pitch or even a reverse pitch, they would tend to continually rethresh the material without moving it to the outside of the body of the machine 32. In this condition, the axial motion is provided by the suction of an impeller 50 located at the end of the tailings auger shaft 42. Once drawn into the impeller 50, the tailings would be accelerated radially and thrown out through a chute 29 directly back to the beginning of the cleaning shoe.

Figure 3.10 Auxiliary rethresher for a combine L.L. Kepkay, 1963.
Massey-Ferguson received another patent for a tailings rethresher in 1963, this time for a unit designed by Leslie L. Kepkay of Toronto, Ontario. Kepkay designed this rethresher with several goals in mind. It was to rethresh the tailings and re-distribute them equally across the width of the cleaning system of the combine. The tailings were to be subjected to essentially a complete revolution of threshing, and the rethresher was to be easily deactivated when not needed.

This rethresher was not fed with a conventional tailings elevator, but with a vertical auger running slightly faster than the horizontal tailings conveyor auger 36. The rethresher attached directly to the top of the vertical auger 43. It used three blades 51 with reinforced tips 52 to thresh the tailings against a sleeve 47 with a rough surface 50. If rethreshing was not necessary, the rough sleeve 47 could be covered with a smooth sleeve that could be stored in the rethresher when not in use. The sleeve walls 47 were sloped outward to encourage the tailings to distribute evenly across the vertical height of the blades 51 by radial forces. Because of this slope, the threshing clearance was readily adjustable by raising or lowering the sleeve with a set screw 72. The rethresher discharged directly out a passage 53 through the wall through the body of the combine 11 and across the cleaning system.

Leslie Kepkay developed another rethresher for Massey-Ferguson and received a patent on it in 1966. The goals of this unit were essentially the same as his 1963 patent, but it included several improvements. It was to be less expensive to manufacture and easier to install. Kepkay also intended for this device to cause less air disturbance and blowing effects.

The tailings were conveyed to this unit with a short vertical chain elevator 58. The conveyor looked similar to the rethreshing conveyor in Belkowski’s 1959 patent. The objective this time, though, was to use a conveyor 31 with some missing flighting 32 to keep the tailings agitated and prevent slugging the chain elevator. The axis of the rethreshing cylinder 50 was horizontal and parallel to the side of the combine body. This rethresher carried some heritage from Kepkay’s 1963 patent, most notably the use of the rethreshing cylinder itself to distribute the rethreshed tailings across the cleaning system of the combine and the ability to cover the threshing surface 63 with a smooth plate 101.
The tailings were introduced into an impeller type cylinder 50 slightly to the left of center where they could be spun radially outward and threshed for about 270 degrees before exiting the rethresher. A portion of the concave 63 was hinged 68 for easy opening, and the threshing surface of the concave could be readily changed for different amounts of threshing aggressiveness. The clearance between the impeller and the threshing wall was also adjustable to correspond to any of a number of locating holes 95 without using any tools.

Figure 3.11 Auxiliary rethresher for a combine L.L. Kepkay, 1966.
This particular design seems to have been reasonably successful. A design very similar to this patent with a combination blade/rasp bar cylinder instead of an impeller was used on many production Massey-Ferguson combines until the mid-1980's.

The next patent for a rethresher was again issued to Massey-Ferguson. This design by Wilbert D. Weber of Mississauga, Canada was another rethresher that doubled as a conveyor. Presumably this patent was an attempt to replace the current production Massey-Ferguson rethresher patented by Kepkay in 1966. This design would have used fewer moving parts and eliminated the chain elevator of the previous design, but it never appears to have reached production at Massey-Ferguson.

Figure 3.12 Auxilary rethresher for a combine W.D. Weber, 1976.
Again, some ideas were carried from earlier designs, but this design was developed to provide more airflow as opposed to Kepkay’s previous design. The housing had holes to allow air in so that the cylinder could act as a centrifugal fan and entrain the tailings in an air stream for delivery back to the grain pan. In this invention, the tailings entered the cylinder tangentially along its periphery. The tailings were not subjected to as much rotation of threshing; this design appears to have provided a concave for only about 90 degrees of wrap for threshing.

Sperry Rand Corporation followed the lead of Massey-Ferguson, patenting a rethresher design for a combine by Frans J.G.C. De Coene of Belgium. The patent art describes the usefulness of this rethresher. With combine capacity increasing, even small percentages of the crop in the tailings constituted a considerable amount of grain. Recycling tailings would tend to unevenly load or overload the main threshing cylinder and cause significant losses.

De Coene reviewed Kepkay’s patents at Massey-Ferguson by spelling out the advantages of his system over Kepkay’s two patents. First, De Coene’s rethresher did not need an elevator or a vertical auger to feed it. Also, De Coene claimed that all previous rethreshing rotors had been compromised to allow them to work as an impeller to discharge and distribute the tailings. Furthermore, any such rotor could not thresh over a substantial portion of its housing because of the inlets and outlets for the tailings. Many of the previous rethreshers also fed the crop in parallel to the rotor axis, making them difficult to spread across the entire width of the rotor.

De Coene’s patent had some unusual characteristics not seen in prior art. It is the first rethresher that fed along the periphery of the rotor, but used an axial flow rotor with helical guide vanes to rethresh the tailings. The rotor was supplied by an impeller below it mounted on the end of the tailings conveyor auger. The rethreshed tailings exiting the rotor axially entered another impeller that supplied them to another auger to return them to the grain pan. The rotor/impeller combination shaft was driven with a belt off a pulley on the tailings conveyor auger.

In 1981 and 1982, Sperry Corporation obtained two closely related patents, one on a tailings conveyor, and another on an included rethresher. The rethresher patent was granted after the conveyor patent, but it was actually filed earlier. These inventions were
Figure 3.13 De Coene’s Rethresher 1977.
designed by Cyriel De Busscher and Francois Van Herpe, both of Belgium. The patents covered a tailings return and rethreshing system for New Holland-Zedelgem's unique "Twin Flow" TF42 and TF 44 combines. The TF series combines had a separator in excess of 9 feet wide. Distributing the 9-foot width of material across a substantially narrower cleaning shoe proved to be a challenge. This design used the tailings conveyors to carry the separated material from the extremities of the wide body to the grain pan for cleaning. Since the tailings conveyors doubled as conveyors for separated grain, they could not return the material to the main threshing cylinder. Rethreshers provided the only option to expose the tailings to a second threshing.

There were two rethreshers, one on each side of the combine. The tailings conveyor auger 53 had flighting 43 wound in opposite directions from the middle of the cleaning system. Each rethresher 45 was mounted directly on the tailings conveyor auger. The rethresher rotors 62 were six blade 65 impellers with rasp bars 66. The lower section of each housing was a concave 63, and the tailings exited along the periphery at the top 64 into an auger 70. At the top end of the auger, there was a four-blade impeller 73 that distributed the tailings and material gathered from the separator across the grain pan.

Figure 3.14 Combine harvester conveyor De Busscher, 1981.
The intentions of this rethresher were very similar to De Coene's in his 1977 patent. The "Background of the invention" section of the rethresher patent is almost verbatim from De Coene's earlier patent.

Figure 3.15 Rethreshing rotor for grain combine M. Underwood, 1996.

A recent patent on a rethresher for a combine was issued to Mark Underwood and Sushil Dwyer, creators of the bi-rotor combine, in 1996. The patent was assigned to Deere & Company.

This rethresher was quite unlike any in previous patent art. It extended the full body width of the combine. The rethreshing cylinder 39 was a rasp bar type of reasonably small diameter and the concave clearance was adjustable. This rethresher took in all
heavy material coming off the back of the chaffer 29 and sieve 31. Anything too heavy to be blown out of the combine by air or thrown out by the beater was reprocessed with the rethresher. After rethreshing, the material was deposited onto a vibrating tailings grain pan 71 to deliver it to a tailings elevator 93. The tailings elevator delivered the tailings back to the main threshing rotor 17 via a spout 79 for another rethreshing. It appears that this machine probably handled large volumes of tailings. It was never produced commercially.

Rethreshers have not been the only alternative to tailings returns appearing in the patent art. There are situations when it is not necessary to rethresh tailings or even advantageous to not rethresh tailings. In such situations, the tailings contain only threshed grain and material other than grain (mog) with no unthreshed heads. Threshing the tailings again only further disintegrates the mog and damages the grain. Through the course of combine development, some inventors recognized this, and they patented systems independent of tailings rethreshers to address such situations.

One such early development was patented in 1947 by ASAE Gold Medallist Charles Scranton and Robert Worell, employees of Allis-Chalmers in LaPorte, Indiana. The intention of their invention was to rethresh only those tailings that needed rethreshing. This design was developed for the very popular Allis-Chalmers All Crop harvester, a pull-type combine. On the All Crop harvester, the tailings were carried up an elevator and across the cleaning system in an auger to be returned to the main threshing cylinder. The invention was very simple; it was a perforated bottom on the tailings auger that crossed the cleaning system. The perforated auger tube would allow single grains and small particles to fall out for only recleaning, and unthreshed grain and larger particles would be returned to the main threshing cylinder.

Shortly after in 1950, J.I. Case patented a tractor mounted combine with a tailings diverter. The patent issued to Sherman C. Heth provided a diverter such that tailings could be directed to the either main cylinder for rethreshing or to the straw rack for re-separation and cleaning only.

Several patents for systems that avoided rethreshing tailings were assigned to Allis-Chalmers corporation. In the first such patent issued to Roger Hanaway in 1979,
the tailings were returned to the distribution augers to be distributed across the shoe for recleaning only.

The next two Allis-Chalmers' patents were filed the same day in 1983 and issued in mid-1984. One was issued to Roger Hanaway, and the other to Wayne Hoefer and Garry Busboom. Both systems provided optional tailings return to the main threshing cylinder or to the distribution augers as in Hanaway's 1979 patent. A variation of Hanaway's patent is still used on some Gleaner combines today, now produced by AGCO corporation in Hesston, KS. These systems were unique to the Allis-Chalmers Gleaner combine in that no other manufacturer used such a distribution system for the cleaning shoe.

**Tailings return studies**

Published papers that pertain to tailings return systems are not as plentiful as patents. There are probably a number of reasons that this information is not common. Tailings flow rates and characteristics are difficult to quantify in a concise way because they vary dramatically with different crops, different conditions, and different combine settings. Setting a combine for optimum performance under so many varying conditions is more an art than an exact science. Even two experts will often disagree on what optimum performance or optimum levels of tailings returns should be. Furthermore, many studies relating to tailings flow rates were combine efficiency tests performed by combine manufacturers. Much of this material was commercial-confidential and is not available to the general public. The following information has been gleaned from privately collected files from industry (courtesy G.R. Quick.)

In 1966, J.I. Case Company performed some efficiency tests on their 660, 900 multitrack, 960, 1660, and X-10 combines and on a Massey-Ferguson 510 combine. The study was not published. The object of these tests was to determine loss characteristics of the combines at different throughputs, but they also analyzed the tailings flow and composition in the 1660 combine. The combines were tested harvesting Mariot barley near Calipatria, California in late May and early June of 1966.

The 1660 combine had modifications to collect tailings from the bottom of the tailings elevator. An electrically controlled air cylinder opened and closed the tailings
catcher. Although testing times are not shown in the paper, it is evident that the tailings collections lasted for approximately 8 seconds, the time it took for the combine to travel 30 ft at 2.45 miles per hour.

The data from the tailings catches is provided in a table in the company report. The tailings grain flow and the combine throughput are expressed in pounds per minute. Some simple analysis of the presented data shows the tailings grain throughput varied from 3.6 to 7 percent of the combine measured throughput. There is not a strong correlation between tailings flow (as a percentage of throughput) and combine total throughput. There appears to be a general trend of increasing tailings percentage of throughput with increasing combine throughput. See graph Figure L.16. The data however is somewhat suspect as in test number 3 the grain in talings flow rate is shown to be higher than the total tailings flow rate.

Tailings flows are closely correlated with cleaning shoe performance, so shoe loss would seem to be related to tailings flow. The data from the 1660 Case combine does not

![Figure 3.16 Tailings vs. throughput](image)

**Figure 3.16 Tailings vs. throughput**

show a strong correlation between shoe loss and tailings flow rates, (with both expressed as a percentage of measured throughput) but tailings flow rates appear to increase with
increasing shoe losses. See figure L.17. There are only four shoe loss measurements given from the six tests, so the data is not very complete.

Geoffrey Cooper, harvesting systems laboratory supervisor of Massey-Ferguson Industries, published a paper on combine shaker shoe performance for the 1966 annual ASAE winter meeting. In this paper he addressed the tailings returns system and some of its performance parameters.

Cooper evaluated the actual function of a tailings return system compared to its intentions. Rethreshing the grain heads that have not been threshed is most certainly desirable, but a combine shoe does not effectively separate unthreshed heads. Often, unthreshed heads have characteristics more similar to chaff and unwanted material than to grain. These properties can make efficient separation of unthreshed heads very difficult.

![Graph](image)

**Figure 3.17 Tailings vs. shoe loss**

Cooper performed some tests in which unthreshed barley heads were injected into the threshed crop material as it entered the cleaning system of a combine. In his tests, only 22% of the unthreshed heads appeared in the returns. Three percent of the
unthreshed heads passed through the sieve into the clean grain. The remaining 75%, though, were discharged off the shoe as loss. This data represented an average of four sets of data, the measured proportion of unthreshed heads in the tailings varied from less than 5 to almost 40 percent.

Little information is available on the proportion of unthreshed heads that actually enter the tailings. However, there is a more general consensus on the composition of tailings returns material; the primary constituent is not unthreshed grain. Sverker Persson found only 1-15% of the tailings material to be unthreshed grain. Similarly, J.R. Goss found less than 2% of the tailings to be unthreshed and 60-90% of the tailings to be free threshed grain in a study in barley.

Cooper does not provide any direct information as to the amount of the total combine throughput that passes through the tailings returns. J.R. Goss states that in tests in barley, 41% of the combine throughput is recycled by the tailings at a given time. This seems to be in contrast with the 3.6-7% figures from the J.I. Case efficiency testing study. J.W. Hall published a study by John Deere that showed response curves of the tailings as they were affected by combine adjustments, but it contained little actual quantitative data on tailings flow rates. The maximum tailings flow rate shown was 0.6 kg/s for a 9600 JD combine. This flow rate translates to about 0.5 tons per hour, at most maybe 5% of the total throughput of a 9600 combine in reasonable operating conditions. Very little additional information is available on tailings flows; it seems the only information to be gleaned from a review of studies on the topic is that the amount varies dramatically.

The composition and amount of tailings are anything but constant during even a single day's harvesting. The important question to answer from available information, though, is what to do with the tailings. There have been numerous approaches, many of which have been previously illustrated by the patents summarized in this review. Cooper summarizes four potential options: 1.) return them to the cylinder. 2.) rethresh them in an auxiliary threshing cylinder. 3.) return them to the separation section of the combine. 4.) return them to the grain pan without rethreshing for recleaning. All of the approaches have some advantages and drawbacks.
Reduced grain damage is one potential advantage of any system that avoids returning tailings to the main cylinder. Very little data is available as to whether there is a significant reduction in grain damage if the tailings are not returned. Cooper provides one figure comparing grain damage of a machine with a rethresher to a machine with a returns system. The graph represents grain damage in barley at varying throughputs and the same cylinder peripheral speed. Cooper does not give details as to what types of machines were used or how he measured damage, but it is clear that the data is from two different machines, not one with and without a rethresher. The figure shows consistently higher grain damage from the machine with the returns system. However, the damage level for both machines was always well under 1 percent.

It seems reasonable that returning tailings that consist primarily of threshed grain back to an aggressive main threshing cylinder would increase damage, but the issue is seldom addressed in literature. None of the rethresher patents listed in this review even mention grain damage. Of the patents on systems to bypass tailings, three of the five described above claimed to be advantageous in reducing grain damage. No research data seems to be available as to whether bypassing or dumping tailings affects the damage level in the grain bin. Dumping the tailings on the ground to reduce grain damage, (no returns) however, is a common practice in damage critical crops like edible beans.

Reduced losses are another potential advantage of a system to eliminate the tailings returns. While none of the rethresher patents included in this review address grain damage, all of them claim reduced losses as an advantage. The general consensus of the rethresher patents is that rethreshing allows reduced grain losses with respect to returning tailings in three ways. 1.) Rethreshers can more effectively deal with a small amount of unthreshed or broken/partially threshed grain heads because they do not intermix the material with incoming partially threshed heads. 2.) If a rethresher is more able to thresh grain from these heads, fewer will recirculate in the tailings again. These recirculating tailings can build up, increasing the throughput of the shoe until shoe losses increase. 3.) Intermixing the tailings, especially the clean grain contained in them, with incoming mug inevitably increases separation loss.
The tailings return system has never drawn as much attention as most other systems of the modern combine. Nevertheless, as long as combines continue to use an imperfect cleaning system, they will always have to solve the tailings dilemma. The patent art shows many attempted solutions, but unfortunately yields little data or information as to their success. The fact that there have been so many attempts, though, provides motivation for new research, especially if there is a possibility of reducing combine cost or complexity.
CHAPTER 4. TAILINGS AT LOW THROUGHPUTS

Hypothesis: Tailings returns are influenced primarily by threshing performance and sieve settings and will be somewhat indifferent to machine throughput.

At the outset of these tailings return studies, the machine throughput was not expected to have pronounced effects on the tailings return system. The primary intended function of the tailings return system is to return under-threshed grain to the main cylinder. The tailings system is to catch any material that is small enough to pass through the chaff or chaff extension, heavy enough that it will not be blown out by the cleaning fan, and too large to pass through the sieve. The tailings return is intended to capture heads or pods that contain some grain after the initial threshing process.

The first study, however, showed that tailings returns are greatly dependent on combine throughput. Furthermore, the throughput effects of unthreshed grain do not seem to be directly related to the threshing performance. In fact, out of the four crops tested, only one (soybeans) ever showed a significant amount of unthreshed grain in the tailings even when the threshing system was poorly adjusted. See figures 4.2, A.4, A.10, A.24, and A.33.

For the tailings return studies, tailings samples were collected and the grain yield could be measured within the same pass. In this manner, the tailings flow rate could be calculated as a percentage of the combine throughput. The "tailings grain percent" as it will be referred to in this paper is the tailings mass flow rate of grain divided by the mass flow rate of grain into the grain tank and expressed as a percentage. The tailings grain percent is therefore not the same as the tailings grain mass flow.

Though the tailings are not intended to accumulate threshed grain, during operation it is normal to have a small level of threshed grain that is not completely cleaned on its first pass through the cleaning shoe. As the combine throughput increases, the mass flow rate of this grain naturally increases. However, the tailings grain percent decreases dramatically with increasing throughput. Again, this phenomenon does not appear to be closely related to threshing performance. See figures 4.1 and A.5-A.11.

This increase in tailings percent appears to be caused by inadequate loading of the cleaning system. The combine cleaning shoe uses a combination aerodynamic-
mechanical process to clean the grain. Without the fan, the process would be a simple mechanical sieving process. With too much fan, the cleaning process would be an aspiration process that would separate grain and chaff only by their differences in terminal velocity. As the loading changes on the cleaning system, its operation varies over a range between these two extremes.

![Tailings percent vs. Grain throughput Oats 990726 JD 4420](image)

**Figure 4.1 Tailings percent vs. Grain throughput.**

When the cleaning shoe is not adequately loaded, there is very little restriction to the airflow through the sieve and chaff. The volumetric efficiency of the fan is relatively high, and the velocity of the air across the sieve and chaff are fairly high. As the velocity across the chaff and sieve approach the terminal velocity of the grain, more of it is fluidized for longer before it can fall through into the clean grain system. The grain moves farther back on the sieve and chaff before passing through them, and more of it floats past the back of the sieve and/or to the chaff extension and into the tailings return.
As the shoe becomes overloaded (at high combine throughputs), the opposite problem occurs. The static pressure builds under the heavy mat of grain and mog on the chaffer and sieve, and the fan airflow decreases. As the shoe becomes badly overloaded, the air velocity is not sufficient to keep the grain and mog mat partially fluidized, and the chaffer and sieve revert to mechanical separation. The heavy mat of material tends to plug the openings, and much of the grain is not able to penetrate the chaffer and is dumped out the machine onto the ground.

The low throughput phenomenon was relatively simple to observe in normal field operation. In fact, it occurs involuntarily when the combine enters or leaves the crop, the grain head is not taking a full swath, or the operator must slow the machine down for any reason. The high throughput effects were difficult to observe because it was difficult to obtain enough capacity with the rest of the John Deere 4420 under test to overload the cleaning system. High moisture corn is one of the few crops that will generally challenge the combine cleaning system before overloading any other combine component. The cleaning shoe was not overloaded by excessive throughput in any tests with any of the combines used in the studies contained in this paper.
Figure 4.2 Tailings composition vs. forward speed.

The composition of the material entering the tailings returns also changes as a consequence of the combine throughput. At under-loaded conditions, the tailings become grain rich because the fan blast that causes the kernels to float into the tailings is effective at removing much of the chaff. As throughput increases, the tailings become more mog rich because the heavier mat of material restricts the air velocity and less of the mog is blown away. See figure 4.2. When the shoe is severely overloaded, the tailings contain a lot of mog, but also become more grain rich as the grain is unable to penetrate the heavy mat of mog on the chaffer and sieve.

Possibly the most interesting part of this low throughput tailings characteristic is that though it applies to essentially every modern combine on the market, it has not been commonly addressed in previous literature. Perhaps it has been elusive because the tailings mass flow rate does not point directly to it. Also, the tailings return system has seldom been studied in this much detail.

Conclusions

The hypothesis was not supported by this study; tailings flow rates appear to be strongly influenced by combine throughput. Tailings flow rate increases with increasing throughput. However, tailings flow as a percentage of throughput increases dramatically at low throughputs. The increase in tailings is not related to low throughput threshing performance, but is caused by the fan blast in the cleaning shoe. The fan blast becomes excessive for an under-loaded cleaning shoe, and the grain is carried to the back of the chaffer and sieve and into the tailings. The nature of this phenomena also causes the tailings composition to reflect under-loading. The tailings from an under-loaded shoe are very grain rich; most of the mog is blown out by the fan blast.

The following chapters will show that the tailings returns does have some important implications on the operation of the combine.
CHAPTER 5. TAILINGS RETURNS AND THRESHING PERFORMANCE

Hypothesis: The tailings return system is designed to handle under-threshed grain, therefore threshing performance will have strong influences on the tailings return system.

The tailings return studies do support this hypothesis, but not quite as expected. As stated in the first chapter, the original intention of the tailings return system was to prevent unthreshed grain from being discharged as loss. However, the capability of the cleaning shoe in separating unthreshed grain into the tailings is questionable. In the studies performed at ISU in 1999 and 2000, unthreshed grain appeared in significant amounts in the tailings only in soybeans. There was a very small amount of unthreshed heads in the tailings in wheat, and essentially no unthreshed grain in the tailings in corn or oats. In a similar study, Cooper found that when unthreshed wheat heads were added to the crop stream of a combine in front of the cleaning shoe, only 22% of them appeared in the tailings returns, with 75% of them discharged as loss. The remaining 3% landed in the clean grain system. (Cooper 1966.)

Since the unthreshed grain does not predominantly find its way into the tailings,

![Figure 5.1 Tailings percent vs. concave setting.](image_url)
under-threshing does not dramatically impact the tailings returns. The 1999 studies gave some evidence that opening the concave beyond optimum caused the tailings to increase. Closing the concave too far also caused a slight rise in tailings returns. When the concave is opened too far, the tailings increase because of under-threshing. Likewise, when the concave clearance is too small, the tailings increase because of over-threshing. See figures 5.1 and A.30-A.32.

![Total tailings percent vs. Cylinder speed](image)

**Figure 5.2 Total tailings percent vs. cylinder speed.**

Over-threshing occurs when the grain and mog are damaged and pulverized to finer particles. The damaged grain will be discussed in a following part of this thesis; the damaged mog goes into the tailings because it is ground to smaller particles with properties similar to grain.

The over-threshing problem becomes dramatically more important as cylinder speed increases. Throughout the 1999 and 2000 studies, the effects of cylinder speed
were much more pronounced than the effects of concave clearance. Tailings increase greatly with increasing cylinder speed. See figures 5.2 and A.26-A.29.

The composition of the tailings does not change drastically with the increase in cylinder speed. As the cylinder speed increases, the amounts of damaged grain and mog rise, while the amount of whole grain remains constant or declines. Again, this is an indication that the damaged particles have a propensity to end up in the tailings. The reasoning behind the increased mog in the tailings is intuitive. The small broken plant particles have size and shape characteristics much closer to grain. Also, because of their small size, they have a higher terminal velocity and are more difficult to separate aerodynamically.

The elevated damaged grain flow in the tailings has more than one cause. First, there is more damaged grain in the tailings because there is more damaged grain in the entire combine. At higher threshing speeds, more of the grain is damaged, and even if the same percentage of throughput enters the tailings, there will be more damaged grain in the tailings.

In addition to the increase in available damaged grain in the system, it appears that damaged grain has characteristics that cause it to be more likely to go into the tailings. Damaged grain has physical characteristics very similar to undamaged grain, but the particles are smaller. The smaller damaged grain is fluidized by the airstream at a lower velocity. This phenomena is readily explained if a grain particle is modeled as a sphere.

A single kernel will remain airborne as long as the wind velocity is large enough that the drag force on it overcomes the weight of the kernel. If a kernel is modeled as a sphere, with a radius R, it will have a volume of $4\pi R^3/3$ and a frontal area of $\pi R^2$. The drag force is a function of drag coefficient, viscosity, fluid density, and frontal area. (Young, 1997.) Now imagine a damaged grain particle as a smaller sphere with the same density suspended in the same fluid (air). Because of the similar shape and the high Reynold’s number in such a situation, its drag coefficient is very similar to the undamaged kernel. In fact, the only properties that change are the weight and the frontal area. Weight is a function of volume (radius cubed) and density, and frontal area is a
function of radius squared. As the radius decreases (the kernel gets smaller) the weight (volume*density) decreases faster than the area (pi*R^2). Therefore, the weight decreases faster than the drag force, and the velocity to cause the particle to become airborne will decrease with decreasing radius.

For example, suppose the radius of the damaged kernel is one-half of the radius of the whole kernel. Its frontal area will decrease by a factor of four because it depends on radius squared. However, its volume (and corresponding weight) will decrease by a factor of eight because it depends on radius cubed. Therefore, the weight goes down by a factor of eight, and the area by a factor of four.

The drag force depends on velocity squared. If the drag force to fluidize the two grain particles is assumed to be equal to their respective weights, the smaller damaged grain will have one eighth of the drag of the larger whole kernel. Drag force depends on area and velocity squared. Since the smaller particle has one eighth of the weight and one fourth of the area of the larger particle, the suspension velocity squared decreases by a factor of two. Likewise, the suspension velocity decreases by a factor of square root of two (1.414). Therefore, it takes 1.414 times as much air velocity to fluidize the larger whole grain.

While simple and convincing, this explanation may be oversimplified for describing the terminal velocity effects of damaged grain. In soybeans, a sphere is a probably reasonably accurate model of a single soybean or even a split soybean. In corn, however, a sphere is probably not a good model of a whole kernel, and almost certainly a poor model of a damaged kernel.

The description of the decreased terminal velocity becomes much more difficult as it is no longer acceptable to assume that the drag coefficient does not change or that the effective frontal area of a damaged kernel and a whole kernel are different by a given factor.

While damaging a kernel may change its shape and size, the drag coefficient at high Reynold’s number flow is not likely to change dramatically, though it will likely be different. However, its effective frontal area may change dramatically. Effective frontal area depends on how the particle orients itself in the air stream. The causes of this
orientation are very complex and beyond the scope of this paper. However, a visualization of the difference in terminal velocity between damaged and undamaged kernels is very useful.

Conclusions

As the hypothesis stated, tailings returns are strongly influenced by threshing performance. Increasing cylinder speed increases tailings returns flows. At high cylinder speeds, less unthreshed grain escapes the cylinder, but the unthreshed grain level has little impact on the tailings. The tailings increase because of over-threshing; the over-threshed and damaged crop material has a propensity to enter the tailings. Damaged grain and mog contains smaller particles that are more difficult to separate in a cleaning shoe and more likely to fall into the tailings.
CHAPTER 6. TAILINGS AND CORN DAMAGE

Hypothesis: An increase in tailings will increase damage in the grain bin. Not returning the tailings to the main cylinder will cause a reduction in grain damage.

The tailings returns have been shown to contain significant amounts of clean, completely threshed grain. (Goss, 1955.) It is expected that re-introducing this threshed grain to the aggressive main cylinder of the combine will cause undue damage.

Grain damage is of primary interest in studying tailings. Presumably, high levels of tailings could significantly influence grain damage in the grain tank. There are some clear relationships between tailings and damage, but the difficult task is establishing cause-effect relationships between the two. For example, in Chapter 5 a graph was shown that showed linearly increasing tailings with increasing cylinder speed. Damage also increased linearly with increasing cylinder speed. Therefore, the damage level also increases with increasing tailings. However, it is more likely that the increase in cylinder speed caused the increase in damage and tailings than that the increase in tailings caused increased grain damage. This same problem occurs when observing damage and tailings at varying throughputs. It is difficult to discern whether the grain damage is influenced by the throughput, or by the tailings, or by both.

The most direct way to capture the effects of the tailings would appear to be to compare grain samples taken with the tailings returned to the main cylinder to grain samples taken with the tailings dumped on the ground. Even this does not necessarily give direct information on the tailings effects on damage. It has been shown that damaged grain has a propensity to end up in the tailings. If so, dumping the tailings on the ground could reduce damage in the grain bin simply by eliminating some damaged grain, not by preventing grain damage. Furthermore, eliminating tailings effectively reduces the throughput of the main cylinder, increasing its damage characteristics.

Nevertheless, this tailings vs. no tailings hypothesis was a key element of the 2000 harvest season studies. Because of limited time and crop in the 2000 season, the damage studies were restricted to corn only.
The first trend evident was that grain damage generally increased with decreasing combine throughput. The John Deere 45 combine illustrated this well in the October 12, 2000 study, especially at high threshing speeds. See figures 6.1 and A.34.

As seen before, the percentage of the crop flowing through the tailings also increased with decreasing throughput. However, it did not appear that the low throughput damage was influenced by the tailings. The data collected from the John Deere 45 combine do not show any significant change in damage between returning the tailings to the main cylinder, bypassing them to the straw walkers, or dumping them on the ground. Damage level changed as expected with changing throughput and cylinder speed, but where the tailings were directed seemed to have no additional effects. (See Appendix B for damage determination procedure.)

SAS statistical software was used to compute an analysis of variance on the October 12, October 30, and November 3 studies. (See Appendix C.) For the SAS analysis, both damage and the log of damage were modeled as a function of forward speed.
speed, cylinder speed, and tailings condition. In all models, both cylinder speed and forward speed appeared to have highly significant effects on damage. None of the models showed tailings condition (returned, bypassed or eliminated) to have a significant effect on the damage level. Also, in each analysis, an estimate of the difference in damage between no tailings and either tailings returned or tailings bypassed was calculated. None of the analyses showed a significant difference in damage with different tailings conditions.

The November 3, 2000 study was much more simplified. The tailings condition was the only treatment, and forward speed and cylinder speed were held constant. This study was evaluated with a 1-way ANOVA in SAS. The tailings did not have significant effects on the damage level. Estimated differences between no tailings and tailings bypassed or tailings returned were also not significant.

The data collected from the John Deere 9750 STS on November 21, 2000 is also not conclusive. There appeared to be a significant difference between the damage levels with tailings returned, bypassed, or eliminated only at the high throughput/high cylinder speed test. See figure A.35. Unfortunately, these data are suspect because randomization was limited by the small plot size. The limited area to harvest with this big machine necessitated taking both samples for each high throughput (high forward speed - 6mph) run in the same pass. Each pass of the plots had a different treatment. (The treatments were for an agronomy experiment for a different researcher.) Because of the plot treatments, the difference in damage may reflect a substantial difference in yield between passes. Despite these problems, the difference in damage is significant enough that it should be investigated further. Unfortunately, no more corn was available. Time and crop ran out in the 2000 season.

The low throughput data points were randomized properly and do not show a detectable difference in damage between tailings returned, bypassed, or eliminated. However, their variability may also have been significantly influenced by the variability of the plot yields.
In short, the tailings returns appear to have very little influence on the grain damage caused by the combine in the 2000 harvest season studies. This lack of correlation was not expected, nor is it readily explained by the studies.

For example, the tailings studies showed that in corn, a higher percentage of the damaged grain flows through the tailings at low throughputs. As stated previously, this increase is caused by an increase in air velocity across the sieve and chaffer with a light load on the cleaning shoe. If the tailings are eliminated, this damaged grain cannot get into the grain bin. One would expect a subsequent decrease in the damage in the grain bin sample. However, it does not appear in the 2000 data. Apparently, the damaged grain that flows in the tailings is recycled or discharged as loss; very little of it ever goes into the grain bin. Perhaps this damaged grain, when mixed with the incoming mog in the main cylinder, is difficult to separate and is discharged as separator loss. (The problem of intermixing threshed grain and mog and causing separation difficulties is mentioned in several patents shown in the literature review of this thesis.)

Also, the aggressive main threshing cylinder must be suspected as a cause of damaging some of the tailings as they are returned. Even at high cylinder speeds, dumping the tailings on the ground did not cause a decrease in damage. There are four potential explanations for this lack of an increase: 1.) The extra damaged grain is mixed with mog and discharged by the separator. 2.) The extra damaged grain is carried off the shoe by the fan blast. 3.) The loose grain does not incur significant additional damage when entering the main cylinder. 4.) Eliminating the tailings reduces the effective throughput of the main cylinder, increasing its damage characteristics.

The first two explanations provide a reasonably good rationale that eliminating the tailings instead of returning them does not change damage appreciably. Furthermore, if this damaged grain is lost, it should be evident by decreased yields. The yield vs. throughput graph previously presented supports either or both of these explanations. There is a substantial decline in yield at low forward speeds where tailings are high and the tailings carry a high percentage of clean grain. An increase in damage because of tailings entering the main cylinder again would also compound the loss problem, adding to the dramatic decline in yield. In addition, the peak yield is lower at high cylinder
speeds, indicating that much of the loss is probably damaged grain. However, it is
difficult to explain why essentially all of the damaged grain in the tailings is discharged
as loss, but there still can be an appreciable amount of damage in the grain bin. If the
combine discharges most of the damaged grain from the tailings, it would likely also
discharge most of the damaged incoming grain.

Figures 6.2 and 6.3 give some insight on the flow of damaged grain within the
combine. Figure 6.2 shows damaged grain flow vs. combine grain throughput at two
different cylinder speeds in corn. Damaged grain flow shown is the amount of damaged
grain flowing in pounds per second in the clean grain and tailings returns, respectively. It
was calculated as the percent damaged grain in each times the total flow rate of each.
Figure 6.3 shows the same data, but with the damaged grain in the tailings expressed as a
percentage of the total (tailings + clean grain) damaged grain flow. These graphs
illustrate how the flow of damaged grain shifts toward the tailings at low throughputs.
See also figure A.11.

![Graph showing damaged grain flow vs. measured throughput](image)

**Figure 6.2 Damaged grain flow vs. measured throughput.**
The total damaged grain flow increases with increasing throughput. Even though the combine damages a lower percentage of the grain at higher throughputs, the throughput increases faster than the damage level decreases. The tailings returns contains approximately a constant flow of damaged grain across throughputs; it is therefore a decreasing percentage of the total throughput and a decreasing percentage of the damaged grain throughput. These conclusions are likely to be slightly different for axial-feed rotary machines as their low throughput damage characteristics are generally more extreme.

The third explanation is not as likely, but it may have some merit. Grain, especially corn, is probably more easily damaged when still attached to the plant material. An ear of corn is many times the mass of a single loose kernel. When a rasp bar strikes a kernel or an ear, the impact of the rasp bar attempts to accelerate the kernel

![Diagram](Image)

**Figure 6.3** Percent damaged grain in tailings vs. throughput.
or ear to a similar speed. The force required for even a very high rate of acceleration of a kernel of corn weighing less than one half gram is not very large. However, the force to accelerate a complete ear of corn is many times higher. The force is distributed over only the kernels that the rasp bar contacts, and those kernels would seem to be much more susceptible to damage. Therefore, loose grain entering a threshing cylinder may incur much less damage than unthreshed grain. This presents an interesting topic for further research.

The fourth explanation may also be useful. Throughout the 1999 and 2000 harvest seasons combine throughput was shown to have very significant effects on grain damage. In general, decreasing throughput caused increased grain damage. The trend was particularly evident in axial flow rotary combines, but less obvious with conventional combines. In normal operation, the tailings add to the total throughput of the threshing cylinder. When the tailings are bypassed to the cleaning system or eliminated, the effective throughput of the threshing cylinder goes down. As the throughput falls, the damage level increases. The damage savings by not returning the tailings may be offset by the increase in damage at the main cylinder because of decreased throughput.

Theoretically, the expected increase in damage with no tailings could be calculated. If the tailings flow rate were known from experimental data, and the damage vs. throughput curve for the particular machine had been established for the specific conditions, one could predict the increase in damage from the decrease in throughput. However, verifying the prediction would be difficult. The combine throughput would have to be increased so that its new level without tailings would equal its previous level with tailings. The idea would be to set up two equal throughput conditions, one with tailings, and one without tailings. If the tailings incur extra damage, but offset it by increasing the throughput, the identical throughput without tailings should yield lower damage. This study was not performed in the 1999 or 2000 harvest season, but it would be useful in future studies. However, the damage difference would probably be pretty small and may be difficult to detect. The study would have to be taken in very uniform crop and would probably require a lot of replication to detect the small difference.
Conclusions

The hypothesis of this chapter was not supported by these studies. The tailings returns system responds significantly to different grain damage levels, but has not been proven to actually influence the grain damage level. There are several potential reasons for this unexpected trend; none of them have been investigated in detail in this research. This tailings research has exposed some important combine damage characteristics, especially at low throughputs. In addition, it has pointed to interesting topics for future study in the areas of grain damage and low throughput combine losses. It should be noted that the testing completed is not adequate to disprove the hypothesis. Tailings probably do influence grain damage, but these studies have shown that the difference is either very small or relatively difficult to measure.
CHAPTER 7. DAMAGE, THROUGHPUT, AND LOSSES

Hypothesis: Low throughput and high damage cause elevated losses.

Tailings are related to losses. Very simply, when tailings flow rates rise, losses can be expected to rise. If more grain is making its way to the tailings, inevitably more of it is discharged as loss. If that is true, and the tailings flow percentage increases with decreasing throughput, it is likely that shoe losses increase with decreasing throughput as well. To test the hypothesis, shoe loss was evaluated in the July 29, July 30, and November 12, 1999 studies. See figures 7.1 and A.15-A.19. Tailings percent vs. forward speed is included in figure 7.1 to show the similarity in the two trends.

One simple way to illustrate the relationship between tailings and loss is to change the fan speed. It is difficult to over-speed the fan by very much in large grains like corn and soybeans, but in cereal grains, the fan can usually be set to a speed that causes severe losses. Figure 7.2, a graph from the July 29 data shows shoe loss in wheat vs. cleaning fan speed.

Shoe loss and tailings vs. Grain throughput Oats 990730 JD 4420

![Graph showing shoe loss and tailings vs. grain throughput.]

Figure 7.1 Shoe loss vs. grain throughput.
In these tests, shoe loss vs. fan speed followed two trends. At lower fan speeds (below 750 rpm) the loss remained nearly constant or may have declined slightly as fan speed increased. In this range, the separation on the shoe was predominantly mechanical. From 750 to 1025 rpm, though, there is an astronomical rise in shoe loss. This loss corresponds closely with the dramatic increase in tailings in the same range. Interestingly, there is a noticeable rise in the tailings flow by 750 rpm, but there is no evidence of an increasing loss by 750 rpm. It appears that tailings levels become elevated before loss levels do.

![Shoe loss vs. Fan Speed](image)

**Figure 7.2** Shoe loss vs. fan speed in wheat.

The July 30 and November 12 studies relate shoe loss to the low throughput increase in tailings returns.

There is a dramatic increase in shoe loss that corresponds well with the increase in tailings at low grain throughputs. The data from the November 12 study in corn also shows this increase in shoe loss. See figures 7.1 and 7.3. These graphs show shoe loss vs. grain throughput with tailings flow plotted on the second axis for comparison. Note that the trends are very similar between shoe loss and tailings percent of throughput.
The graphs of yield vs. forward speed (throughput) become more interesting when they are compared with actual measured yield data. A graph of shoe loss vs. grain throughput at two different cylinder speeds was constructed from the November 12, 1999 data.

![Graph of shoe loss vs. grain throughput](image)

**Figure 7.3 Shoe loss vs. grain throughput.**

A graph of yield vs. forward speed was also prepared from the same data. The November 12 data is particularly good because the plot harvested that day was very uniform high yielding corn and was standing very well. The shoe and walker losses were measured, but the walker loss was negligible in all of the tests. The highest shoe loss measured for the low and high cylinder speeds were 0.3 and 0.7 percent respectively. However, the difference between the low throughput yields and the peak yields for the low and high cylinder speeds are 21.6 and 14.0 percent respectively. This data is somewhat open to criticism because header loss was not accounted for. However, at the same forward speed the yield was between 4.1 and 17.5 percent greater for the low cylinder speed. It is extremely unlikely that header loss varied that much in a very uniform field at the same forward speed. See figure 7.4.
This data is not replicated, and the error in measurement is not known, but there are almost certainly some good indicators here. This "invisible" loss is probably grain that was ground to very small particles or dust. This dramatic difference in yield has substantial economic value and demands further investigation.

Figure 7.4 Measured yield vs. Grain throughput

A little bit more information on invisible losses can be gleaned from the November 12 study. The grain lost on the shoe was predominantly damaged grain. This damaged grain was counted as grain loss. The shoe loss samples from the rethresher contained from 0.6 to 9 percent whole kernels. The whole grain loss from the rethresher itself was not detectable, but the rethresher was not getting all of the damaged grain separated from the shoe mog. Even if the rethresher was able to clean out all of the damaged grain, by the percentages of whole grain in the loss samples each whole kernel represented from 10 to 165 more kernels that had been ground up. When an operator looks on the ground behind a machine for loss, this damaged or "invisible" loss is not
evident. This single study is certainly not adequate to quantify invisible losses in general, but it does indicate that they are probably important, especially if the combine is not properly adjusted.

Conclusions

Field studies support the hypothesis of this chapter. Low throughput and high damage can cause dramatic increases in combine losses. Furthermore, low throughput and high cylinder speed in combination appear to exacerbate the loss problem. Low throughputs, for example, cause both increased damage and under-loading of the cleaning shoe. Elevated cylinder speed adds significantly to this damage. The damaged grain particles are easier to fluidize as shown in Chapter 5, and the under-loaded cleaning system is very capable of fluidizing them as shown in Chapter 4. Therefore, at low speeds, the grain is more likely to be lost by the cleaning system, and the cleaning system is operating in a fashion that is more likely to lose grain. In addition, at low throughputs, the tailings returns carries a much higher portion of the throughput back to the main cylinder to be potentially damaged again. These studies have not given conclusive evidence that clean grain in the tailings returned to the main cylinder causes increased damage in the grain bin. However, if there is additional damage from the returned tailings, it would tend to increase loss at low throughputs even more.

These studies have also shown that low throughput losses may be difficult to see or measure; they are often “invisible” losses. The economic value of these losses can be substantial, yet many combine operators may not ever realize they are occurring.
CHAPTER 8. OPTIMAL MACHINE OPERATION

Hypothesis: The data shows that information about tailings is an indicator of combine performance and may help locate optimum operating conditions.

A combine in any crop and condition it is capable of harvesting will have an optimum operating point. The optimum operating point is the combination of settings and operation (i.e., cylinder speed, fan speed, sieve setting, throughput, etc.) that yields the best performance. "Optimum" performance, however, depends on the criteria by which it is measured. J.W. Hall describes optimization well. He stated that a machine is optimized when adjusting any one characteristic of the combine will degrade at least one of the performance indicators of the machine. The performance indicators are the criteria by which the operator evaluates the performance of the machine (i.e., throughput at 1% loss, grain damage, grain sample purity, etc.)

In most situations, the performance indicators are chosen and optimized such that the economic returns from the combine will be maximized. However, machines are very seldom truly optimized because operators generally optimize one thing at a time. Optimizing only one adjustment at a time will optimize that setting only in accordance with the other settings of the combine at that time; it will not optimize the combination of settings. The data collected in these tailings return studies has pointed toward a very useful and reasonably simple approach to machine optimization.

The best indicator of economic value of the harvesting performed by the combine is the measured grain yield. Yield measurements allow direct and simple calculations of returns in dollars per unit of field area, probably the most important factor in effective farm management.

Detailed measurements have shown that yield is maximized when combine settings are optimized. For example, Chapter 7 discussed low throughput losses. These losses are immediately apparent in a measured yield vs. throughput graph for the machine. A yield vs. throughput graph for essentially any combine will have a dome shape. The yield will be optimum at some throughput, and increasing or decreasing the throughput will cause a reduction in yield.
Even most inexperienced combine operators expect losses at excessively high throughputs. However, many combine operators, even experienced operators, do not expect or understand low throughput losses.

Figures 8.1 and 8.2 show plots of grain yield vs. throughput in soybeans and oats respectively. See also figure A.14. All the graphs show the characteristic dome-shaped curve. Also, note that the peak yield occurs at very nearly the same throughput in both crops. This suggests that the optimum operating grain throughput may not depend on the type of crop, but is intrinsic to the machine.

Low throughput losses present an interesting topic for further study for several reasons. 1.) Their economic value may be substantial, and is quite likely much higher than high throughput losses. 2.) They have not been well quantified or published, and most combine simulation models ignore them. 3.) They are generally invisible losses.

Figure 8.1 Measured yield vs. throughput in soybeans.
All but the most extreme low throughput losses are very difficult to detect just by looking at the field the machine leaves behind. 4.) It is generally not difficult to prevent high throughput losses by operating the machine slower, or with a smaller grain head, but low throughput losses are often unavoidable with machines configured as they are at present. Quick (personal communication, 2001) has data that shows that axial feed rotary type combines accentuate this low throughput phenomena more than conventional tangential feed machines.

**Measured yield vs. Throughput Oats 990729 JD 4420**

![Graph showing measured yield vs. throughput in oats.](image)

**Figure 8.2 Measured yield vs. throughput in oats.**

The focus of these studies was the tailings return system, not combine optimization. However, combine optimization is closely related to tailings returns. In general, the tailings returns are minimized when the combine is operating at its optimum performance.

Measuring yield vs. throughput, however, provides direct information as to the amount and value of low throughput losses. In fact, plots of yield vs. other combine
settings provide similar dome shaped curves. Cylinder speed, for example, has an optimum point for maximizing yield where threshing losses are minimized, but grain damage is not excessive.

Conclusions

The factors that directly influence the tailings returns all have an optimum operating point. Tailings returns are generally minimized when each factor is optimized; the composition and amount of tailings returns is a reasonably good indicator of combine performance. Many early self-propelled combines reflect this in their design. On many early self-propelled combines, provisions were made so that the operator could view the material flowing in the tailings returns while the combine operated. The most recent combine built with such provisions was the Gleaner conventional combine manufactured by Duetz-Allis Corporation through 1987. Operators could view the tailings amount and composition to help them optimize the cleaning and threshing performance of the machine.

"Optimum" performance is very subjective, depending on the goals of the combine operator, but this approach to maximizing yield is very useful in almost all situations. In addition, yield is relatively easy to measure, it avoids the difficulty of loss catching and rethreshing, it includes gathering loss and invisible loss, and it translates directly into dollars of return for the producer.
CHAPTER 9. LOAD SENSITIVE CLEANING SYSTEM

Hypothesis: The tailings return system and general combine cleaning shoe performance could be improved if the cleaning shoe was load sensitive.

These tailings return studies have indicated many shortcomings of combine performance at low throughputs. Grain damage increases, shoe losses increase, and invisible losses increase as well. Most of these low throughput problems can be related directly or indirectly to the combine cleaning shoe. There is a potential to greatly reduce the tailings at low throughputs and improve the shoe performance if the shoe can be sensitive to the load on it.

Chapter 4 showed that the conventional cleaning shoe used in most modern combines has a tendency to lose grain at very low throughputs primarily because of the fan. Furthermore, it allows more grain to fall into the tailings returns. This grain is potentially damaged further, and returned to the cleaning shoe. Chapter 7 illustrated how increased damage exacerbates shoe losses. Chapters 7 and 8 showed that the economic implications of these low throughput shoe losses are substantial, that they are often invisible, and that they often cannot be prevented.

A combine cleaning system with the capability to compensate for the load of material entering it could greatly enhance combine performance at low throughputs. It may also be able to provide extra capacity at high throughputs.

Most generally the problem with the cleaning system seems to be the velocity of the air that contacts the grain. If the shoe is under-loaded and the velocity of the air across the chaffer and sieve are too high, grain is fluidized by the air and blown away as loss. If the shoe is overloaded, the fan airflow tapers off under the elevated static pressure. If the velocity could be held more nearly constant, the shoe may have better performance at both under-loaded and overloaded conditions.

There are several potential approaches to accomplishing this; none of them have been tested or modeled in the development of this paper.

One approach to keeping the velocity more nearly constant under different loads would be to replace the fan with some type of a positive displacement air pump. Positive displacement would mean a near constant airflow across a wide range of static pressures.
However, pumps are notoriously inefficient at low static pressures (like the fan in a combine cleaning shoe), and they require a lot of power to develop high airflow rates.

Another approach would be to use a larger, more powerful fan capable of higher static pressures. The airflow could be restricted with a wind board or some other apparatus to maintain a certain airflow rate. The wind board could be controlled via a feedback controller that would maintain the same static pressure from the fan. At the same static pressure and same outside air conditions, the fan would deliver the same airflow regardless of shoe loading. However, an oversized fan would undoubtedly be more expensive and less efficient.

There are certainly other ways to develop a cleaning shoe that is sensitive to the load on it. Perhaps there is a way to optically or mechanically measure the mat of mog on the chaffer or sieve, or the mass or volume flow rate of material from the grain pan. The information could feed back to a controller that could control fan speed or a fan choke to maintain a constant air velocity across the sieve and chaffer.

**Conclusions**

All of the studies in this thesis have shown that the performance of a combine cleaning system is directly influenced by its loading conditions. This thesis was not intended to develop a load sensitive cleaning shoe, and none of the above ideas have been tested, but the issue has arisen as an outcome of this work. The data collected for this research have shown that shoe performance is highly dependent on shoe load. This chapter is a discussion of one aspect of combine performance that relates directly to the tailings returns. A load sensitive cleaning shoe has the potential to reduce the volume of tailings returns, and make the material in the tailings returns more consistent. Any system that could compensate for changing shoe loading could offer performance advantages for the combine, especially at low throughputs. This information presents an interesting topic for future study.
CHAPTER 10. DEVELOPING A RETHRESHER

Hypothesis: A tailings returns rethresher is a useful and practical replacement for a conventional tailings returns system.

**Goals of a rethresher**

A tailings rethresher must fill a need on modern combines to be successful and marketable. There are a number of goals to meet to make sure that a rethresher is a useful and practical addition to a combine.

The tailings returns studies from the 1999 and 2000 harvest seasons were intended to provide information for the development of a tailings rethresher. They helped to define the goals of a rethresher. The studies also provided useful information to determine the necessary capacity of a rethresher and the types of materials it will encounter.

1. **A rethresher must offer some performance advantages for the combine.**

   The most likely performance advantages are reduced grain damage and losses. The tailings return studies were not conclusive as to whether handling tailings differently can reduce grain damage. However, if the damage can be reduced as is expected, the invisible losses will subsequently decrease. Avoiding intermixing tailings with incoming crop may promote better separation and reduce losses as well. Furthermore, a rethresher that is capable of distributing the tailings evenly across the body width of the shoe will help prevent overloading a narrow band of the chaff when tailings flows are high. It may also offer advantages when the machine is operating on side slopes.

2. **A rethresher that is to be marketable should be readily adapted to current production combines.**

   Even if a rethresher offered some performance advantages, it would not attract the attention of combine manufacturers or aftermarket companies if it required extensive re-engineering of production machines.

3. **A rethresher should not add significantly to the cost of a combine.**

   Rising costs with technology increases have already made the cost of new combines difficult to justify. Increases in cost, even with improved performance, make combines difficult to sell.
4. *A rethresher should not require substantially more power to drive than a conventional tailings return system.*

Power requirements are directly related to costs. More horsepower is available for combines, but its cost is substantial. Also, higher power drives and bearings are more expensive and require more maintenance.

5. *Rethreshing the tailings material should be optional.*

The tailings returns studies clearly indicated that in many crops and conditions, the tailings returns contain essentially no unthreshed grain. This free grain needs only to be re-cleaned. Exposing it to threshing again is completely unnecessary and probably detrimental. A rethresher should provide a means for returning the tailings to be re-cleaned without exposure to threshing again.

6. *A rethresher must not interfere with any other operation of the combine.*

A rethresher will not be acceptable if it is too large or poorly located so that it interferes with the steering or ground clearance of the combine. Also, if the rethresher offers optional rethreshing, it must be able to deliver material to be re-cleaned so as not to interfere with the cleaning system. It should be able to provide a reasonable distribution across the cleaning system so that none of it is overloaded, and it should not interfere with the cleaning airflow. The even distribution will also be advantageous in balancing the shoe load on sideslopes.

7. *A rethresher should not limit the capacity of the combine.*

The tailings studies have shown that the tailings returns system may handle a very large amount of grain in some conditions. A good goal for a rethresher is to design it for a continuous capacity of 50% of the capacity of the clean grain system. A rethresher capable of this would probably never limit the capacity of the combine. In general tailings returns of 25% of the combine throughput or more are an indicator that the combine is overloaded or not set properly.

**Prototype 1**

The first prototype was developed concurrently with the 1999 harvest season studies. It was an attempt to meet most of the above goals (not all of which were clearly defined prior to its development.).
Though it fell short in some areas, the first main design principle of this rethresher was to convey the tailings with airflow. The advantage of conveying the tailings with airflow is eliminating the tailings returns elevator. Eliminating the elevator reduces the complexity of the system, and reduces cost to offset the added cost of the rethreshing cylinder.

A combination threshing cylinder/centrifugal fan was the key element to limit cost and complexity of this prototype. The first cylinder was a six blade centrifugal fan. The end of each blade was bent backwards to accept a rasp bar. The blades were designed such that they could accept short sections of John Deere 9000 series combine rasp bars. The diameter of the rotor was 13.5 inches without the threshing elements. Adding rasp bars was to bring the final diameter to approximately 14.5 inches.

![Figure 10.1 Generation 1 rethresher cylinder](image)

Figure 10.1 Generation 1 rethresher cylinder

The cylinder was intended to run at approximately 1000 rpm for a peripheral speed of about 3800 feet per minute. This determination of this peripheral speed was not
really scientific; it was intended to be approximately the maximum peripheral speed acceptable for threshing soybeans without excessive damage. Soybeans were chosen because they are a large grain that often requires rethreshing, but requires lower peripheral speeds than small grains. (The velocity of 3800 fpm is in general too high for corn, but these tailings studies showed that corn tailings never contained unthreshed grain. Though this design did not allow for optional rethreshing, it was the intent for future prototypes.) The speed was maximized to provide maximum airflow from the fan for conveying large grains. Small grains are much less limiting to this rethresher design for two reasons. 1.) Small grains can be conveyed with air more easily than large grains. 2.) Small grains are less susceptible to damage and are threshed at higher peripheral speeds. The intention of this design was to use a single cylinder speed for a crop range to limit cost and complexity. The velocity of 3800 fpm was chosen as a balance between damage and airflow and as a starting point for testing.

The housing was circular, not scroll shaped like most centrifugal fans. It was circular because the fan needed to be close to the bottom of the housing. The fan acted as a threshing cylinder and the housing as a concave. This design provided a threshing surface (concave) for about 135 degrees of wrap. The tailings entered the housing at the top rear and exited on the front at an upward angle of 45 degrees. Air entered through the sides of the housing and through the sides of the cylinder. It was accelerated outward by the blades and exited through the upward opening on the front. A chute attached to the opening was to direct tailings back to the grain pan. However, this prototype was only tested in the lab, never on a combine in the field.

During testing it was immediately apparent that the rethresher did not develop enough airflow to convey grain. It could convey grain, but almost all of the conveying force came from contact with the cylinder, not from the airflow. Loose corn kernels dropped into the exit of the rethresher would float, but not be blown out by the air. Some airspeed measurements with a pitot tube across the opening revealed problems with the airflow distribution as well. Table 10.1 shows the airflow distribution of the first generation rotor.
The airflow of prototype with the first generation rotor was evaluated by dividing the 5-inch x 10-inch opening into a 3 x 6-point grid. Air velocity pressure was measured at each point in the grid with a pitot-static tube and a Magnahelic pressure meter. The air velocity was calculated from the measured velocity pressure at each point, assuming air at standard conditions. The airflow volume flow rate was calculated as the velocity at each grid point multiplied by the area of the corresponding grid square.

The average velocity was 19.9 ft/s and the peak velocity was 33 ft/s. The calculated volume flow rate was 415 cfm. The airspeed was not only well below the target of 50 ft/sec, but weak near the center, and near the top center of the opening, it seemed that air was not moving or may have been flowing back into the cylinder.

Table 10.1 Generation 1 cylinder velocity distribution

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<th>3.5</th>
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Rotor Revision 2

The first attempt to correct the shortcomings of the first prototype cylinder was to replace the cylinder. For this attempt, the cylinder was replaced with a forward-curved centrifugal fan with no threshing elements. The intention of using a fan was to attempt to prove whether the concept was even viable. If a fan would not develop adequate airflow, a combination threshing cylinder/fan certainly would not work.

Figure 10.2 Generation 2 rethresher cylinder
This fan had a diameter of 13.5 inches, and 24 blades each 2 inches deep and angled forward 20 degrees. The blades on the fan were forward-curved to produce higher air velocity. Forward-curved blade fans have relatively poor efficiency, but they cause the air to exit the periphery of the fan faster than the peripheral velocity. (Bleier, 1998.) This was another way to increase air velocity and minimize peripheral fan speed. Also, the air inlet hole diameter in the fan was increased from 6 to 7 inches, and the spokes were narrowed from 1 inch to 0.75 inches. See figure 10.2.

The tests with this fan rotor were much more promising. At the same speed, the fan was able to carry loose corn out of the opening without the fan blades ever touching the corn. The air velocity was markedly improved as was the airflow distribution.

The airflow was measured with the same method as described for the first cylinder, but this time a more precise 5 x 7 grid was used. Table X shows the airspeed at each square in the grid.

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<th>3.5</th>
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</tbody>
</table>

The weighted average velocity was 38 ft/s and the peak velocity was 59 ft/s. The airflow was concentrated toward the center and the airspeed was higher near the lower edge of the fan opening. The total airflow was calculated at 811 cfm, much higher than the generation 1 cylinder.

Rotor revision 3

Since replacing the cylinder with a fan allowed the rethresher to convey grain, there was still hope for a combination fan/threshing cylinder. The third generation cylinder for this prototype was based directly on the forward-curved fan design of the second-generation cylinder. The side plates of the cylinder were identical, but the blades were different. The blades were bent to cover every other air opening between blades. A
threshing element could then be placed on each of these blocked openings. See figure 10.3.

The lab tests with the third generation cylinder were also promising. It did not develop as much air velocity as the second-generation cylinder, but it was still able to convey loose corn with airflow. The airflow distribution suffered somewhat from the design changes, but was still much better than the first cylinder.

The airflow developed by the third-generation cylinder was measured with exactly the same method as was used for the second-generation cylinder. The air velocities for each grid are shown in table 10.3.
The weighted average velocity was 30 ft/s, and the peak velocity was 63 ft/s. The total air delivery was approximately 628 cfm. As expected, the generation 3 cylinder balanced the airflow characteristics of the generation 2 cylinder with the threshing capability of the generation 1 cylinder.

**Prototype 2**

With some of the airflow problems alleviated, there still was considerable room for improvement in the design of the rethresher. The first prototype did not allow optional rethreshing. All of the tailings material that entered the cylinder inevitably contacted the threshing cylinder. The second prototype rethresher offered the ability to divert the tailings directly into the air stream leaving the cylinder so that grain avoided contact with the cylinder. It used the same cylinder as the first prototype.

In the second prototype, the tailings entered the cylinder housing via the tailings auger in the top center. There was a swiveling door on the tailings auger that could be positioned to allow the tailings to exit the front side or the back side of the tailings auger. If they exited the front side, they would slide down directly across the exit of the cylinder housing and would be entrained in the exiting air stream. If they exited the rear of the tailings elevator, the tailings would fall into the cylinder and be pulled outward against the concave. They would be threshed for approximately 150 degrees of wrap before exiting with the air stream to be returned to the grain pan. See figure 10.4.

![Figure 10.4 Rethresher prototype 2 installed on John Deere 45 combine.](image-url)
The second prototype was assembled to be tested on a John Deere 45 combine instead of in the lab. It was mounted on the side of the combine over the tailings auger exit hole. Note that the duct from the rethresher outlet to the cleaning system is not installed in the picture. The installation was not completed because preliminary testing showed the airflow was inadequate for conveying the tailings.

The prototype 2 rethresher was driven by a hydraulic motor. Oil for the hydraulic motor was taken from the power steering circuit of the combine. The cylinder was capable of about 1000 rpm. However, it became apparent that this rethresher would not develop enough airflow to convey the tailings. It was not field tested because it was unable to convey loose corn during several test runs in the shop. An attempt was made to increase the velocity by adding a chute of smaller cross sectional area, but the rethresher did not seem to be able to produce enough static pressure to force a higher velocity airflow through a smaller chute. Furthermore, this rethresher design caused a severe ground clearance problem. While acceptable to prove a concept, this rethresher was obviously not marketable in its present form, even if it had worked well.

**Prototype 3**

More research was necessary to develop adequate airflow from a rethresher to convey tailings. The cylinder/fan housings of the first two prototypes were far from the ideal scroll shape of an efficient centrifugal fan housing. However, a scroll-shaped housing could not use a concave on the bottom because the cylinder/concave clearance would be excessive.

The third prototype rethresher was designed with a scroll-shaped housing and an inverted concave. The tailings auger entered the rethresher housing directly above the outlet. Removable panels allowed the tailings from the auger to be diverted either to the air stream or to be delivered to the front of the rethreshing cylinder. The first portion of the top of the housing, where the cylinder to housing clearance was moderately small, acted as a threshing concave. See figures 10.5 and 10.6.

This third prototype was tested with the third generation cylinder. The preliminary airflow tests were promising, but the air velocity was below optimum for entraining large grains in an air stream. The airflow was evaluated by dividing the 8-inch
by 10-inch opening into an 8 x 10 grid and using the method previously described. The flow through each of the 80 grid points was taken to be the velocity at the point multiplied by the 1 square-inch area that it represented. The calculated velocities are shown in Table 10.4.

The average velocity was 28 ft/s and the peak velocity was 45 ft/s. The total flow rate was approximately 930 cfm.

Table 10.4 Housing 3 generation 3 cylinder airflow distribution

<table>
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<td>42.84</td>
<td>39.66</td>
<td>35.60</td>
<td>25.60</td>
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</tbody>
</table>

Figure 10.5 Prototype 3 rethresher on lab test stand.
Subsequent testing with corn showed the shortcomings of this prototype, though. In the rethresh mode where the corn was directed into the threshing cylinder, the capacity of the rethresher seemed to be reasonably good. However, when the rethresher was set to bypass the crop only into the air stream, the capacity was extremely limited, if the rethresher conveyed the grain at all.

Without the agitation of the cylinder to accelerate the grain, the airflow was not fast enough to entrain the corn in the air stream before it fell to the bottom of the housing. The corn collected in the bottom of the rethresher housing, and the air stream was unable to move it. See figure 10.7. The rethresher needed some provision to either agitate the grain to entrain it in the air stream, or slow its fall so that it would have more time to be conveyed aerodynamically.

No agitator or other device has been tested yet for this prototype. In the near future, at least one device will be tested. An angled screen will be placed in front of the fan outlet and underneath the auger discharge. The grain will fall onto the screen and roll down and forward toward the bottom of the fan housing. The grain will thus be held in the air stream for a longer period, giving it more opportunity to be fluidized and carried
Figure 10.7 Corn collected in the base of the housing of prototype 3 away by the air from the cylinder. It is expected that this will improve the capacity of the rethresher, but the capacity will still be severely limited.

**Conclusions**

The rethresher developed in this thesis shows some potential, but it has not been reduced to practice yet. There are two major problems with the design presented here: 1.) It is very difficult to design a combination fan/threshing cylinder that will develop enough airflow for good conveying capacity without excessive peripheral speed. 2.) Forcing grain to become entrained in an air stream without allowing it to be accelerated by the cylinder requires some creative methods or a very high velocity air stream.

There are other important deciding factors in the fate of this rethresher not discussed in this thesis. The power requirements have not been analyzed, but are probably significantly higher than a tailings elevator. The costs of construction are also not yet known because the prototype was not designed specifically for minimum cost. It was designed for simple assembly and avoiding the use of permanent tooling. Only when the performance of the rethresher is improved and these additional criteria are evaluated would such a rethresher be practical for production.
CHAPTER 11. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The objectives of this thesis were stated at the beginning of each chapter with a hypothesis to be tested. Each chapter is summarized with the respective outcomes:

1. Tailings flow rate is not independent of combine throughput; it increases with increasing combine throughput. The tailings as a percentage of throughput increases dramatically with decreasing throughput. This is not a result of threshing performance; it is caused by the high fan blast exposure in the under-loaded cleaning shoe.

2. Threshing performance strongly influences the tailings returns, but not as expected. Tailings increase with increasing cylinder speed; this study does not agree with most published literature. The elevated tailings occur because of over-threshing. The over-threshed and damaged grain and mog have properties that make them more difficult to separate and more likely to enter the tailings returns.

3. The tailings returns system responds to different damage levels, but it has not been proven to cause additional grain damage. In fact, there is some evidence that damage decreases if the tailings are dumped on the ground.

4. Grain damage has a strong effect on grain losses in addition to its effects on the tailings returns. Elevated grain damage means elevated losses. These losses may be substantial, and they are often invisible and difficult to detect or quantify.

5. Tailings returns amount and composition is a reasonably good indicator of combine performance. Furthermore, the information gathered and the methods used in these studies provide some useful insight into combine optimization.

6. A load sensitive cleaning shoe would help negate the varying throughput effects. It could help decrease the amount and improve the consistency of the tailings to enhance the operation of a rethresher and decrease shoe losses.

7. A tailings rethresher offers some advantages to combine performance. The design proposed in this thesis needs further development before it will be practical for production. Conveying tailings with air in the proposed way is difficult without some
type of mechanism to agitate the grain and entrain it in the airstream. Other systems need to be considered.

In addition to the conclusions above, there are many characteristics of the tailings returns system not thoroughly investigated in these studies. There is much room for future research. Some recommendations for future studies are as follows.

Tailings come from either the chaffer extension or from the back of the sieve. These included tailings studies contain almost no information as to how much of the tailings comes from each. Information about the amount of material from each source and its composition would give some insight to the operation of the cleaning shoe. The amount of grain coming through the chaffer extension may be a good indicator of shoe loss.

There were some indications that the sieve setting affected the airflow distribution across the sieve. Opening the sieve too far may cause too little restriction and a subsequent drop in static pressure. Some level of static pressure is certainly necessary to keep a reasonably good airflow distribution across the sieve. However, these studies contain no information about airflow amount, distribution, or static pressure. Airflow across the sieve is a whole topic in itself, but some information on the way air flows over a sieve would be a valuable addition to the completed studies.

More information about combine invisible losses would also be very useful. Invisible losses were apparent in several of the studies. Generally, when the combine was adjusted so that it caused increased grain damage, there was a substantial reduction in measured yield. Only a very small portion of this apparent loss could be detected with loss catching equipment. It would be important to know more about the actual level of invisible loss.

Invisible loss also has implications on the tailings vs. damage studies, too. It is possible that there is a significant difference in damage between tailings returned and no tailings, but it is washed out because much of the damaged grain is invisible loss. It would be very interesting to know the relationship between grain damage and invisible loss. The most significant economic loss in damaged grain may prove to be the grain left
in the field, not the storability or grain quality discounts. Little data is currently available on this subject, and the economic impacts of it may be surprising.

Combine grain damage in general is of interest because of the invisible losses pointed out by these studies. One potential topic for future study shown in chapter 6 is an investigation of whether corn is more likely to be damaged on the ear as opposed to free kernels. An unthreshed corn ear has many times the mass of an individual kernel, so the force to accelerate at a similar rate is much higher. Does this make the kernels on the ear particularly vulnerable to damage in comparison to free kernels in the incoming tailings?

The relationship between tailings and damage was not well quantified in this research. Specifically, the grain damage in the grain bin was not statistically different with or without tailings. It was expected to be different. Chapter 6 discusses this in some detail and proposes some potential explanations for the lack of a difference, but the research conducted so far has not been adequate to draw any firm conclusions.

The method of plotting yield vs. throughput and/or other combine parameters demands further investigation as well. Chapters 7 and 8 further explain this plotting method. In general, published literature states that combine losses cannot be acceptably estimated by yield measurements, but the data taken in these studies points very much to the contrary. Furthermore, yield is a very meaningful parameter especially to combine operators because it translates directly into economic returns. This yield vs. throughput curve may also be the key to estimating invisible losses.

The topic of Chapter 9, a load-sensitive cleaning shoe for a combine, is an interesting topic for future study. A load-sensitive cleaning shoe could potentially offer low throughput grain savings as well as increased capacity. The methods proposed in Chapter 9 require much research and may not be feasible, but a workable load sensitive cleaning shoe could be a significant development.
APPENDIX A – GRAPHS

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Figure A.1 Tailings percent vs. Fan speed Oats 990726 JD 4420

2.5 mph
0.7 mph
1.5 mph

Tailings percent of throughput
Fan speed (rpm)
Figure A.2 Tailings percent vs. Fan speed Wheat 990729 JD 4420
Figure A.3 Tailings grain vs. Fan speed Soybeans 991005 JD 4420
Figure A.4 Tailings composition vs. Fan speed  Soybeans 991005

- **Whole soybeans**
- **Splits**
- **Unthreshed**
- **MOG**

<table>
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<th>Fan speed (rpm)</th>
<th>Percent of total tailings</th>
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<td>1100</td>
<td>40.00</td>
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</tbody>
</table>

- **Legend:**
  - Solid line: Whole soybeans
  - Dotted line: Splits
  - Dashed line: Unthreshed
  - Crossed line: MOG
Figure A.5: Tailings percent vs. Grain throughput. Oats 990726 JD 4420

- 850 fan rpm
- 650 fan rpm
- 1040 fan rpm

Grain throughput (tons/h)

Tailings percent of grain throughput
Figure A.6 Tailings percent vs. Grain throughput Oats 990730 JD 4420

![Graph showing tailings percent vs. grain throughput for oats 990730 JD 4420. The graph plots tailings percent on the y-axis and grain throughput (tons/h) on the x-axis. The data points are connected by a curve, indicating a decreasing trend in tailings percent as grain throughput increases.]
Figure A.7 Tailings percent vs. Grain throughput Corn 990928 JD 4420
Figure A.8 Tailings percent vs. Grain throughput Soybeans 991005

JD 4420

Grain throughput (tons/h)

Tailings percent of throughput

3.5 3 2.5 2 1.5 1 0.5 0 4 6 8 10 12
Figure A.9 Tailings percent vs. Throughput Case IH 2388

Corn 991022

Grain throughput (tons/h)

Tailings flow (% of throughput)

410 rpm

660 rpm

10 20 30 40 50 60 70 80 90

0 10 20 30 40 50 60 70 80 90

84
Figure A.10 Tailings composition vs. Throughput Corn 991022 Case IH 2388

- ♦- Undamaged Grain
- ▐- Damaged grain
- ▲- MOG
Figure A.11 Tailings grain flow vs. Throughput Soybeans 991005
JD 4420
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JD 4420

Measured Yield (bu/acre) vs. Throughput (tons/h)
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 JD 4420

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Shoe loss (% of Yield)

Fan speed (rpm)
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JD 4420
Figure A.21 Tailings percent vs. Cylinder Speed  Corn 990928 JD 4420
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JD 4420
Figure A.23 Tailings vs. Cylinder speed Corn 991004 JD 4420
Figure A.24 Tailings Composition vs. Cylinder speed Corn 990928

JD 4420

Whole Grain
- Damaged grain
△ MOG

Cylinder Speed (rpm)

Percent of total

80 70 60 50 40 30 20 10 0

350 450 550 650 750 850 950 1050
Figure A.25 Tailings percent vs. Cylinder speed Soybeans 991005
JD 4420

Tailings percent of throughput

Cylinder speed (rpm)
Figure A.26 Damage vs. Cylinder speed Soybeans 991005

JD 4420

Percent Visible damage

Cylinder speed (rpm)
Figure A.27 Total Damage vs. Cylinder Speed Corn JD 45 MM1012

- 0.9 mph
- 1.8 mph
- 3.8 mph

Cylinder Speed (rpm) vs. Total Damage (%)
Figure A.28 Total Damage vs. Cylinder speed Corn JD45 MM1030

- 0.9 mph
- 1.8 mph
- 3.8 mph

Cylinder Speed (rpm)

Total Damage (%)
Figure A.29 Visible damage vs. Cylinder speed JD 4420 990916
Figure A.30 Tailings percent vs. concave setting Soybeans 991005
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Figure A.32 Tailings percent vs. Concave setting Corn 991022 Case IH 2388
Figure A.33 Tailings composition vs. Concave setting Corn 991022
Case IH 2388 410 rotor rpm

- Whole kernels
- Damaged grain
- MOG

Percent of total tailings vs. Concave setting

0 10 20 30 40 50 60

0 1 2 3 4 5 6 7 8 9
Figure A.34 Total damage vs. Forward speed Corn JD 45 MM1030
Figure A.35 Total Damage vs. Forward Speed 650 rotor rpm Corn
JD 9750 STS MM1121
Figure A.36 Measured yield vs. Lower sieve setting Corn 991004 JD
Figure A.37 Tailings percent vs. Lower sieve setting Corn 991004

JD 4420

Tailings percent ot throughput

Lower sieve setting (in)
APPENDIX B - TEST EQUIPMENT AND METHODS

A brief description of the test equipment is necessary in understanding the methods used in the following tailings return studies. Through the course of the 1999 and 2000 harvest seasons, data was collected from four machines in a total of four crops. The test equipment and machines were as follows.

The 1999 tests were conducted predominantly with a John Deere 4420 combine. The machine was a 1983 model with a 100 horsepower diesel engine. In oats, wheat, and soybeans, it was tested with a John Deere 13-foot platform, and in corn it was tested with a John Deere model 543 5-row 30-inch head.

The 4420 combine also had some modifications to facilitate testing. A tailings catch system was added to the base of the return elevator. The system consisted of a sliding door that could be opened or closed by a person walking beside the combine. When the door was opened, the tailings would fall into a removable 10-inch cube-shaped catch bin with a pouring spout. The catch bin slid off of its hanger so that its contents could be emptied into a sample collection bag.

In addition to a tailings catching system, the 4420 combine was also modified so that the discharge from the straw walkers and the cleaning shoe could be captured. The material discharged from the shoe slid down a steel grain pan and into a bag. The material from the straw walkers was blown into another bag with the existing combine chopper. The first design used a catch bag without the chopper, but the material did not flow easily into the bag and catches could only be achieved for very short periods. Both bags could be opened or closed simultaneously by an operator standing on top of the rear section of the combine. The bags were constructed of black nylon sunscreen. The sunscreen was durable enough for this rugged application, yet it allowed air to pass through so as not to disturb the material flow.

All of the loss catches were retreshed for loss determination. The retresher used for this procedure was built by KEM of Kansas and generously donated to ISU by ACGO corporation.

A Case-International 2388 provided additional testing data in the 1999 season. The 2388 was a standard production 1998 model machine loaned to ISU for research.
purposes. The machine had a 280 horsepower diesel engine and was equipped with AFS, the Case IH yield monitoring system. This combine was fitted with an 8-row 30-inch corn head.

The only modification to the 2388 machine was a device to catch tailings. The catch system used the same catch bin as the 4420, but the sliding door was mounted on the auger tube between the machine body and the tailings elevator. The door could be opened and closed by an operator riding on the steps by the tailings elevator on the combine.

Grain bin samples were collected in almost all tests in both seasons. The grain samples were collected with a coffee can attached to a 2x2 wood stick.

A 1964 model John Deere 45 combine with a 50 horsepower gasoline engine was used for testing in the 2000 harvest season. The 45 was fitted with a 2-row 30-inch corn head.

The 45 combine was also modified to catch tailings. The tailings catch on this machine was very similar to the system used on the Case-International 2388 combine. The door could be opened or closed by a person walking beside the combine.

In addition to a modification to catch tailings, the 45 was fitted with a different returns elevator for additional testing. The elevator was a modified clean grain elevator from a Massey-Harris 35 combine. This elevator carried tailings back to the straw walkers instead of returning them to the main cylinder. It was driven with a hydraulic motor that had been plumbed into the power steering circuit of the combine.

A John Deere 9750 STS with a 330 horsepower diesel engine was also used for testing in the 2000 harvest season. The machine was a prototype that John Deere donated to ISU. It was not a regular production machine, so it did not have a model year. The machine was very comparable to a 1999 model John Deere 9750 STS. It was fitted with an 8-row 30-inch corn head.

The 9750 STS had only one modification for testing. The tailings return material could be bypassed to the augers on the grain pan instead of returned back to the main cylinder. This bypass system was installed on the auger tube from the tailings elevator to the rotor. A sliding door could be opened to allow the tailings to exit the auger tube and
slide down a chute onto the grain pan. The flighting on the auger above the hole was removed for the entire width of the hole to prevent the tailings from carrying across it.

**Study Methods**

The studies were conducted according to ASAE standard S.396.2 (ASAE, 1998.) when possible, and all exceptions are noted.

All tests were performed after the combine reached equilibrium operating conditions. The person catching the grain sample at the grain bin determined when the combine was at equilibrium operation. No tests were started within 20 seconds of entering the crop. The person catching the bin sample also would not start testing until there was a steady flow of grain coming into the grain tank.

All tailings and loss samples were collected for a minimum of 20 seconds. There were a few exceptions to this rule because in some situations the tailings catch bin would fill completely in less than 20 seconds. The 20 second catch times did not always allow traveling at least 30 feet as stated in the ASAE standards when the machine forward speed was very slow. All bin samples were collected before the tailings within the same run so that diverting the tailings would not affect the bin sample. Combine throughput was determined with the weigh tank in the John Deere 4420, and with a weigh wagon for all other machines.

The corn bin samples were processed to determine damage levels. The samples were divided down to 100-gram sub-samples. The sub-samples were sieved with a 12/64 sieve to determine BCFM, then hand sorted to determine visual damage. Visual damage was defined as any damage to the seed coat that exposed the starch of the kernel.

The tailings samples were weighed to the nearest 0.5 grams and the corn and soybean samples were sub-sampled and hand sorted to determine composition. The samples were sorted into undamaged grain, damaged grain, mog, and unthreshed grain. Tailings sample weights ranged from 500 to 5000 grams depending on the machine, crop/conditions, distance of catch, combine settings, and throughput.

The wheat and oats bin samples were sub-sampled and hand sorted to determine trash levels. The damage level was not determined.
The soybean samples were sub-sampled to determine damage and trash levels. Damage was determined by hand sorting the split beans from the whole beans.

**Studies**

Fourteen separate studies were completed over the 1999 and 2000 harvest seasons. The specific studies varied as will be described, but the objective of all of the studies was to evaluate the relationship of the tailings return to the combine's performance. The studies are identified by date, by crop, and by combine.

**Oats, July 23 1999 John Deere 4420**

The temperature was near 90 F and the relative humidity was around 80%. The oats were very dry at 10.5% MCWB, and they were standing very well. Tailings samples were collected at six different forward speeds, five cylinder speeds, three concave clearance settings, and two sieve settings. The yield for each tailings catch was determined with the combine weigh bin. This study was not a complete factorial study; one factor was studied only while the others were held at a predetermined standard. There was no replication; the study was intended only to be a preliminary study to determine different trends for future study, not to evaluate variability. By not replicating, the study could cover many more factors in one very limited test plot.

**Oats, July 26, 1999, John Deere 4420**

It rained in the morning, so harvesting was delayed until about 2:30 p.m. It was in a different field of oats than the previous study, and this time the oats were about 14.5% moisture. The oats were not standing as well as the first field, but it was estimated that less than 20 percent of the crop was lodged. The weather was nearly the same, still very hot and humid.

The first set of samples taken were replications of the July 23 study, varying the combine forward speed from 0.7 to 4.8 mph while keeping all other settings standard as before. Samples were collected for three different forward speeds at a fan speeds of 350 and 500 rpm, for four different forward speeds at a fan speed of 650 rpm, and for five different forward speeds at a fan speed of 1040 rpm.
Wheat, July 29, 1999, John Deere 4420

The July 29 study was aimed at the effects of fan speed on tailings flow and trash content in the grain bin in wheat. This was also the first study in which separation and shoe loss were determined. The wheat was very dry (<10% MCWB), very weedy, and much of it was lodged. About half of the 2 acre plot contained too many tall green weeds to be harvestable.

The tailings return flow, all of the chaff from the shoe and the straw walkers, and bin samples were collected at 6 different fan speeds. All of the samples from the catch bags for the chaffer and the walkers were weighed and processed with the rethresher to remove the remaining grain for loss determination. These rethreshed samples and the tailings samples were subsequently cleaned with a Carter-Day dockage tester to determine the actual amount of grain in each. The bin samples were also cleaned with the dockage tester to determine trash content.

Oats, July 30, 1999, John Deere 4420

The July 30 study was performed in the same field of oats as the July 26 study. The weather was again very hot and humid with a temperature near 100 F and a relative humidity of over 80%. The oats were very dry at about 10.5% moisture. A considerable portion of the oats was lodged. Tailings, all of the chaff, and bin samples were collected at five different forward speeds. As with all previous studies, this study was directed at determining trends. To be efficient with labor and plots, no replication was completed.

Corn, September 16, 1999, John Deere 4420

This study was completed to examine tailings in high moisture corn. The corn moisture was around 34 % MCWB. The weather was cool, around 60 F, and very humid. Tailings samples and bin samples were collected for four different cylinder speeds. Two of the tests were replicated, but replication was minimized as the AERC technicians had no good way to dispose of the high moisture, high damage corn. Yield was determined with the combine weigh bin, and the bin samples were evaluated for grain damage. Throughput (forward speed) was not varied, because the combine capacity was severely limited in the very wet corn. Forward speeds over 2 mph caused the clean grain elevator to plug.
**Corn, September 28, 1999, John Deere 4420**

The September 28 study was intended to be a preliminary study in corn to cover a large number of factors without replication. The weather was slightly warmer and drier than the September 16 study. The corn moisture content had fallen considerably to around 22% MCWB. Tailings and bin samples were collected, and the yield was determined again with the combine weigh bin. The settings evaluated included seven forward speeds, five cylinder speeds, four concave settings, and three sieve settings. The bin samples were examined for grain damage, and the tailings samples were hand sorted to determine their composition.

**Corn, October 4, 1999, John Deere 4420**

The October 4 study was somewhat a continuation of the September 28 study. Many of the tests were similar to the September 28 study, but the corn moisture was again lower. The weather was warm and dry, around 70°F. The corn moisture was near 18% MCWB. Tailings and bin samples were collected and the yield was determined. This time the settings included five forward speeds, five sieve settings, three concave clearance settings, three fan speeds, and three cylinder speeds. The standard setting condition was replicated, but no other conditions were replicated because of time and labor constraints.

**Soybeans, October 5, 1999, John Deere 4420**

The October 5 study had similar objectives to the October 4 study, but this time the crop was soybeans. Again, tailings and bin samples were collected, and the yield was determined. This time the settings included seven forward speeds, five cylinder speeds, three concave settings, and three fan speeds. No replications were performed. This time the bin samples were examined for damage and impurities, and the tailings samples were analyzed to determine their composition. Tailings were divided into threshed soybeans, unthreshed soybeans, splits, and mog.

**Corn, October 22, 1999, Case IH 2388**

The October 22 study was the first study completed with a rotary combine. The Case IH 2388 did not have a weigh bin, but it did have an Ag Leader 2000 yield monitor. The tests were performed on the ISU Bilsland Memorial farm. The corn moisture was
about 16% MCWB, and the weather was warm and dry, around 60 F. The yield was taken to be 190 bushels per acre, the average shown by the yield monitor in the plot harvested for testing. Measured yield tends to vary with machine throughput, however, the Ag Leader monitor could not show this yield difference in the short passes used for testing. The corn in the testing area seemed to be fairly uniform, and it was standing very well.

The factors studied in the October 22 study were five forward speeds at two cylinder speeds and three concave settings at two cylinder speeds. Tailings samples and bin samples were collected. No replications were made.

**Corn, November 12, 1999, John Deere 4420**

The final study in 1999 was completed on November 12 on the ISU Bilsland Memorial farm. The weather was unseasonably warm for November, near 70 F, and the corn was very dry, about 13.5% MCWB. Tailings samples and bin samples were collected as before, and the yield was measured. For these tests, the chaff from the shoe and straw walkers was collected and reprocessed for loss determination.

The tests were a full factorial experiment of two cylinder speeds and four forward speeds. The number of tests was limited to eight because of the time required to reprocess the chaff for loss determination.

**Corn, October 12, 2000, John Deere 45**

This test was performed on the ISU Bilsland Memorial farm with a John Deere 45 combine. The weather was warm and dry, about 65 F. The corn was dry for early October, around 15% MCWB. The combine did not have modifications to measure yield, so the yield was determined four times in the plot with a weigh wagon. The average of the four yields was taken to be the plot yield. The yield could not be measured for each individual test because the weigh wagon was available for only a short time. Tailings and bin samples were also collected. The bin samples were analyzed for damage, and the tailings samples were sorted to determine composition.

The October 12 tests were a full factorial of three forward speeds, three cylinder speeds, and two tailings conditions (returns and no returns). Each test had one replication. The emphasis of these tests (and others in the 2000 season) was to more
thoroughly investigate the relationship between tailings and grain damage. The factors chosen, forward speed and cylinder speed, were chosen because of their effects on tailings flow and grain damage respectively.

**Corn, October 30 and November 2, 2000, John Deere 45**

These tests were continuations of the October 12 test. The bulk of the tests were performed on October 30. However, the tailings bypass elevator was driven from fluid from the power steering circuit, and as the oil got warmer, its performance declined. As the evening progressed on October 30, some of the high-speed tests could not be completed because the bypass elevator would not run at the higher flow rates. The weather was dry on October 30 and the corn was about 15% MCWB. There was a strong thunderstorm on October 31 that delayed further harvesting until November 2. On November 2, the corn moisture content had risen to about 17% MCWB. The corn had a significant amount of lodging both days, and no increase in lodging was noted between the two.

For the October 30/November 2 tests the combine was modified so that the tailings could be bypassed to the cleaning system instead of returned to the main cylinder. The tests performed were the same as the October 12 tests, but this time the two tailings conditions were tailings bypassed to the straw walkers vs. no tailings instead of tailings returned vs. no tailings. Tailings samples were not collected; only bin samples were collected. The objective of this study was to compare the grain damage of the combine with the tailings bypassed to the damage with tailings returned to the main cylinder in the October 12 study. The object of the no tailings tests was to determine if the damage level in the grain bin could be reduced because of damaged grain in the tailings being left on the ground or if the tailings incurred significantly more damage when re-entering the main cylinder.

**Corn, November 3, 2000, John Deere 45**

The November 3, 2000 study was a very brief study. Its objective was to get a better comparison of tailings returned vs. tailings bypassed on the same machine in the same field on the same day. The weather was very similar to November 2. The combine was tested as modified, then returned to stock operating conditions and tested again the
same day. A total of eight bin samples were collected, two with tailings bypassed, two with tailings returned, and four with no tailings. The tests were completed in the same field as the October 30/November 2 study, but the corn moisture had again fallen to about 15.5% MCWB.

**Corn, November 21, 2000, John Deere 9750 STS**

The final tests for the 2000 season were completed on November 21, 2000. The weather was cold, about 30 F, but sunny and dry. The corn was standing reasonably well, but it was not uniform. Its moisture content was fairly uniform at about 13% MCWB. The fields were test plots located on an ISU farm near Ankeny, IA, and the yield variability in the plots was substantial. The yield was measured with a weigh wagon.

The combine, a John Deere 9750 STS, was modified to allow the tailings to be diverted to the grain pan or returned to the main threshing cylinder. A total of 24 bin samples were collected. Eight samples were collected for each of three tailings conditions (tailings returned, tailings bypassed, and no tailings). The other factors were two forward speeds and two cylinder speeds. (Each of the four tests was replicated once.) As with the JD 45 tests, the objective was to evaluate differences in damage for the three tailings conditions.
SAS statistical software was used to evaluate the grain damage data from the fall 2000 field studies. The October 12, October 30, and November 3 studies were evaluated. The point of interest in these studies was the grain damage level with tailings returned, tailings bypassed, or tailings dumped on the ground. The October 12 study compared the grain damage level with no tailings to the damage level with the tailings returned to the main cylinder. The October 30 study compared the grain damage with the tailings bypassed to the separator to the damage level with no tailings, and the November 3 study compared both. The November 3 study was much more limited in its scope. Removing the bypass system and installing the original returns system took most of the day, leaving little time to complete the studies within one day. The November 3 study was intended to compare damage with all three tailings conditions on the same day in the same field.

The GLM procedure in SAS was used to perform an analysis of variance (ANOVA) on the data from the studies. The first ANOVA was calculated for the October 12 data. Table C.1 shows the SAS output ANOVA table for the October 12 data. The designations cspeed and fspeed denote cylinder speed and forward speed respectively. Similarly, the designations “none” and “ret” represent no tailings and tailings returned. The dependent variable in the regression was grain damage.

Table C.1 SAS output from October 12 tailings and grain damage study

<table>
<thead>
<tr>
<th>Class</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>cspeed</td>
<td>3</td>
<td>386 536 786</td>
</tr>
<tr>
<td>fspeed</td>
<td>3</td>
<td>0.9 1.8 3.8</td>
</tr>
<tr>
<td>tailings</td>
<td>2</td>
<td>none ret</td>
</tr>
</tbody>
</table>

Dependent Variable: damage

<table>
<thead>
<tr>
<th>Sum of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
</tr>
<tr>
<td>Model</td>
</tr>
<tr>
<td>Error</td>
</tr>
<tr>
<td>Corrected Total</td>
</tr>
</tbody>
</table>

R-Square Coeff Var Root MSE damage Mean
0.894219 33.60036 5.224575 15.54917
The value of primary interest in this SAS output is in the last line. Across all samples in the October 12 data, the estimated difference in grain damage between returning the tailings or dumping them on the ground is not significant. The p-value is 0.6239. The p-value represents the probability of measuring a value as extreme as difference in damage shown (0.863%) if there is no actual difference. Since the p-value is high (much greater than 0.05), there is no evidence to suggest a difference in damage between returning the tailings or dumping them on the ground.

The ANOVA table also supports the 1999 data that measured cylinder speed and forward speed effects on grain damage. Note that the p-values for the effects of both are very small, indicating that both have significant effects on grain damage.

A subsequent analysis was performed on the data from the October 30 study. The focus of the October 30 study was to search for a difference in grain damage between bypassing the tailings to the combine separator and dumping them on the ground. The ANOVA table is not of primary interest in this study, so only the output from the estimate statement is included. See Table C.2.

Table C.2 SAS output from October 30 tailings and grain damage study

| Parameter | Estimate | Error         | t Value | Pr > |t| |
|-----------|----------|---------------|---------|------|---|
| none-byp  | 0.42000000 | 1.52735289 | 0.27    | 0.7852 |
While this difference is not significant, it is still further evidence against the original hypothesis that returning tailings to the main threshing cylinder causes increased grain damage.

There is some evidence to suggest that a multiplicative model would fit the data set better. Figure C.1 shows evidence the variability of the damage is not constant across cylinder speeds.

**Figure C.1 Total damage vs. Cylinder speed**

The damage measurements show very little variability at the low cylinder speed. At 786 cylinder rpm, though, the spread of the damage measurements is much higher. Non-constant variability such as this is evidence that a multiplicative (logarithmic) model will better fit the data.

The SAS analyses for both the October 12 and October 30 data were repeated, but this time the regression model used the log of damage as the dependent variable. The damage difference estimate statements for the revised models are expressed in Table C.3.
Table C.3 SAS output from October 12 and 30 tailings and grain damage studies

October 12 data

| Parameter         | Estimate | Error     | t Value | Pr > |t| |
|-------------------|----------|-----------|---------|------|--------|
| none-ret log damage | 0.00264922 | 0.06613277 | 0.04    | 0.9683 |

October 30 data

| Parameter         | Estimate | Error     | t Value | Pr > |t| |
|-------------------|----------|-----------|---------|------|--------|
| none-byplog damage | 0.13945027 | 0.10028410 | 1.39    | 0.1746 |

The new regression model changed the p-values of the estimates, but they are both still not significant. Interestingly, the logarithmic model pointed to less evidence of a difference in damage between returning the tailings or dumping them, and more evidence of a difference in damage between bypassing the tailings or dumping them.

SAS software was also used to analyze the data collected in the November 3 study. In the November 3 study, only eight samples were collected. The samples were collected randomly in the following manner: Four grain damage samples were collected with the bypass elevator installed, two with the tailings bypassed and two with the tailings dumped. Similarly, four grain damage samples were collected with the original returnselevator installed, two samples with the tailings returned and two with the tailings dumped.

SAS was used to perform an analysis of variance on the damage level of these eight samples. The SAS output is expressed in the Table C.4

Table C.4 SAS output from November 3 tailings and grain damage study

<table>
<thead>
<tr>
<th>Class Level Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class Levels Values</td>
</tr>
<tr>
<td>tailings 3 byp none ret</td>
</tr>
<tr>
<td>Number of observations  8</td>
</tr>
<tr>
<td>Dependent Variable: damage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2</td>
<td>3.02002500</td>
<td>1.51001250</td>
<td>1.79</td>
<td>0.2594</td>
</tr>
<tr>
<td>Error</td>
<td>5</td>
<td>4.22092500</td>
<td>0.84418500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>7</td>
<td>7.24095000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In this regression model, the main effect of tailings condition is not shown to be significant. The p-value for this main effect is 0.2954 as shown in table 14.4. Also, the estimated differences in damage between no tailings and tailings returned and no tailings and tailings bypassed are both not significant. Both p-values are significantly higher than 0.05. There is no evidence of a difference in grain damage among the three tailings conditions.
REFERENCES


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