DESIGN AND EVALUATION OF A CORN SILAGE-MAKING SYSTEM WITH SHREDDING

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by

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Abstract

A novel harvester using shredding/crushing mechanism was designed, fabricated, and tested during two harvesting seasons. The objective was to create a harvester that could improve the feed value of corn silage for dairy cows by increasing the digestibility of both fibrous components and corn kernels and provide more effective fiber from corn silage. The machine used two pairs of corrugated rolls which turn at different speeds to shred whole-plant corn. Good particle size reduction was achieved with certain machine configurations; corn stalks were shredded and torn apart, kernels were damaged, and there were no large cobs.

Machine power usage and silage particle sizes were recorded for various conditions including combinations of roll speeds, the minimum clearance between the rolls within a pair, and the unit roll forces on the rolls. Effects of machine configurations on power and energy consumptions were studied on dryer crop in 2000 while more moisture levels and various machine throughputs were examined in 2001. A flail cutting mechanism was placed behind the shredding rolls during the 2001 testing.

Average specific energy requirement for shredding ranged from 2.5 to 5.9 kW h/Mg DM. Average specific energy requirements for shredding varied significantly among different roll speed treatments at unit roll force of 15 N/mm (front and rear) but no significant effect of roll speed configuration was found at other unit roll forces. Minimum roll clearances of 10 mm (front rolls) and 1 mm (rear rolls), along with unit roll forces of 15 N/mm (front) and 45 N/mm (rear) produced more processed material with thinner stalks and shorter pieces than other minimum roll clearance and unit roll force configurations.
Samples of treatments and chopped samples were collected to make silage in laboratory scale silos for ensiling evaluation. The shredded particles ensiled well in lab-scaled silos (approx: 9 kg) with pH values reaching after fermentation 3.8 to 4.1. There was no significant difference in packed density among different roll speed configurations for 51% moisture content silage. Silage harvested at 66% moisture content showed significantly higher packed density than silage harvested at 60 and 71% moisture content for both chopped and flail-cut samples. Particle size distributions of flail-cut samples were similar with moisture of 60 and 66%; however, the 71% moisture crop was coarser. Shredded samples produced fewer small particles (<8.98 mm) and more large particles (>8.98 mm) than chopped silage; while shredded and flail-cut samples had more small particles and more large particles than chopped samples.

System simulation on dairy farms showed great potential of the novel harvester in increasing milk production and farm profitability. When shredded corn silage was fed to high producing Holstein cows, milk production was increased up to 2.6% compared to chopping and up to 0.3% compared to kernel processing. Annual profit increased by $74/cow and $27/cow compared to chopping and kernel processing respectively on the 250-cow farm; the improvement in annual profits were $100/cow over standard chopping and $86/cow over kernel processing for the 100-cow farm. The simulation results were moderately sensitive to the assumption on silage density but insensitive to machine power requirement. The simulation results were very sensitive to changes in stover digestibility, fill and roughage factors for large particles. A great feed would have high stover digestibility, less filling large particles, yet a higher roughage effect. The shredded silage is a move in this direction.
# Table of Contents

List of Figures ........................................................................................................... vii  
List of Tables ............................................................................................................ ix  

Chapter 1:  Introduction .............................................................................................. 1  

Chapter 2:  Objectives ............................................................................................... 4  

Chapter 3:  Literature Review ..................................................................................... 5  

3.1  Role of Silage in Agriculture .............................................................................. 6  
  3.1.1  Alfalfa Hay and Silage ................................................................................. 9  
  3.1.2  Corn Silage .................................................................................................. 11  

3.2  Corn Silage Production—Improving Digestibility ............................................. 12  
  3.2.1  Planting Management ................................................................................. 14  
  3.2.2  Harvesting Consideration ......................................................................... 16  
  3.2.3  Brown Midrib Corn ................................................................................. 21  
  3.2.4  Brief Summary ......................................................................................... 22  

3.3  Silage Storage—Making Good Corn Silage ....................................................... 24  
  3.3.1  Principles of the Ensiling Process ............................................................... 24  
  3.3.2  Effects of Kernel Processing .................................................................... 28  
  3.3.3  Storage Management ............................................................................... 30  
    3.3.3.1  Silo Types ......................................................................................... 31  
    3.3.3.2  Filling and Packing ......................................................................... 32  
    3.3.3.3  Sealing ............................................................................................. 33  
    3.3.3.4  Feed-out .......................................................................................... 34  
  3.3.4  Brief Summary ......................................................................................... 34  

3.4  Livestock Feeding—with Focus on Fiber and Energy ..................................... 35  
  3.4.1  Microbial Digestion in the Rumen and Rumen Fill ..................................... 35  
  3.4.2  Ration Balancing ..................................................................................... 37  
  3.4.3  Total Mixed Rations ................................................................................ 41  
  3.4.4  Brief Summary ......................................................................................... 42  

3.5  Silage Quality ................................................................................................... 43  
  3.5.1  Nonstructural and Structural Carbohydrates ............................................ 43  
  3.5.2  Protein .................................................................................................... 45  
  3.5.3  Particle Size—Importance and Measurement Methods ............................ 47  
  3.5.4  Quality Assessment ............................................................................... 50  
  3.5.5  Brief Summary ......................................................................................... 53  

3.6  Forage Harvester and Kernel Processor—Power Requirements .................... 54  

3.7  Systems Analysis—Use of DAFOSYM .............................................................. 58  

Chapter 4:  Methodology ........................................................................................... 62  

4.1  Machine Design and Fabrication ..................................................................... 63  
  4.1.1  Shredding Chamber and Hydraulic Drive ................................................. 63  
  4.1.2  Machine Fabrication ............................................................................... 67
List of Figures

Figure 1. U. S. total corn silage production from 1993 to 2000 (Source-USDA NASS, 2001). ................................................................. 7
Figure 2. Schematic of the shredding harvester (side view). ................................................................. 64
Figure 3. Schematic of the hydraulic drive on the novel harvester. ......................................................... 65
Figure 4. A segment of the shredding rolls used on the novel harvester (photo). ........................................ 69
Figure 5. Drawing of the side sheet supporting the shredding rolls (Pro/E) (all dimensions in mm). ................................................................. 70
Figure 6. Assembled shredding chamber showing removable floor and side sheet covers for cutout (photo). ............................................................................. 72
Figure 7. Right side of shredding chamber showing bearing housing configuration (photo). ............................................................................. 72
Figure 8. Power transmission from tractor PTO, the hydraulic tandem gear pump, 1 to 4 ratio gearbox and tractor PTO shaft (photo) ............................................................................. 73
Figure 9. Hydraulic motors connected directly to shredding rolls (photo) ............................................. 73
Figure 10. Hydraulic reservoir and hydraulic control panel (photo) ...................................................... 74
Figure 11. Particle size separator meeting ASAE Standard S424 (photo). ................................................ 81
Figure 12. Laboratory scale silos (photo). ................................................................................................. 83
Figure 13. Heterogeneous samples of whole plant corn generated by the harvester (photo). ...................... 86
Figure 14. The “not-long” (a) and “very long” (b) particles from a sample—used to improve consistency of proportions in sub samples (photo) ............................................................................. 86
Figure 15. Dismounted flail cutter (photo). ............................................................................................... 91
Figure 16. Cutting mechanism powered by the tractor hydraulic remote (photo) ........................................ 91
Figure 17. Larger particles (> 26.9 mm, 70% moisture) from samples collected from experiments with rear rolls set at 1 mm clearance (photo) ............................................................................. 94
Figure 18. Specific energy requirement for shredding at four different roll speed configurations (A, B, C, D, see Table 13) with minimum roll clearance at 10 mm (front) and 2 mm (rear) and two different unit roll forces. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box) .......... 109
Figure 19. The silage processed at 1 mm (rear) minimum clearance (a) and that processed at 2 mm (rear) minimum clearance (b). Unit roll forces were 15 N/mm (front) and 45 N/mm (rear) (photo). ................................................................. 110
Figure 20. Specific energy requirements for different unit roll forces and roll speed configurations at minimum roll clearance of 10 mm (front) and 1 mm (rear). Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box). See Table 13 and Table 14 for letter definitions ........................................... 113
Figure 21. Specific energy requirements for shredding for different minimum roll clearances and roll speed configurations (see Table 14) at unit roll forces of 15 N/mm (front) and 45 N/mm (rear). Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box) ............................................................................. 113
Figure 22. Specific energy requirements for shredding at different roll speed configurations (see Table 13) at roll clearance of 10 mm (front) and 1 mm (rear) and unit roll forces of 15 N/mm (front) and 45 N/mm (rear). Shown are
the mean (dotted box), 90 percentile range (line), and standard deviation (box).

Figure 23. Average dry matter densities with standard deviation for laboratory scale silos.

Figure 24. Particle size distributions for laboratory scale silos of 51% moisture silage.

Figure 25. Total specific energy of four rolls for shredding 70% moisture corn with roll clearance at 10 mm (front), 1 mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

Figure 26. Total specific energy of four rolls for shredding 65% moisture corn at a roll clearance of 10 mm (front), 1 mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

Figure 27. Total specific energy of four rolls for shredding 65% corn at a roll clearance of 15 mm (front), 1 mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

Figure 28. Total specific energy of four rolls for shredding 60% moisture corn at a roll clearance of 10mm (front), 1mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

Figure 29. Total specific energy of four rolls for shredding 60% moisture corn with a roll clearance of 15 mm (front), 1 mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

Figure 30. Average specific energy requirements for shredding silage at various moisture and roll clearance conditions.

Figure 31. Particle size distribution of chopped samples and samples processed without a flail cutter with a minimum roll clearance of 10 mm (front) and 1 mm (rear) (70% moisture content).

Figure 32. Particle size distributions of chopped samples and samples processed with a flail cutter for three moisture levels.

Figure 33. Silage densities for the lab-scale silos for each test with standard deviation shown as an error bar.

Figure 34. Fermented shredded samples of 65% moisture content silage.

Figure 35. Mold spots in chopped silage of 65% moisture content.

Figure 36. Front view of assembled compactor unit (from Hoover, 1998).

Figure 37. The relationship between silage density and packing pressure.

Figure 38. Specification of proximity speed sensor.

Figure 39. Schematic of instrumentation on the shredder.
List of Tables

Table 1. Principal components of the hydraulic drive ........................................................... 67
Table 2. Target speed configurations of the shredding rolls used during testing ............... 80
Table 3. Hole sizes (diagonal of the square hole) of the screens in the ASAE Particle Size Separator ........................................................................................................... 81
Table 4. Factors of Experiment 1 used to determine the effect of roll speed combination(s) on machine energy requirements ..................................................... 87
Table 5. Factors of Experiment 2 used to determine the effect of roll clearance and pressure on machine energy requirements ...................................................... 88
Table 6. Factors of Experiment 3 used to fill laboratory scale silos and evaluate particle size distributions ................................................................................................... 89
Table 7. Factors used to evaluate power requirements of shredding in Experiment 4 .......... 92
Table 8. Treatments used to collect corn silage to fill lab-scale silos (tractor ground speed @ 2.0 km/h) in Experiment 5 ................................................................. 94
Table 9. Model parameter multiplicative adjustments for shredded silage in comparison to standard chopped and processed silage—baseline analysis for the novel harvester ........................................................................................................... 98
Table 10. Model parameter multiplicative adjustments for sensitivity analysis for the novel harvester (bold numbers are changed comparing to baseline values) ........ 100
Table 11. Machines and structures used for the analysis of two representative dairy farms ....................................................................................................................... 103
Table 12. Economic parameters and prices assumed for various system inputs and outputs for the analysis of the representative dairy farms ......................................... 104
Table 13. Energy requirements to shred corn silage (67% w.b., Experiment 1) at four different roll speed configurations and two different unit roll forces. Minimum roll clearance was set at 10 mm and 2 mm for front and rear sets of rolls, respectively ........................................................................................................... 108
Table 14. Energy requirements to shred corn silage (62% w.b.) at four roll speed configurations and three unit roll forces. Minimum roll clearance was (10 mm and 2 mm) and (10 mm and 1 mm) for front and rear sets of rolls, respectively ........................................................................................................... 112
Table 15. Silage densities of the lab scale silos (4 silos for each treatment) of silage at 51% moisture content ............................................................................................. 115
Table 16. Actual moisture content of whole-plant (WP) and parts of the corn plant and yields at three moistures of whole-plant ................................................................. 119
Table 17. Energy requirements to shred corn silage (70% w.b.) at three different throughput capacities. Minimum roll clearance was set at 10 mm and 1 mm for front and rear rolls, respectively ................................................................. 119
Table 18. Energy requirements to shred corn silage (65% w.b.) at three different throughput capacities. Minimum roll clearance was set at 10 mm and 1 mm for front and rear rolls, respectively ................................................................. 123
Table 19. Energy requirements to shred corn silage (65% w.b.) at three different throughput capacities. Minimum roll clearance was set at 15 mm and 1 mm for front and rear rolls, respectively ................................................................. 125
Table 20. Energy requirements to shred corn silage (60% w.b.) at three different throughput capacities. Minimum roll clearance was set at 10 mm and 1 mm for front and rear rolls, respectively. ................................................................. 126

Table 21. Energy requirements to shred corn silage (60% w.b.) at three different throughput capacities. Minimum roll clearance was set at 15 mm and 1 mm for front and rear rolls, respectively. ................................................................. 127

Table 22. Silage densities of laboratory scale silos. .......................................................... 134

Table 23. Silage pH values for laboratory scale silos. ...................................................... 136

Table 24. Major nutrients of lab-scale silage analyzed by commercial laboratory*. .................. 139

Table 25. Model parameter multiplicative adjustments for shredded silage in comparison to standard chopped and processed silage—baseline analysis for the novel harvester .......................................................................................... 143

Table 26. Model parameter multiplicative adjustments for sensitivity analysis for the novel harvester (bold numbers are changed comparing to baseline values). .......... 143

Table 27. Effect of corn silage shredding on annual feed production, feed use, costs, and net return of a 100-cow dairy farm in central Pennsylvania.......................... 145

Table 28. Effect of corn silage shredding on annual feed production, feed use, costs, and net return of a 250-cow dairy farm in central Pennsylvania.............................. 145

Table 29. Effect of corn silage shredding on annual feed production, feed use, costs, and net return of a 100-cow dairy farm in central Pennsylvania. Comparisons are made with the same milk production (8700 L/cow). ................................................. 146

Table 30. Milk Production and net return by changing major input parameters for the 100-cow farm when using the novel forage harvester............................................ 148

Table 31. Milk Production and net return by changing major input parameters for the 250-cow farm when using the novel forage harvester............................................ 148

Table 32. Specifications of the pressure transducers (Omega)............................................. 186
Chapter 1: Introduction

As many dairy farms become larger and more mechanized, silages have generally replaced long dry hay in the cows’ diet. Economic pressures during the last decade related to the high costs of grain and forage have resulted in interest in forage quality of whole plant corn (Johnson et al., 1999). One attempt to improve forage quality is the processing of corn silage. When corn silage is harvested at mature stages, uncracked grains are hard to digest. Honig and Rohr (1982) reported that as much as 25% of mature, uncracked kernels in the corn silage may be undigested and end up in ruminal feces. With mechanical processing, a pair of corrugated rolls having narrow clearance is placed behind the cutterhead to break the grain kernels to facilitate digestion of starch within the grain.

Interest in field processing of corn silage has increased during recent years (Shinners et al., 2000). New nutritional research has shown that increased theoretical length of cut (TLC) (12 to 20 mm) with processing whole plant corn silage can yield improved animal performance compared to control diets comprised of short TLC unprocessed corn silage (Bal et al., 2000; Johnson et al., 1999).

Since kernel processing reduces particle size of stover, a longer chop length has been recommended to obtain longer yet very digestible forage material (Jirovec et al., 1999; Roberge et al., 1998; Hoover et al., 1998; Savoie, 1997; Harrison et al., 1997). Adequate forage amount and proper physical and chemical traits are necessary for proper ruminal function in dairy cows. When minimum fiber levels are not met, cows often show one or more of a variety of metabolic disorders, including reduced total DM digestibility, reduced milk fat percentage, displaced abomasums, and an increase in the incidence of laminitis, acidosis, and fat cow syndrome (Nocek 1997; Armentano and Pereira 1997; Owens et al.
These conditions can exist when effective fiber is insufficient. Since effective fiber is an interaction between chemical fibers measured as neutral detergent fiber (NDF) and physical length, particle size is very important.

Shredding of herbage crops to split stems and increase surface area has been shown to be beneficial enhancing silage fermentation, improving intake, and facilitating rumen degradation of forage fiber (Koegel et al., 1992; Petit et al., 1994; Charmley et al., 1997). In a simulation study, Rotz et al. (1999a) predicted that kernel processing of corn silage increased farm profitability; it provided about a 2% increase in milk production and $50/cow in annual net return when processed corn silage was fed to high producing Holstein animals with 40% of their forage requirement met by corn silage.

If it were possible to increase surface area, yet maintain physical length, perhaps a much better feed could be generated. In their review of the nutritive value of processed corn silage, Johnson et al. (1999) concluded that mechanical processing can result in forage that ensiles more quickly, has less loss of DM during ensiling, and has increased digestibility of starch and fiber as well as increased milk production.

Besides the nutritive benefits, processing may require much less power than chopping and produce a feed that is easier to pack. Roberge et al. (1998) noticed that power requirement for processing was considerably smaller than power requirement for chopping. Shinners (1987) concluded that longitudinal shear energy was about 10% of that for transverse shear per unit area in alfalfa maceration. Excessive maceration could also lead to shorter fiber length (Savoie et al., 1999). Studies at Penn State University suggested that shredding alone might produce a feed that could be stored successfully in bunker or bag silos (Hoover, 1998). Longer fiber particles in processed corn silage are more compatible for use
in bunker silos (Jirovec et al., 1999) than tower silo due to the mechanical packing and ease of removal. Maceration may facilitate compaction in that macerated material has more stress relaxation. The released juice and starch of kernels may also make more sugar and starch available for fermentation. With the objective of making corn silage without chopping, an experimental prototype harvester was developed. The prototype used two pair of corrugated rolls to shred, tear, and crush whole-plant corn instead of chopping it with knives.
Chapter 2: Objectives

The objectives of this research were:

1. To design and develop a corn silage harvester which processes whole plant corn silage with narrow clearance rolls.

2. To evaluate the effect of processing roll configurations on energy consumption, particle size distribution, and compaction of the feed made from the new harvesting system.

3. To evaluate, using DAFOSYM—Dairy Forage System Model, the feasibility and economic benefits of this harvest method.
Chapter 3: Literature Review

The novel forage harvester will produce particles completely different from those generated by a conventional forage harvester. Changes in particle sizes affect corn silage quality by influencing the storage process, handling, and feeding. The goal of this research was to improve feed value by increasing whole plant corn digestibility. While silage storage method is essential to the investigation, silage production, livestock feeding and machine management are highly related and affect silage management. The literature review follows the natural sequence of silage production and feeding on a dairy farm with focus on corn silage particle size, fiber level, and energy content of the silage. Mechanical processes such as kernel processing and crop maceration alter particle size distribution and might affect digestibility and thus are included in the review. Energy consumption of conventional forage harvesters was provided for comparison with the novel harvester. Introduction of new technologies on farms affects the whole farm system and farm profitability. System analysis through the use of farm modeling to predict farm performance was reviewed.
3.1 Role of Silage in Agriculture

Forages contain significant levels of protein, fiber, energy, and vitamins providing suitable feed for ruminant animals. Forage typically represents 40 to 60% of a cow’s diet; most farms feed 50 to 100% of their forage in the form of silage. Forage has high nutritive value if it is high in digestible dry matter or energy, high in digestible protein, and palatable. Forage includes hay and silage. Hay is defined as forage harvested during the growing period and preserved by drying for subsequent use. Silage is the feedstuff produced by the fermentation of green forage of high moisture content, generally greater than 50%. Alfalfa and grasses are often harvested as hay. Corn is the mostly widely used silage crop, but grasses and alfalfa can also be harvested as silage.

Silage provides the primary forage source in most dairy rations in the U.S. Total corn silage production in the U.S. has been increasing during the past eight years (Figure 1). The recognition of the advantages of corn silage system versus hay systems (see below) is probably the reason for this increase. Conserved forages are used to feed animals during portions of the year when forage cannot be grown or throughout the year to avoid the need for pasture systems. In the northeastern United States, stored forages provide most of the feed needed for livestock year round. Corn harvested for silage is an important feed crop in Pennsylvania where cropland often is limited. Corn silage produces more energy per acre than any other Pennsylvania forage crop (Roth and Adams, 1995).
Two methods of harvest are practiced to make silage. In the direct-cut method, the forage is cut, chopped, transported to the silo, and ensiled. In the pre-wilt method, the cut material is left in the field to wilt prior to being picked up and chopped.

Corn is a crop naturally low enough in moisture at the time of cutting for proper ensiling and, therefore, requires no wilting. Alfalfa is harvested at relatively low dry matter content (around 30% DM) and thus needs wilting to reduce moisture. Alfalfa leaves contain most of the crop’s nutrients. Leaf loss through shedding would be substantial if they were harvested at high dry matter content. Therefore, wilting is required to reduce plant moisture to promote a desirable fermentation. Mechanical treatment has also been practiced to crush alfalfa stems in order to increase drying rate. Once the crop is ready to ensile, it is chopped by a forage harvester and transported to silos.

Figure 1. U. S. total corn silage production from 1993 to 2000 (Source-USDA NASS, 2001).
Comparable milk production was found among cows fed diets based on either high quality alfalfa silage or corn silage balanced with corn grain, soybean meal, and other supplements (Broderick, 1985). Since the early 1950s, both the total quantity of forage produced and the percentage of it preserved as silage have increased steadily (Bolsen, 1995). The increased use of silage is due to a number of factors summarized below (McCullough, 1978; Woolford, 1984; Rotz and Muck, 1994; Bolsen, 1995):

1. The continuing growth in average herd size and the use of bunker silos to accommodate the feed needs of large herds.

2. Reduced weather damage at harvest. Silage making is much less weather dependent than haymaking. Once a crop is grown, the greatest danger for nutrient loss is from adverse weather during harvest. Minimum field losses occur with direct cut silage, influenced very little by weather conditions. Drying hay on the ground produces more field losses in comparison to wilted silage (wilted to 30 to 40% dry matter). Average losses in hay making are estimated between 24 and 28%. Most of this loss occurs during harvest with about 5% loss during the storage of dry hay.

3. Harvesting maximum nutrients per acre. Harvesting of whole-plant corn provides the maximum usage of the crop in comparison to harvesting of grain, which leaves 50% or more of the available nutrients in the field. Harvesting of whole-plant corn, sorghum or other grain crops also provides a source of fiber for dairy animals.

4. Suitable for total mixed rations (TMR) feeding programs. Dairy feeding programs are based on total balanced rations including chemical analysis of the forage fed. TMRs are fed by mixing the forage and concentrates prior to feeding. Silage is ideal for such programs. The chemical composition of silage is relatively stable, it is already chopped
for easy mixing, and its moisture content provides an ideal media to keep dry grain in the mixed feed.

Silage has some disadvantages (McCullough, 1978; Rotz and Muck, 1994):

1. The feedstuff is hard to market as silage quality is highly variable. Also, the large amount of water that has to be moved around, stored, and handled in silage production creates extra costs of storage and handling.

2. Silage has a short storage or bunk life once it is removed from the silo. This limits the distance silage can be moved and necessitates daily feeding for best utilization.

3. Greater storage loss and nutritive changes. Average losses in silage production are 14 to 24% with about half of this loss occurring during storage. A major cause of silage dry matter loss and nutritive changes is plant and microbial respiration. Digestible carbohydrates are largely lost through respiration.

4. Greater energy requirements in harvest.

3.1.1 Alfalfa Hay and Silage

Alfalfa has the highest feeding value and is the most widely used among hay crops (Marten et al., 1988). Hay can be made from legumes, i.e., alfalfa and clovers; grasses, or cereal crops. Hay has always been one of the least expensive and most suitable sources of feed for livestock; it can be as high in feeding value as many concentrates (Barnes and Sheaffer, 1995). It produces more protein per hectare than grain or oil seed crops. However, the quality of hay varies greatly, much more than any other North American agricultural crop. Dry matter and nutrient losses that occur after hay is cut frequently amount to 30% or
more (Rotz and Muck, 1994). Alfalfa has more cell contents in relation to the amount of cell walls than grass and is therefore more digestible.

Alfalfa is primarily harvested and stored as dry hay, haylage or silage. Haylage is defined as forage ensiled between 40 and 60% moisture and thus undergoes less fermentation (less acid production) than silage (Barnes and Sheaffer, 1995). Haylage often is stored in oxygen-limiting tower silo structures to minimize infiltration losses. Harvesting alfalfa as haylage (40%-60% moisture) or as wilted silage (60%-70% moisture) will increase forage quality and decrease storage losses as compared with direct cutting of alfalfa (Barnes and Sheaffer, 1995).

Maturity is the most important factor determining feeding value of alfalfa (Collins and Moore, 1995). As alfalfa plants mature, their dry matter concentration increases. Alfalfa leaves contain more protein, digestible nutrients, and vitamins than stems (Marten et al., 1988). Alfalfa leaf loss increases during harvesting operations as hay moisture content decreases. Forage conserved as haylage requires about 24 hours of field drying before storage while forage stored as hay can require 2 to 4 days or even more, depending on weather conditions. Forage conditioning equipment, which crushes, crimps, or breaks alfalfa stems, and increases rate of drying (Savoie et al., 1992). It also preserves quality by reducing losses from weather.

Maceration causes the stems to be split into numerous fibrous pieces while mashing or pureeing the leaves and small stem segments. Maceration is generally preferred to chemical (chemical conditioners) or thermal means because of its operating costs. Maceration not only reduces field-curing time and the losses associated with field curing; it may also improve the feed value of the forage to the animal. Maceration increased the rate
and extent of fiber digestion (Hong et al., 1988). The improvement in digestion allows animals to obtain more energy from the forage and to increase their intake of forage.

Among hay crops alfalfa is also the most difficult to ensile (Bolsen, 1995). Alfalfa has high concentrations of organic acids, minerals, protein and low water soluble carbohydrate (WSC) contents compared to other hay crops. It also has less sugar than grasses. These features give alfalfa a very high buffering capacity that neutralizes the acids and prevents a drop in pH. A rapid drop in pH is desirable to reach a stable fermentation during ensiling. It must be field wilted to 35-50% DM before ensiling. If alfalfa is ensiled too wet, it can be predisposed to clostridia fermentation with high losses of DM and energy and protein quality in addition to extensive production of effluent. If alfalfa is ensiled too dry, it can undergo an extended aerobic phase that utilizes the WSC before the fermentation phase. This results in less extent of fermentation, less acid production, higher pH, and excessive heating for reduced energy and protein digestibility.

3.1.2 Corn Silage

Corn is a versatile crop that can be planted from early to late spring and harvested in the fall. Whole plant corn harvested as silage contains digestible nutrients such as protein, carbohydrates, fat, vitamins and minerals. It can also help meet the fiber requirement of dairy animals.

Corn silage, as the sole forage in diets of dairy cows, was satisfactory when the ration was supplemented with adequate protein, minerals, and vitamins, and was fed as a complete mixed ration (Noller, 1981). Other researchers (Colenbrander et al., 1986; Dhiman and Satter, 1994) also observed that similar milk production could be attained using either corn or
alfalfa forages. Borton et al. (1997) used the dairy forage system model, DAFOSYM, to compare the overall farm performance and economics for representative Michigan dairy farms. Assuming equal milk production among different systems of alfalfa and corn silage, they found that an all-alfalfa system brought the highest net return, but the economic differences among forage systems were small compared with the variation caused by weather among years. Costs for machinery, labor, and energy were higher for alfalfa systems because of greater equipment requirements and more harvesting procedures for alfalfa systems.

Corn silage nutrient digestibility and dry matter yield per hectare reach maximum near physiological maturity. The nutritive quality of corn silage is related to grain and stover digestibility, which is affected by genetics, environmental conditions, and maturity at harvest (Bolsen, 1995). Grain digestibility can be improved by breaking kernels with a kernel processor at harvest (Jirovec et al., 1999). Kernel processing reduces particle size and this can affect fiber digestibility. More extensive review on kernel processing is included in later sections.

3.2 Corn Silage Production—Improving Digestibility

The stage of maturity at harvest is a major factor in determining the nutritive value of silage. Many factors affect the stage of maturity of the crop are related to planting and harvesting management, weather, and variety. Planting density also affects whole-plant corn yield and quality. Key factors related to harvesting management include: crop moisture content, harvester settings for particle size and use of kernel processing.
In selecting corn silage hybrids, both grain yield and stover digestibility are important factors. Grain has higher energy density while stover accounts for a large portion of the yield and affects rumen fill. The nutritive value of corn stover decreases with increasing maturity.

As stover typically represents about 45-60% of the total DM yield of corn silage, its nutritive value when selecting hybrids for silage production cannot be neglected (Verbic et al., 1995). Significant variation exists for nutritional quality traits of stover and whole-plant corn and stover quality is an important factor influencing whole-plant nutritional quality (Wolf et al., 1993). The nutritive value of corn silage can be improved by increasing the proportion of grain and/or by improving the nutritive value of stover (Deinum and Bakker, 1981; Verbic, et al., 1995). Possibilities for genetically improving the quality of grain are limited because of its rather small variability in comparison with the variability in stover (Deinum and Bakker, 1981).

When corn silage was harvested at grain moisture levels of 28-30, 20-23, and 10-12%, grain yield standardized to 12.5% moisture content increased; however cob, stover, total crop residue and total biomass dry matter (DM) yield decreased with increasing stage of maturity. The declining trend in stover yield with increased stage of maturity was due primarily to leaf loss (Verbic et al., 1995).

Corn silage harvested with grain moisture of 20% to 30% gave higher leaf-stem ratio, higher CP and lower NDF content in stover without a significant change in grain and stover yields. The reduction in nutritional value of stover with increasing stage of maturity was characterized by a reduction in CP content and increasing concentrations of fibrous constituents (Verbic et al., 1995).
There are many corn hybrids available commercially. Yellow dent, waxy, high-lysine, high-oil and brown midrib corns are examples of contemporary corn types. Except for brown midrib corn, U.S. corn varieties are dual-purpose crops, i.e. they can be harvested as either grain or forage. Each variety has unique characteristics that affect its use. Brown midrib mutants consistently decrease the lignin content of forages and increase NDF digestibility (Cherney et al., 1991).

3.2.1 Planting Management

Depending on the variety, planting date for corn can range from early to late spring. Planting date affects yields by affecting grain moisture content and the susceptibility to frost before harvest. Although corn for silage should be planted in a timely fashion, it is more tolerant of late planting than corn harvested as grain (Roth and Lauer, 1997). Early-planted corn destined for grain will have higher yields, less susceptibility to frosts, and lower grain moisture content at harvest than will late-planted corn (Roth and Lauer, 1997).

Relative maturity among hybrids in performance reports is best shown by grain moisture content. Hybrids are ranked from earliest to latest in each of the reports. Days to maturity and growing degree days (GDD) are two methods of expressing the energy required for corn to mature. Short season hybrids have the shortest GDD and late season hybrids have the longest GDD. The typical GDD for corn silage in Pennsylvania ranged from 2100 to 2900 (PSU, 2001).

On a whole-plant basis, maturity effects often account for significant differences in dry matter digestibility. Plant maturity effects can confound relationships between yield and quality. Later-maturing genotypes may have greater dry matter yields but lower grain-to-
stover ratios (Russell et al., 1992). Consequently, later-maturing genotypes tend to have higher whole-plant fiber and lower whole-plant digestibility relative to earlier maturing genotypes harvested on the same date.

Cusicanqui and Lauer (1999) studied the effect of plant density and hybrid on yield and quality. They grew two adapted hybrids of high and low quality characteristics at five plant densities ranging from 44,500 to 104,500 plants/ha at six locations in Wisconsin during 1994, 1995 and 1996. They found that forage chemical compositions among hybrids were similar across the range of plant densities evaluated. As plant density increased, dry matter yield increased. In vitro true digestibility decreased 16 to 23 g/kg as plant density increased. Crude protein decreased 6 to 8 g/kg as plant density increased. NDF increased 20 to 35 g/kg, and acid detergent fiber (ADF) increased 19 to 29 g/kg with increasing plant density.

In New York, Cox et al. (1998) evaluated eight hybrids at densities of 44,500, 59,300, 74,100, 89,000, and 104,000 plants/ha in 1994, 1995, and 1996 to compare yield, quality, and economics of corn silage production at 38 cm and 76 cm row spacing. When averaged across years, hybrids, and densities, corn silage yielded slightly higher (55.8 Mg/ha) at 38 cm than at 76 cm row spacing (53.6 Mg/ha). Maximum economic yields occurred at about 97600 plants/ha and in vitro true digestibility decreased and NDF increased with the increase of plant density. They predicted more gain in annual net farm income for farmers producing more area of silage with the 38 cm row spacing than the 76 cm row spacing. They concluded that as plant density is increased, yield may increase but IVTD may decrease and NDF content may increase.
3.2.2 Harvesting Consideration

Proper maturity at harvest assures adequate fermentable sugars for silage bacteria and maximum nutritional value for livestock. Maturity of corn silage can best be determined by the location of the milk line (ML). This line is the interface between the liquid endosperm (milk) and solid endosperm (starch) portions of the kernel, and it will not appear until the corn is at the dent stage of maturity. As the plant matures, the milk line moves away from the base of the kernel. Black layer formation is a visible black line at the base of the kernel that indicates transport of nutrients to the kernel has stopped (physiological maturity). Its nutrient digestibility and dry matter yield per hectare approach maximum between the 80% ML and 7-10 d post-black layer stages (Bolsen, 1995).

Grain and starch content increases in corn silage with advancing maturity (1/3 ML through kernel black layer) but sugar content decreases. The digestibility of the stover portion of corn silage declines dramatically with progressive maturity. At a less mature stage, corn kernels are soft and easy to break up in the forage harvester.

Moisture content of whole plant corn is inversely related to stage of maturity at harvest (Wiersma et al., 1993). At an immature stage of kernels, whole plant moisture content can be above 70%. Ideally, corn should be harvested at close to kernel maturity to maximize the nutritive value of kernels. However, whole plant moisture should be around 65% for harvesting. At a mature stage when the kernels are hardened, mechanical processing has been used to modify the nutritive value of corn silage (Deboever et al., 1993; Jirovec et al, 1998; Dhiman et al., 2000).

The moisture content of corn is usually in an acceptable range (63% to 70%) for about two weeks during the harvest season, and its high proportion of grain contributes to
high-density silage. Bal et al. (1997) suggested that 2/3 ML (65% moisture) was the optimum maturity stage for harvesting corn silage for lactating dairy cows. They found that corn silage at 2/3 ML (between ¼ ML and 2/3 ML; or 65 to 68% moisture) resulted in higher animal intake, more digestion and higher milk production than corn silage at other maturity stages.

Hard, dry corn kernels resist digestion and thus reduce the digestible energy content of silage. Corn silage that is harvested at above 2/3 ML can result in ruminal and intestinal bypass of corn into feces. With the trend toward longer chop length (10 to 15 mm), most kernels in corn silage remain unbroken after chopping. A rapid dry down or a killing frost may prevent farmers from harvesting at a more immature stage. When corn silage harvested at ½ ML was compared to that harvested at black layer, there was a decrease in ruminal starch digestibility from 72% to 56%, a decrease in intestinal starch digestibility, and a decrease in total tract digestibility compared to silage harvested at black layer stage (Harrison, 1996). Additionally, flow of ruminal microbial nitrogen, lysine, and methionine were reduced when cows were fed the black layer silage (Harrison, 1996).

When weather permits, farmers may desire to harvest their corn at or near physiological maturity—usually about ½ milk line. It is well established that as the corn plant matures there is an increase in grain content with increases in DM yield and digestible DM yield (Allen et al., 1997). It is also known that certain hybrids maintain the digestibility of the stover fraction as the plant matures, while the stover digestibility of other hybrids declines rapidly as the plant approaches physiological maturity (Allen et al., 1997). Selection of a hybrid that maintains its stover digestibility and harvesting a crop at near physiological maturity seems to be a logical forage management strategy.
Kernels in corn silage should have high moisture and be of soft texture to increase starch digestion by the animal (Allen et al., 1997). Soft kernel texture may not be as important for producers storing corn silage at lower dry matter levels or for those processing corn silage before feeding. Kernel processing crushes or breaks hard kernels and can serve as an alternative to soft textured kernels. Mechanical processing of corn silage not only crushes kernels, it also causes cob damage and the reduction of fodder particle size.

Processing of corn may increase the ruminal degradability because of increased kernel breakage that facilitates starch digestion (Savoie et al., 1999). Processing of kernels benefits silage by making more of the nutrients in the grains available to the cow. However, kernel processing after chopping reduces particle size. Dairy cattle have a need for fiber in their ration; therefore, a greater potential benefit comes from coarser chopping of corn in conjunction with processing. This combination should ensure maximum stimulation of rumen function while achieving high digestibility. Processing corn silage after chopping might result in a larger portion of long particles compared to chopping-only and thus might reduce the need for coarser cut haylage. Increasing the TLC on corn silage then allows producers to harvest alfalfa with a shorter chop length. This improves the packing of a crop that often has dried too fast in the field resulting in less than ideal moisture for compaction (Ruppel, 1995).

An important consideration in the shredding process is the effect shredding has on feed value, intake and milk production. Hong et al. (1988) suggested that macerated crop was more digestible than conventional alfalfa forage. The increased digestibility allowed the animal to receive more energy from the forage, assuming intake did not change. Hong et al. (1988) also documented an increase of 6% in animal intake. Improvements in intake of 0 to
11% are reported from feeding trials comparing processed and unprocessed silage (Harrison et al., 1997).

Grinding is the most studied physical treatment for enhancing the utilization of fibrous feedstuffs by ruminants. Grinding decreases particle size, increases surface area, and increases the bulk density of leaf and stem fractions of forages (Laredo and Minson, 1975). The most consistent animal responses to grinding and pelleting of forages are increases in feed intake, gain and improvement of feed efficiency (Beardsley, 1964; Minson, 1963). Intake of ground roughages generally increases with decreasing particle size and is not maximized until mean particle size is less than 1 mm for most forages (Osbourn et al., 1976). Less extreme processing of forages, such as chopping, may increase wastage and sorting (Beardsley, 1964). Meyer et al. (1959) concluded that fine grinding was the major factor causing the increased consumption of ground and pelleted hay, while pelleting increased acceptability by reducing dustiness.

Digestibility of ground and pelleted roughages generally is depressed relative to that of the parent material fed in either long or chopped forms (Berger et al., 1994). The decrease in digestibility of ground forage is primarily due to reduced fiber digestion (Beardsley, 1964). While in vitro studies demonstrate that fine milling of forage increase cell wall degradability (Dehory and Johnson, 1961), in vivo studies generally show a reduction in cell wall digestion (Thomson and Beever, 1980). This effect can be attributed to the shorter gastrointestinal tract residence time for ground than for long or chopped roughages (Minson, 1963; Alwash and Thomas, 1974). The relationship between digesta transit time and total tract digestibility is evident from the results of Blaxter et al., (1956). The increased flow of undigested structural carbohydrate to the small intestine can account for 65 to 75% of the
increase in energy flowing out of the reticulorumen of ruminants consuming ground forage when compared to unprocessed forages (Thomson and Beever, 1980).

Kernel processors are a post-harvest treatment to maximize corn grain starch digestibility. Several machine designs have been used for kernel processing (Savoie, 1997). Mostly commonly, a kernel processor is a pair of closely spaced rolls that crack the corn kernels and cobs. These rolls have different linear velocities at the tip and can tear forage particles. Kernel processing can be done in the field, at the storage site, or after storage.

When corn is harvested at mature stages the kernels are likely to become harder and less digestible. Hard kernels cannot be digested as well and will pass to feces. Honig and Rohr (1982) reported that as much as 25% of mature, uncracked kernels in corn silage may be undigested and end up in the feces of ruminants. Joanning et al. (1981) observed substantial reductions in digestibility of mixtures of corn silage and corn grain in beef cattle. Their results indicated that about half of the depression in digestibility for corn silage was due to reduced starch digestibility. Owens et al. (1986) reported that dry-rolled corn had higher ruminal digestibility than whole corn.

Studies in Washington show that kernel processing has a greater effect on rate of fermentation in the silo when silage is harvested at a more advanced maturity (Harrison et al., 1997). Kernel processing has little or no effect on pH decline for 1/3 milk line silage. But at 2/3 milk line processed silage was observed to ferment more quickly and had a lower pH by day 10 after ensiling than unprocessed silage of the same maturity.
3.2.3 Brown Midrib Corn

Brown midrib plants are characterized by a brown pigmentation in the leaf midrib and a light brown coloration of the pith after tasselling. Brown midrib corn contains a gene (bm3) that causes a lower lignin content in corn plant tissue. Lignin is a relatively indigestible compound that limits digestibility of the fiber in the corn plant. The reduced lignin in brown midrib results in silage with fiber that is more digestible than that of normal corn.

Research conducted since the early 1970’s showed that the lignin content of brown midrib corn was significantly lower than its normal counterpart, and that in vitro NDF digestibility of brown midrib corn is consistently higher than its normal counterpart (Cherney et al., 1991). Enhanced dry matter intake (Rook et al., 1977; Block et al., 1981), higher milk production (Frenchick et al., 1976; Kieth et al., 1979), and higher body weight gain (Rook et al., 1977; Sommerfeldt et al., 1979; Block et al., 1981) were attributed to feeding brown midrib corn silage. One experiment with a large performance difference was reported by Muller et al. (1972). Brown midrib corn and its normal counterpart were ensiled without ears and fed to eighteen rams. Lignin concentrations were 4.5% and 6.8% for the brown midrib corn silage and normal corn stover silage, respectively. They reported a 29% greater dry matter intake for brown midrib corn stover silage.

Recent studies also indicate increase of intake for brown midrib corn silage. Tine et al. (2001) evaluated the effects of genotype and level of intake on net energy for lactation values of corn silage using lactating and dry, nonpregnant dairy cows. Dry matter (DM) intake was 2.4 kg/d greater for cows fed the bm3 diet ad libitum compared with cows fed the isogenic normal corn silage diet. Apparent digestibility of DM, organic matter, neutral
detergent fiber, and acid detergent fiber were greater for cows that were restricted-fed bm3 compared to the isogenic diet. Apparent digestibility of DM, organic matter, neutral detergent fiber, and acid detergent fiber were greater for cows fed bm3 compared with isogenic corn silage. Digestible energy and metabolizable energy were greater for maintenance diets containing bm3 compared with isogenic corn silage, respectively. Their data indicate increased milk production seen in other studies is a result of increased DMI rather than an increase in energy efficiency. Increased organic matter digestibility of bm3 corn silage resulted in greater digestible energy and metabolizable energy values in cows fed at maintenance energy intake.

Studies on brown midrib forage sorghum showed that milk production was significantly higher for brown midrib than for standard sorghum (Aydin et al. 1999). They found that both in situ and in vitro extent of ruminal fiber digestion were significantly higher for BMR than for standard sorghum though rate of fiber digestion was not different. Although dry matter intake and body condition score were not significantly different between cows fed BMR and standard sorghum, cows fed BMR sorghum resulted in long-term milk production greater than that of cows fed standard sorghum and similar to cows fed corn silage. Disadvantages of brown midrib, however, are lower dry matter yields and lodging. Unfortunately, there is no available documentation on the mechanical properties (such as the energy requirements for cutting and packing density) of BMR versus standard forage crops.

3.2.4 Brief Summary

- Stover typically represents about 45-60% of the total DM yield of corn silage. Stover digestibility is important in corn silage digestibility.
• The nutritive value of corn stover decreases with increasing maturity. The reduction in nutritional value of stover with increasing stage of maturity is characterized by reduction in CP contents and increasing concentrations of fibrous constituents (Verbic et al., 1995).

• Corn for silage is more tolerant of late planting than corn harvested as grain.

• Higher plant density may increase yield but IVTD may go down and NDF content may rise.

• The lignin content of bm3 (brown midrib) corn is significantly lower than its normal counterpart, and in vitro NDF digestibility of brown midrib corn is consistently higher than its normal counterpart. However, lower dry matter yields and lodging have been reported with bm3 corn.

• Processed corn silage cut at a long TLC is one way to produce a feed with sufficient kernel breakage while still maintaining desired fiber length.
3.3 Silage Storage—Making Good Corn Silage

The preservation of green crops of high moisture content can be problematic. If such materials are exposed to the air, microbial activity involving yeast, fungi and bacteria result in high gaseous losses of dry matter and degradation of digestible nutrients. The product is usually less digestible and it may be toxic. Rapid achievement and subsequent maintenance of anaerobic conditions in storage may minimize this anaerobic deterioration.

Nutrient losses are expected during the ensiling process. Crop moisture content, maturity, packing, sealing, and particle size are the major factors that influence the process. Kernel processing is a technology that has been used widely to improve starch availability of corn kernels. Kernel processing breaks corn kernels, alters fodder particle size, and may influence the ensiling process.

3.3.1 Principles of the Ensiling Process

The material going into a silo consists of plant material and aerobic microorganisms—the most numerous organisms on fresh herbage. The ensiling process inside a silo essentially involves two phases—the aerobic respiration phase and the anaerobic fermentation phase. The aerobic phase occurs between harvest and sealing of the silo when oxygen is present. The anaerobic fermentation begins when entrapped oxygen is consumed.

Immediately after harvest, and for a few hours after ensiling, the crop and microbes continue to respire until oxygen becomes depleted and anaerobic conditions start. Lactic acid bacteria (LAB), which are present on the crop prior to harvest, grow rapidly using sugars as a source of energy. Lactic fermentation results in lactic and acetic acid production which lowers pH.
The undesirable aerobic microorganisms include primarily clostridia, enterobacteria, yeasts and molds (Edwards and McDonald, 1978). These compete with lactic acid bacteria for plant carbohydrates. Clostridia fermentation can occur as secondary fermentation. One of the primary factors affecting the type and success of fermentation is the activity of clostridia in silage. Clostridia generate butyric acid and are sensitive to water availability—requiring very wet conditions for active growth. At crop moisture contents lower than 70%, clostridia are virtually inactive (Edwards and McDonald, 1978). Their activities are also inhibited by high acidity. In ensiling, good preservation is achieved by fermentation of sugars in the crop into lactic acid to produce an environment that has low enough pH to inhibit clostridia activity. Under anaerobic conditions, corn silage with a pH of 4.2 or less is stable for long storage periods.

LAB perform acidification in silage under anaerobic conditions. LAB get their energy by fermenting carbohydrates. The efficiency of ensiling is judged according to the relative proportions of the fermentation acids produced: the greater the ratio of lactic acid to butyric acid the higher the efficiency. The dominance of LAB ensures good silage. Anaerobic bacteria (clostridia) break down sugars to butyrate, and degrade amino acids to simple compounds such as amines and ammonia. The resulting product is likely to be rejected by animals due to bad smell. In addition, the degraded amino acids are less digestible.

Yeast are present on most silage and can become very active in aerobic conditions, Lactic acid-assimilating yeast are especially linked to aerobic deterioration, particularly following the opening of the silo or the removal of the silage from the silo (McCullough, 1978; Woolford, 1984).
Sufficient lactic acid can only be produced if a good supply of soluble carbohydrates is available in the ensiling process. Corn is a plant that has readily available carbohydrates and fermentable sugar. Other influencing factors include the ability to achieve and maintain anaerobic conditions in the silo, the quantity and type of bacteria present on the crop, and the extent and type of fermentation. With other factors non-limiting, microbial fermentation will continue until enough acid (pH of 4.2 or lower) is produced to stop bacterial action.

If too much air is present or if oxygen penetrates, respiration will continue and consume too much sugar and carbohydrates. This wastes nutrients needed by the desirable bacteria for fermentation. Too much heat will also be generated when a large amount of air is trapped inside the silo. Excessive heating can change protein when temperatures exceed 40°C. Parts of the silage protein (amino acids) are bonded chemically to fiber, forming a brown, lignin-like material that is indigestible by animals. Thus, heating lowers silage digestibility. The degree of the loss of digestibility is dependent on the temperature reached and the length of the heating period.

There are three major groups of substances in forage crops that are subject to change during ensiling: carbohydrates, organic acids and nitrogenous substances including protein and amino acids. The water-soluble carbohydrates are important sources of energy for microorganisms that are responsible for silage fermentation. Carbohydrates will be broken down to carbon dioxide, water and heat during respiration. During ensiling, there is a rapid and complete breakdown of organic acids. Some lactic bacteria are capable of dissimilating organic acids with a consequent rise in pH and the formation of carbon dioxide and neutral products such as water. The organic acids are responsible for buffering power of herbage.
Once the corn is chopped, proteolysis occurs during the first few days following ensiling (Woolford, 1984; Rotz and Muck, 1994). Nitrogen gases will be formed during silo filling and for about two weeks after storage begins. Plant proteins are degraded to non-protein nitrogen and ammonia. During the first couple weeks, the extent of proteolysis depends on acid formation, temperature and moisture of the ensiled crop. Lower pH is desirable to reduce protein break down. If insufficient acid is formed, clostridia may grow rapidly, causing silage deterioration.

Proper moisture content of the crop ensures preservation and minimizes spoilage during storage by aiding packing and excluding air. High moisture requires more acid and thus lower pH for plant stability. Silage ensiled too wet may ferment poorly and seep. Seepage removes nutrients, particularly soluble nitrogen and carbohydrates, and it may damage the silo. Silage that is too dry will contain air pockets that prevent anaerobic fermentation and allow molds to develop. Ideally, moisture content of the forages going into the silo should be sufficiently low to prevent seepage loss.

The recommended moisture content for corn silage stored is 60-65% for upright silos, 50-60% for upright “oxygen-limiting” silos and 65-70% for horizontal silos. The amount of moisture content is different for different types of silos because of the different packing and sealing method used in each type of silo. Upright silos are sealed structures and packing is done by silage weight, they require drier material. Bunker silos require mechanical packing and manual sealing and therefore need wetter material to facilitate packing and exclusion of air.
3.3.2 Effects of Kernel Processing

Since kernel processing crushes kernels and stems and releases juices, it is logical to expect some effect on the fermentation process inside the silo. Bruised material will also have different mechanical properties compared to chopped material. Therefore kernel processing might influence silage compaction.

Greenhill (1964) regarded the breakdown of cells and the consequent release of juices to be a necessary prerequisite for the formation of lactic acid in silage. He suggested that mechanical treatment like maceration would aid the release of juice because of the rupture of plant cells. Maceration also favors consolidation and excludes air, thus indirectly assisting the release of juices. It seems that chopping, macerating, and bruising generally improves the chance of successful ensiling (Murdoch et al., 1955; Gordon et al., 1959).

On the other hand, the release of organic acid contained in the cell sap can lead to a drop in pH of a crop prior to ensiling (De Man, 1952; Anderson, 1956). This suggests that crushing or maceration might contribute more to cellular breakdown than indicated by Greenhill (1964). This release of organic acids may have a slightly negative effect on ensiling owing to their buffering properties.

Recent studies confirmed the effect of processing on fermentation. Studies in Washington show that kernel processing has a greater effect on rate of fermentation inside the silo when silage is harvested at a more advanced maturity (Harrison et al., 1997). Kernel processing has little or no effect on pH decline for 1/3 ML silage. But the 2/3 ML processed silage was observed to ferment more quickly and had a lower pH by day 10 after ensiling than non-processed silage. Charmley et al. (1997) found that maceration enhanced the fermentation characteristics of alfalfa silage. Research by Lu et al. (1980) and Hong et al.
(1988) on alfalfa show that the crushing and laceration of leaf surfaces increases the surface area for microbial attachment and released soluble sugars that served as substrate for lactic acid bacteria.

Apparent digestibility of forage may be improved by maceration. This has been demonstrated in studies with hay (Petit et al., 1994; Koegel et al., 1992). In feeding trials comparing macerated and conventionally harvested alfalfa as either hay or silage, increases in dry matter digestibility of 10 to 15% and increases of dry matter intake of 5% were observed (Koegel et al., 1992). However, in studies with precision-chopped silage no increase in digestibility has been observed (Frost et al., 1995; Charmley et al., 1997). This is presumably attributed to the nullifying effect of fine chopping at ensiling on the modified physical characteristics attributed to maceration at mowing.

Silage density might be affected by kernel processing and thus may further influence the fermentation process as density is directly related to air exclusion. Shinners et al. (1988a) found that macerated alfalfa consolidated at a faster rate than chopped alfalfa, but final densities were not significantly different. They also observed that the macerated material compacted to a greater bulk density than chopped alfalfa when subjected to a dynamic load. When a dynamic load was applied to the macerated material, the interwoven, compliant fibers may have interlocked and thus did not rebound as in the chopped material. This characteristic would be of substantial benefit in horizontal storage structures, where chopped material must be compacted repeatedly before it reaches the required density for proper preservation. Shinners et al. (1988a) concluded that maceration of forage before storage in these structures would reduce the number of compactions required, thereby saving energy.
and time, and possibly producing higher quality silage due to faster, more complete oxygen exclusion.

However, no difference was observed in the consolidation or compaction characteristics between the macerated-only or the macerated-and-chopped treatments (Shinners et al., 1988a). Therefore, the benefits of faster consolidation and greater dynamic compaction could be achieved without additional processing after or before maceration, thereby saving energy and time. Higher densities (20 to 50% greater) were also observed by Koegel et al. (1992) in their sheep feeding trails with macerated alfalfa either in the form of compacted silage or baled hay.

3.3.3 Storage Management

Regardless of the type of silo, silage making involves four key steps: harvesting, filling/packing, sealing, and feed-out. Each of the four processes has to be managed properly to minimize dry matter and nutrient losses.

Harvesting within the recommended moisture content ranges will promote good packing and minimize losses from heating and effluent loss. Chopped forage is compressed as it is ensiled in silos. The compressing process directly affects silage quality. Filling and packing should begin immediately after harvest. Filling delays will result in excessive respiration and increased silage dry matter loss. Furthermore, better preservation is obtained by sealing the silage with coverings. Lastly, the removal of silage is important in managing aerobic deterioration in silage. Loose silage is more porous and allows greater air infiltration, increasing the rate of aerobic growth.
3.3.3.1 Silo Types

Chopped forage is normally ensiled in tower silos, silo bags, or horizontal silos. Major considerations in selecting a silo type are structural cost, volume of storage needed, and speed of loading and unloading. Other considerations may include silo longevity, initial investment cost, and potential to purchase or sell feed.

Tower silos are relatively sealed silos by construction. They offer smaller exposed surface area of silage, require less area for construction, and allow greater mechanization during filling and feed-out. Some disadvantages of this type of silo can be high initial cost and slower unloading. The requirements for drier silage and shorter particle sizes in tower silos might affect silage quality negatively. Dry silage might imply mature crops and hard kernels, which means more fiber and less starch digestibility. Finely chopped particles may not meet the dairy cow’s requirement for effective fiber.

Silage bags are long tubes of plastic offering low initial investment costs and good temporary storage for silage. The bags must be protected to prevent mechanical and rodent damage.

Horizontal or bunker silos are normally constructed of concrete panels used to form a rectangular structure with one or more open ends. Silage is packed within the walls to a depth of 2.5-5.0 m. Silage can be preserved very well in this type of silo. Bunker silos have become popular during recent years because they may cost less to construct and they can have large capacity, ideal for larger enterprises. Bunker silos offer large capacity and faster unloading rates. They can be filled with standard farm equipment and they require less energy to load and unload forage than tower silos.
Bunker silo management is highly variable due to the fact that packing is entirely up to the management team, as opposed to being provided by the silage weight in a tower silo. There is a greater use of bunker and bag silos in North America. They are more compatible with longer TLC silage because they are typically unloaded with front-end loaders. Long particles pose a removal challenge in tower silos, and they reduce packed density.

### 3.3.3.2 Filling and Packing

In general, the faster the silo is filled the better the resulting silage will be. Rapid filling (1) minimizes the risk of feed losses from rainy weather, (2) reduces labor and overall ensiling costs, and (3) improves fermentation by minimizing exposure of the chopped forage to oxygen.

Bunker silos are commonly built in 1 to 2 m increments of length and width. When ensiling forage in bunker silos, forage should be compacted in progressive wedges using a wheel tractor with a front-end loader or blade to move and pack silage. This technique minimizes exposure of silage to air before covering. A wheeled tractor is preferred as a packing vehicle, as it will supply greater downward pressure than a track-type vehicle. Track-type tractors do not provide enough downward compaction pressure. Dry matter densities can range from 106 kg DM/m$^3$ to 434 kg DM/m$^3$ (Muck and Holmes, 2000).

Ruppel et al. (1995) found that density in bunker silos was highly variable and correlated with various factors. The most important factors were packing tractor weight and packing time (minutes per unit top surface area). Muck and Holmes (2000) measured density in over 160 bunker silos across Wisconsin and surveyed the filling practices. The results of their research were reasonably consistent with Ruppel et al. (1995). Three factors were
found highly correlated to silage densities. The highest correlation was with the initial layer thickness of the forage before packing. Density decreased with increasing layer thickness. The next important factor was the average packing tractor weight. DM content was correlated to DM density within the recommended ranges of DM contents for bunker silos. The last factor was packing time; packing time per Mg (wet basis) was more strongly correlated with density than packing time per Mg DM. They found that prolonged packing only brought diminishing returns, which was also reflected in our experiment done at Penn State (see Appendix A).

Studies on bunker silo density showed that the effect of particle size on density seemed ambiguous. Ruppel et al. (1995) found no correlation between particle size and density. Muck and Holmes (2000) also found weak correlation between particle size and bunker silage densities. Many earlier studies looking directly at the effect of particle length have shown some reduced density with increasing particle length. In alfalfa, Shinners et al. (1994) observed that the initial bulk density in a bunker silo was reduced 14% as geometric mean particle size was increased from 8.7 to 25.2 mm. Final wet and dry bulk densities were reduced 12 and 21%, respectively. McGechan (1990) performed a survey and found that the ensiled density of grass silage in bunker silos decreased by approximately 20% as median chop length increased from 20 to 100 mm.

### 3.3.3.3 Sealing

Once filled, silos should be sealed with an airtight cover to prevent surface spoilage losses from penetration of air and rainfall into the silage mass. In addition, the resulting silage has a higher digestibility since the losses are mostly highly digestible nutrients
(Buckmaster et al., 1989). Covering a large silo is not a trivial matter but silage without proper sealing or not sealed tight results in excessive waste. It has been estimated that covering a bunker silo with plastic can return $8.00 for every dollar spent through reduced losses and increased animal productivity (Rotz and Muck, 1994). Old tires and sandbags can be placed over the plastic cover. Cutting tires in half will double their use and prevent water from collecting inside the tire.

3.3.3.4 Feed-out

Keeping an even, clean, undisturbed face on bunker silos when removing silage is an important management factor. Silage should not be scooped from the face as this allows more air to enter, resulting in unnecessary spoilage. Removing silage from the whole silo face at a rate of at least four to six inches per day reduces losses from poor aerobic stability. Slow feed-out rates allow more time for losses from the growth of yeast, molds, and aerobic bacteria. This, in turn decreases dry matter intake.

3.3.4 Brief Summary

- Corn silage quality depends greatly on silage storage management.
- Kernel processing and maceration aids fermentation and compaction.
- Both moisture content and particle length should be considered to maintain good silage density.
- Packing tractor weight and packing time are important factors affecting bunker silage densities.
3.4 Livestock Feeding—with Focus on Fiber and Energy

The unique characteristic of forage is the relatively large concentration of fiber fractions, compared with those of high-starch grains and some concentrate by-products fed to cattle. For dairy cows, the rumen provides a site where the rumen microorganisms can digest carbohydrates, proteins, and fiber. The digestion of virtually all of the cellulose and much of the hemicellulose in forages is by microbial action in the rumen. Through this digestion process, energy or volatile fatty acids (VFA’s) and microbial protein that can be utilized by the animal are produced.

In order to improve forage utilization in dairy cows, rations have to be balanced to meet the cow’s fiber and energy need with feed nutrients. Dry matter intake (DMI) is an important criterion when formulating diets, especially for high-yielding dairy cows. The dairy cow’s need for increasingly greater dietary energy density has led to rations that must be relatively high in concentrates as compared to the average producing cow twenty years ago (Heinrichs and Lammers, 1997).

3.4.1 Microbial Digestion in the Rumen and Rumen Fill

Ruminant animals have four stomach compartments: the reticulum, the rumen, the omasum, and the abomasum. The reticulum, the first stomach compartment, acts as a sieve and prohibits large particles from moving further into the digestive tract. Reduction of large particle size is a requisite to flow from the reticulum. Large particle breakdown in the reticulum is primarily a result of rumination and primary mastication, with relatively little breakdown directly resulting from digestion and detritions (McLeod and Minson, 1988).
The rumen is the site for the synthesis of VFA’s and microbial protein from feed nitrogen. The primary VFA’s in descending order of abundance are acetic, propionic, butyric and small amounts of other acids. Acetic acid can constitute up to 60% of the total VFA’s (Church, 1991) and dominates in a high forage diet. Production of adequate acetate in the rumen is essential to maintain adequate quantities of milk fat.

In the omasum, the particle size of digesta is reduced, and water is removed before the digesta enters the abomasum. The abomasum is referred to as the “true stomach”, where the acids and enzymes further digest the cow’s digesta (feed being digested) (Church, 1991).

The use of energy by dairy cattle depends to a large extent on the microbial fermentation that occurs in the rumen. The extent and type of fermentation determine the nature and amounts of the various metabolites that are absorbed from the digestive tract. These metabolites affect the efficiency of milk production, and they also influence the way energy is used. In general, diets that result in low ruminal acetate:propionate ratios (such as high concentrate diets) lead to increased body fat formation at the expense of milk fat synthesis. Such decreased milk fat synthesis occasionally may be accompanied by a modest increase in milk protein (NRC, 2001).

A proper balanced diet of forage and grain helps maintain the ideal pH level inside the rumen. Controlling the ruminant’s diet can encourage production of saliva. Saliva acts as a buffer to maintain adequate rumen pH. The more a cow chews, the more saliva it produces. Saliva production can drop dramatically if the cow does not receive adequate effective fiber. For example, when cows are fed high amounts of concentrates and finely chopped forages. When rumen pH is too low, the growth of the cellulolytic organisms can be reduced, allowing for an increase in the propionate-producing microbes. This can cause a
decrease in the acetate to propionate ratio and potentially result in a lower milk fat percentage.

Indigestible DM is a major constraint on feed intake in ruminants (Conrad, 1966). Within limits, DMI increases as the digestibility of the diet increases. Rumen fill appears to be the limiting factor for DMI when forage is the major ingredient of a diet (Blaxter et al., 1961). NRC (2001) concludes that DMI is depressed when a major portion of the diet is composed of fermented feeds. This depression may be the result of organic acids, amines, and ammoniacal nitrogen or its precursors in the feeds, all of which have been shown to shorten meal length and meal weight.

3.4.2 Ration Balancing

Formulating rations to meet the energy needs of dairy cattle is dependent upon production level, body condition score, environmental stress, and deviations in dry matter intake. A balanced ration provides nutrients in such proportions and amounts that it will properly nourish a given animal for 24 hours (NRC, 2001). In addition, the required nutrients must be contained in the amount of DM the animal is able to consume in the 24-hour period or the ration cannot be considered balanced. Therefore, the first step in formulating a ration is to calculate the probable DMI of the animal in question; the second step is to calculate the nutrient requirements of the animal; and the third step is to determine the amount of available ingredients that must be fed to fulfill the animal’s nutrient requirements within its expected DMI limits.

A dairy cow’s diet is usually composed of various feed ingredients, which meet her nutrient requirements. The amount of fiber in the diet of dairy cows is normally expressed as
Crude fiber, ADF, or NDF. Crude fiber represents the fiber fraction that is resistant to degradation in acid and alkali. Acid detergent fiber consists of cellulose, lignin, acid detergent-insoluble nitrogen, and acid-insoluble ash; NDF consists of hemicellulose, cellulose, lignin, acid detergent-insoluble N, and acid insoluble ash. Variation in NDF content, NDF digestibility, and starch digestibility of corn silage hybrids can affect animal performance. For dairy cows consuming high forage diets, corn silage hybrids that have low NDF content and high NDF digestibility will increase dry matter and energy intake. High starch digestibility is also important to maximize digestible energy intake and microbial protein production in the rumen. Fiber that is less digestible and corn kernels that pass through the rumen undigested decrease energy available to the rumen microbes reducing microbial protein production.

DM intake per animal is dependent upon animal characteristics such as bodyweight and fat corrected milk production as well as feed characteristics such as NDF concentration or energy level (NRC, 2001). The NRC (2001) recommends dry matter amount according to animal body weight and forage NDF ranging from 0.75% to 1.10% of body weight depending on the stage of lactation. For early lactation when energy requirement is highest, forage NDF content can be low. Forage dry matter intake should range between 1.4 to 2.4 percent of body weight regardless of forage NDF intake parameters.

A nutritionally balanced diet provides a rumen environment that maximizes microbial production and growth. When designing rations for ruminants, the needs of both the animal and the rumen microorganisms must be considered. Diet should be formulated to maintain adequate mean ruminal pH, and feeding management should minimize variation in ruminal pH. Effective fiber is required to maintain adequate ruminal pH. Acid production in the
rumen is due primarily to fermentation of carbohydrates, which represent over 65% of the DM in diets of dairy cows and they have the most variable ruminal degradation across diets.

Energy for dairy is usually the first limiting factor in the diet of high-producing cows; they cannot consume enough dry matter in the form of forages to fulfill their energy requirement. While fiber is not a nutrient by strict definition, it plays a critical role in optimal rumen function and must be considered when formulating rations. Analysis of forage and addition of specific and concentrated sources can easily meet requirements of minerals and vitamins.

Energy is defined in net energy for lactation terms (Mcal/kg DM) where needed. The critical components of forages relative to energy are energy density (energy per unit of forage weight), rate of digestion of energy relative to retention time of forage in the digestive tract, and factors in the diet that influence the energy value of forages (Bull, 1995).

Energy density of forage is related to plant species and the composition of the forage. A critical factor in energy density variation is concentration of fiber fractions in total dry matter, created by advanced maturity of the plant. While total fiber (NDF) content usually increases with maturity, relative amounts of cellulose and lignin increase also, and the percentage of total plant energy that is potentially available to the animal declines.

Of the variation in energy intake among forages, approximately 65%-75% may be related to intake, 20%-30% to differences in digestibility, and only 5%-15% to differences in metabolic efficiency (Buxton and Mertens, 1995). Mertens (1985) reports that digestibility is negatively correlated with ADF content of forages, a fraction made up primarily of cellulose and lignin. In addition, rate of digestion of forage dry matter declines with advanced maturity (Bull, 1995).
When ration digestibility is too low, animals usually cannot eat enough to meet their nutrient needs. If the energy density in the diet is less than 1.45 Mcal/kg NEL, then it may be impossible for high producing cows to meet their energy requirements. Rations that are relatively high in digestibility may be consumed at a lower level since energy needs may be met with less intake. High-quality rations for high-producing dairy cattle should contain approximately 1.63 Mcal/kg NEL. Rations containing too much concentrate and not enough forage and effective fiber may result in depressed intake, milk production, and fat test and may adversely affect health because of less chewing and subsequently higher rumen pH levels.

In most cases, 2 to 3% fat in the basal diet is adequate. For high producing cows, the total dietary fat can be increased up to 5 or 6% of the total ration dry matter (NRC, 2001). However, for palatability, fat should not exceed 5% of the total ration dry matter. In a cow’s diet, fat originates from both plant and animal sources. Common plant sources include soybean meal, cottonseed and canola. Animal fat is used sparsely as it is not palatable for cows.

Energy for the dairy cow can be expressed in several ways: total digestible nutrients (TDN), net energy for maintenance (NEM), net energy for gain (NEG), and net energy for lactation (NEL). By expressing energy values in these terms, feed energy losses through feces, urine, gas and heat can be accounted. Some guidelines to follow for high-producing cows are: early lactation, 1.67-1.76; mid lactation, 1.59-1.67; and late lactation, 1.5-1.59 NEL Mcal/kg of dry matter.

Net energy is subdivided into maintenance, gain, and lactation. It takes into account energy losses from feces, urine, gases, and heat. NEM and NEG are used in ration
formulations for growing cattle and fattening animals. NEL is used for ration formulations of milking animals.

NRC (2001) recommends at least one-third of the total diet DM for lactating cows belong hay or its DM equivalent as medium-to-coarsely chopped silage or other forage; alternatively, fiber should be fed as hay equivalent DM at a minimum of 1.5 percent of live weight.

A minimum of 21% ADF and 28% NDF is recommended for cows during the first 3 weeks of lactation. During times of high milk production, however, ADF and NDF contents of the diet may be reduced to 19 and 25%, respectively, so that adequate dietary energy can be included to meet the cow’s requirement. The ADF and NDF contents of the diet should be increased in later lactation to help prevent milk fat depression and because less energy is required for milk production. Forage should supply at least 75% of the NDF in the diet.

The recommended amounts of fiber that should be included in the diet of dairy cattle may vary depending on the body condition of the cow, the particle size of the feed, the buffering capacity of the diet and feeding management.

3.4.3 Total Mixed Rations

Total Mixed Rations (TMR) are blends of feedstuffs (both forage and grain) formulated to meet specific nutrient requirements and generally fed free choice. Theoretically, this uniform mixture should supply a balanced diet and stabilize rumen function. The advantages of the TMR system include:

- Cows cannot choose among feedstuffs and feed intake efficiency is improved.
- Digestive problems are reduced.
Feeding is well adapted to mechanization.

It has been generally accepted that rumen pH variation over time is less with increased feeding frequency. Feeding a TMR to a restricted intake and designated meals may have positive effect in stabilizing daily fermentation patterns (Nocek, 1991).

Feeding long hay to a partially full rumen instead of grain will stimulate more chewing and saliva production. When grain is fed later, the rumen is already buffered and pH will not drop dramatically. However, long hay is difficult to incorporate in TMRs and different herd groups may need different TMR systems. Many dairymen have eliminated the feeding of long hay and have developed grouping systems. Cows are grouped according to the stage of lactation and each group is fed different TMR rations (Mahanna, 1998).

Silage may not have the same effect as long hay regarding promotion of chewing. Mixing will reduce feed particle size, thus it is essential to monitor carefully the mixing process (Heinrichs et al., 1999). There is considerable variation among diets fed to dairy cattle in the effect of the level of intake on nutrient and energy availability, but the effect is much greater with mixed diets than it is with diets consisting of all forage (NRC, 2001).

### 3.4.4 Brief Summary

- The dairy cow’s rumen provides a site where rumen microorganisms can digest carbohydrates, proteins, and fiber.
- Indigestible DM is a major constraint on feed intake in ruminants. DMI increases as the digestibility of the diet increases. Rumen fill appears to be the limiting factor for DMI when forage is the major ingredient of a diet.
- Rumen pH variation over time is less with increased feeding frequency of TMRs.
3.5 Silage Quality

Assessment of forage quality is critical when formulating livestock rations and selling or purchasing forages. One challenge in utilizing silage in rations is the large variation that exists in both forage quality and fermentation characteristics. Crops harvested for silage represent a large number of forage types, maturity levels, and a wide range of moisture levels. The interactions between moisture content, silo types, particle size, packing, and covering all affect the type and quality of the fermentation process.

The stage of maturity at which corn is cut has the major influence on the quality of corn silage. As corn plants mature, fiber and grain starch concentrations usually increase while crude protein concentrations decline. Although fiber is not a nutrient chemically, it is an important component in animal rations and it can be assessed for its physical form and chemical composition.

Besides the nutritive value, the value of forage must be evaluated in the context of its contribution to livestock production. One method of defining forage quality is the relative performance of animals when fed herbage ad libitum, i.e., their performance when fed excess forage. Forage quality is often estimated by in vitro or chemical means because of limitations from the cost and time in using animals.

3.5.1 Nonstructural and Structural Carbohydrates

Carbohydrates are the primary energy source for the ruminant. They can be divided into two main fractions, nonstructural (NSC) and structural (NRC, 2001). The nonstructural carbohydrates consist of the cell contents, including sugar starches and pectin, which are highly digestible. The structural portion of the plant is the cell wall material, which is
analytically defined as NDF. NDF consists of cellulose, hemi-cellulose, lignin, and a portion of the pectin. ADF is another fiber measure, which contains only cellulose and lignin. Ruminants are unable to digest lignin; thus the higher the lignin content of a feed, the lower its digestibility. These complex carbohydrates are more slowly digested than nonstructural carbohydrates. A proper intake of NSC is necessary to meet the animal’s energy needs to allow for adequate microbial protein synthesis.

Most concentrates (grains, human food waste, etc.) are too fine in particle size to simulate sufficient chewing. The NDF found in most concentrate ingredients is less effective because of finer particle size, greater density, higher digestibility, and quicker passage from the rumen than forage NDF (NRC, 2001). Most of the NDF in the diet should be in the form of forage. Lack of sufficient effective fiber can lower milk fat test and production and cause metabolic problems, such as rumen acidosis and infectious diseases (Owens et al., 1998).

Nutritive value of corn used for forage varies with both grain content (NSC) and stover composition. Grain is highly digestible (if rolled) and typically accounts for about 50% of the total dry matter feed (Coors et al., 1997). When grain yield is reduced because of stress, stover quality can be quite important. Stover is important to corn breeders who attempt to improve the nutritive value of corn silage because most cell wall carbohydrates are in the stover, and the whole-plant digestibility is primarily influenced by composition of the cell wall fraction (Merchen and Bourquin, 1994). Kernel development may also influence stover composition directly because starch accumulation requires remobilization and translocation of available carbohydrates produced and stored in stover tissue. In a silage trial with a significant range in maturity, grain yield tended to be inversely correlated with stover quality (Wiersma et al., 1993; Coors, et al., 1997).
The purpose of processing is to increase the suitability of high fiber feeds to the animal, thus increasing feed intake, and enhancing the rate and (or) extent of digestion, thus increasing nutrient availability (Nicholson, 1981). Ensiling usually has little effect on structural carbohydrate composition of forages, but the soluble carbohydrate fraction of forages is reduced considerably (Edwards and McDonald, 1978). Alterations in structural carbohydrate composition of hay are primarily a consequence of leaf loss during harvest. Grinding of forage results in large alterations in extent and site of digestion of cell wall carbohydrates. Voluntary intake of ground forage is consistently higher than forage fed in the long or chopped form. The intake response to forage processing increases with advancing forage maturity (Merchen and Bourquin, 1994).

Studies also have been conducted on fractional separation of crop residues. Leask and Daynard (1973) separated corn stover into leaf, husk, and stalk fractions and found that IVDMD of husk and leaf fractions was greater than intact stover IVDMD. Whereas isolated stalks had considerably lower IVDMD values than stover. In intact stover IVDMD declined at a rate of 15 g/kg/wk following grain physiological maturity, indicating that stover harvesting and separation should be conducted soon after grain maturity to maximize its nutritive value.

3.5.2 Protein

Certain levels of degradable, soluble, and undegradable intake protein must be present in the dairy cow’s diet to meet the needs of rumen microbes as well as provide essential amino acids to the small intestine (NRC, 2001). Rumen microbes require an adequate supply of ruminally available nitrogen including both protein and non-protein
nitrogen sources. In addition, the rumen microbes benefit from a limited amount of protein readily dissolving in the rumen, which is referred to as soluble intake protein. Protein that escapes or bypasses the rumen is referred to as undegradable intake protein.

The dairy cows’ rumens contain microorganisms that produce microbial protein through microbial degradation of dietary protein and non-protein nitrogen. The biological value of microbial protein is 66 to 87% of total protein produced in the body (NRC, 2001). Microbial protein is high-quality protein because it provides a good balance of the essential amino acids contributing a large portion of protein for the ruminant animal to digest in the small intestine. Bypass protein may be needed to meet the needs of high producing cows for essential amino acids (NRC, 2001).

The crude protein (CP) value reported for forage and feeds is a measure of their nitrogen content; the nitrogen can be amino acid, true protein nitrogen or some non-protein nitrogen source. Less than 30% of the total protein in corn silage is available to the animal as absorbable true protein. Much of the total protein is degraded by fermentation in the silo and in the rumen to non-protein nitrogen.

Some of the crude protein is bound and is totally or partially unavailable to the animal. Although it is usually negligible, this fraction can be substantial for silage that has heated extensively in the silo; in these conditions, it must be considered when balancing rations. Crude protein levels of untreated corn silage range from less than 6% to over 10% of dry matter depending on environmental conditions, fertilization, hybrid, and maturity (Allen et al., 1995).

In order for fiber fermentation to be optimized in the rumen, adequate nitrogen (soluble and available for microbial assimilation during growth) is required. Poos et al.
(1979) showed that fiber digestion in dairy cattle was significantly influenced by ruminally available N, and that dry matter intake was significantly reduced when fiber digestion was reduced by feeding inadequate amounts of ruminally available nitrogen. Therefore, even if total protein requirement is balanced in the diet, excess degradation in the rumen leads to inefficient protein use and may induce protein deficiency in the animal at the tissue level (NRC, 2001).

3.5.3 Particle Size—Importance and Measurement Methods

Adequate particle size of forage is necessary for proper rumen function. Having the proper particle size distribution of forage ensures sufficient fiber in the ration both in terms of physical form and chemical composition. Standard methods for recording particle sizes are available (ASAE, 1999b). Recording of particle sizes should be done at feeding to account for particle size reduction from handling and processing (Heinrichs et al., 1999).

The energy demands of lactating cows are usually met with rations high in grain and non-structural carbohydrates (NSC) (Beauchemin and Rode, 1997). Ruminants require coarse forage to stimulate chewing (Beauchemin et al., 1994), saliva flow (Cook, 1995) and the formation of the rumen mat (Van Soest, 1994). Inadequate coarse fiber levels may result in depressed ruminal pH, decreased acetate:propionate ratio (Grant et al., 1990a and 1990b), sub-clinical or clinical ruminal acidosis (Owens et al., 1998), or laminitis (Nocek, 1997).

When minimum fiber levels are not met, cows often show one or more of the following metabolic disorders: reduced total DM digestibility, reduced milk fat percentage, displaced abomasum, and increased incidence of laminitis, acidosis, and fat cow syndrome (Sudweeks et al., 1981). Cows consuming sufficient NDF with a finely chopped forage can
also exhibit the same metabolic disorders as cows fed a diet deficient in fiber (Weston and Kennedy, 1984; Fahey and Berger, 1987). These factors may ultimately impair production (Armentano and Pereia, 1997).

With increased mechanization in the modern dairy operation, particle sizes are reduced in order to facilitate feed processing and delivery. Current recommendations (NRC, 2001) detail the dairy cows’ chemical requirement for fiber but fail to specify the physical nature of that component and the animals’ need for it. The concept of effective fiber was created to combine the chemical and physical nature of the forage, and to quantify its value in rumen function. Effective fiber is defined as the dietary fiber source that aids in the maintenance of overall ruminal health and function. It is a combination of forage particle size and forage NDF content. Effective fiber index method proposed by Buckmaster (2000) explicitly linked particle size distribution to NDF. The index, which weights NDF concentration by particle size, contained more information than the mean particle length or NDF concentration alone and can help make optimal ration formulation easier (Buckmaster, 2000).

Adequate effective fiber is necessary for proper rumen function. Cows spend less time chewing smaller particles and therefore produce less saliva, which will reduce the buffering in the rumen and cause low rumen pH. When rumen pH is below 6.0, propionate-producing microbes will increase thus reducing the acetate/propionate (fatty acids) ratio. The reducing of this ratio will result in lower milk fat content.

A variety of different-sized particles are important in a dairy ration because these particles can form a good fiber mat in the rumen. A fiber mat assures adequate microbe activity and growth which results in adequate VFA’s and microbial protein.
Reduced forage particle size can increase DM intake by increasing the passage rate. But digestibility may be decreased since less time is available for the microbes to digest the feeds. If cows are fed rations with small forage particles for a longer period, their rumen will not function properly; this will lead to reduced intake, displaced abomasums, acidosis, and fat cow syndrome. Similar to the physical size of the feed, fiber content is also important in that fiber is needed to provide complex carbohydrates that slow digestion and control the acidity in the rumen.

Forage and TMR particle sizes are potentially reduced by all phases of harvesting, storing, removing from storage, mixing and delivery of feed to the dairy cow. For example, mixing in TMR’s causes a reduction in size of all feed particles, and the size reduction is related to mixing time (Heinrichs et al., 1999).

The mean particle size and the variation in particle size are important nutritionally to the cow and, under normal circumstances, the cow consumes particles of many different sizes (Heinrichs and Lammers, 1997). This variety of particle sizes allows for a steadier rate of digestion in the rumen and passage out of the rumen (Van Soest, 1994). A description of the distribution of the length of feed particles (rather than only the mean) is needed for proper nutritional management (Mertens, 1997). This distribution should provide a sufficient quantity of long particles for cud chewing and smaller particles for rapid fermentation to allow maximal dry matter intake.

Particle size distribution can be determined by the standard method and device documented in ASAE S424, (ASAE, 1999b). Recently, a simplified separator (Penn State Forage and TMR Separator) was developed at Penn State (Lammers et al., 1996). The Penn State separator can be used easily for on-farm evaluations.
The ASAE device is a laboratory-scale separator of forage particle sizes, containing five screens of varying hole sizes and a solid bottom pan to separate particles into six unique fractions. The square-holed screens of the ASAE device have nominal openings of 19.1, 12.2, 6.4, 4.1, and 1.3 mm from the top to the bottom screen, respectively. The square hole diagonal openings from top to bottom screens are 26.9, 18, 8.9, 5.6, and 1.7 mm. The Penn State separator has two screens and a bottom pan with round hole sizes of 19.1 and 7.9 mm for the upper and lower screens.

The hole sizes of the Penn State separator were selected to appropriately characterize the larger particles and separate the sample into measurable fractions (Heinrichs and Lammers, 1997). Because the larger particles were considered important, the top screen was selected to measure this fraction. The bottom screen was selected to separate the remaining portion nearly equally. The particles on the lower screen are digested at a moderate rate while the fraction on the bottom pan are expected to degrade rapidly upon entering the rumen or pass out of the rumen (Van Soest, 1994).

### 3.5.4 Quality Assessment

Energy content and intake potential, as well as content of protein and minerals determine the quality of corn silage. Methods used to evaluate corn silage quality include chemical methods such as fiber analysis, biological methods such as fermentation with rumen microbes, and Near Infrared Reflectance Spectroscopy (NIRS).

The energy content of corn silage is primarily determined by the amount and digestibility of fiber. The original NDF method (Van Soest and Wine, 1967; Goering and Van Soest, 1970) used sodium sulfite to remove contaminating proteins from NDF. It was
discovered that the original method did not adequately remove starch from grains and corn silage (NRC, 2001). The amylase-treated NDF modification was developed to measure NDF in all types of feeds which uses both heat-stable amylase and sodium sulfite to remove protein. This was adopted as the reference method for NDF by the National Forage Testing Association (Undersander et al., 1993).

ADF contains lignin (totally indigestible) and pectin (highly digestible). The ADF content of silage is the most common method used by commercial feed testing laboratories to predict energy content. As ADF decreases, the digestibility and therefore the energy content increases. This method offers low cost and quick turnaround, which are requirements for balancing animal rations. The relationship between ADF and energy content is not absolute, however, since ADF accounts for less than two-thirds of the variation in energy content in corn silage. The inaccuracy of this method is caused by significant variations in the digestibility of the fiber in corn silage.

Analyzing the following chemical components can develop more thorough assessment of corn silage:

1. **Dry matter**---Traditionally, this is done by drying silage samples at high temperatures for short time periods.

2. **Carbohydrate fractions**---ADF, NDF and lignin provide the information for some energy prediction equations. Starch analysis may also be useful. Measurements of end products may also be useful in examining the digestion rates of the soluble carbohydrate fraction.
3. **Protein fractions**---Total, soluble and undegradable fractions are suggested as the minimum protein fractions to be determined. Determination of ammonia-N may also provide valuable information relative to fermentation quality.

4. **pH**---This can provide an index of the type and length of the fermentation process. A combination of pH and moisture content can also be used to predict clostridia fermentation. The desired degree of acidity, a pH no higher than 4.2, should occur within 3 weeks after the silo is filled (McCullough, 1978).

5. **Fermentation end products**---Lactic acid and VFA analysis can assist in defining silage quality. Silage may be similar in CP and ADF but vary significantly in lactic acid or VFA’s (Cushnahan and Mayne, 1995).

Animal intake and the influence of fermentation on the dynamics of digestion must also be considered. Animal intake of forage is related positively to the acceptability of forage and negatively to the amount of time that forage is retained in the rumen and reticulum (Sollenberger and Cherney, 1995). Fine particles may increase intake initially as they require less time to digest in the rumen. However, too many fine particles may depress intake as rumen condition is deteriorated from less chewing. On the other hand, too much fibrous material with low energy content will fill the rumen before the energy requirement of the cow is met.

Digestibility analysis can be done using either in vitro or in situ techniques. In vitro digestibility methods use fermentation by ruminal microbes in test tubes or artificial rumens to determine digestibility. In situ digestibility methods allow forage digestion inside the rumen of a cow. These methods offer greater accuracy of energy prediction because they account for variation in fiber digestibility but they are time consuming and expensive.
3.5.5 Brief Summary

- Nutritive value of corn used for forage varies with both grain content (NSC) and stover composition.
- Whole-plant digestibility is primarily influenced by stover composition of the cell wall fraction (Merchen and Bourquin, 1994).
- Grinding of forage may alter the digestibility of structural carbohydrates.
- Fiber digestion in dairy cattle is significantly influenced by ruminally available N.
- Certain levels of degradable, soluble, and undegradable intake protein must be present in the dairy cow’s diet to meet the needs of rumen microbes as well as provide essential amino acids to the small intestine (NRC, 2001).
- Adequate particle size of forage is necessary for proper rumen function.
- Energy content and intake potential as well as content of protein and minerals determine the quality of corn silage.
3.6 Forage Harvester and Kernel Processor—Power Requirements

Silage systems enable greater mechanization, but require more power or energy for harvesting, handling and feeding than hay systems. Equipment for silage harvesting continues to become larger and is operated at faster speeds. The dairy industry, as the major user of forage harvested and fed as silage, is affected by such trends (Shinners, 1997). Despite the trend toward more forage fed as chopped silage, sales of forage harvesters remain flat (Shinners, 1997).

Energy requirements are high for corn silage harvest though labor requirements are normally less than hay harvest. Forage harvesters are available with minimum tractor size requirements of 30-150 kW with most greater than 50 kW. Fuel requirements range from 12 to 20 liter/Mg DM, about double that of typical hay harvest systems (Miller and Rotz, 1995).

Forage harvesters are designed to cut particles to facilitate storage and feeding. The forage harvester consists of a pickup or cutting mechanism that carries the crop into the machine. Rotating knives and a counter shear are used to chop the material into short lengths. The chopped material is conveyed into a blower mechanism that throws the material through a spout into a trailing wagon or truck. The chopped corn is then transported to the silo to be packed.

Corn silage is normally chopped at 9.5-12.7 mm theoretical length of chop. Longer chop (without roll processing) can create difficulties in: 1) packing, 2) functioning of silo unloaders, 3) more kernels passed through the animal, and 4) preferential sorting of stover or larger cob pieces in total mixed rations (Seglar and Mahanna, 1998).

The energy requirement for forage harvesters ranged from 0.7 to 2.2 kW h/Mg (Hennen, 1971; O’Dogherty, 1982) on a wet basis. Assuming 35% dry matter, the above
numbers translate to 2 to 6.3 kW h/Mg DM. About 40% of a harvester’s power requirement goes into the cutterhead (Srivastava et al., 1995). The width, rotational speed and number of knives determine the capacity of the cutterhead. Increasing any of the parameters will increase cutterhead capacity. Cutterhead power requirements are affected by the knife tip speed, and increasing knife speed increases machine power requirement. Self-propelled machines typically use higher cutterhead speeds because capacity is deemed more important than energy efficiency in these expensive machines. Sharp knives and close clearance between the cutterhead knives and stationary shear bar is essential for uniform cutting and reduced power consumption. Dull knives and improper knife-to-shear bar clearance greatly increases cutterhead power needs and adversely affects cut-quality.

Increasing the machine’s TLC setting decreases the power requirement (Srivastava et al., 1995). Longer TLC is recommended for healthy ruminal activity of dairy cows and is feasible for forage stored in bunk silos with mechanical packing compared to tower silos. However, silage density is reduced when harvesting at longer TLC’s. One study found that silage density was reduced by almost 14% when TLC was increased from 6 to 31 mm (Shinners et al., 1994). Shinners (1997) warned that harvesting capacity could be significantly reduced as forage wagon capacity was reduced by more than 30% under the same circumstance. However, if this is the case, using a larger wagon can solve some of the problem.

After the forage is chopped by the cutterhead, centrifugal force holds it against the housing as the cutterhead moves it toward the exit of the harvester. In a cut-and-blow machine, a separate impeller-blower is used to convey the chopped material. The blower typically requires 40% of the harvester’s power requirement.
Two problems are usually associated with the blower: (1) poor blowing and (2) excessive power (Shinners, 1997). The crop can be wedged between the housing and paddle because, for example, a large clearance between the blower and the housing. This increases friction loss and requires more power and may cause plugging. Dependent on the kind of crop, the blower speed can be adjusted to save energy. Faster speed can be used in haylage and lower speed can be used to blow corn silage. An accumulation of sugars and starches on machine components occurs with some crops, like alfalfa. This, referred to as gumming, significantly increases friction power needs and adversely affects blower performance. A spray of water can eliminate this problem.

In forage maceration, Shinners et al. (1988b) concluded that material moisture content had a significant effect on machine energy requirement and capacity. They found that energy requirement increased and capacity decreased as material moisture content was reduced from 79% (w.b.) to 50% (w.b). In another study on the performance of forage maceration, Shinners et al. (1988b) observed that greater cylinder rotational speed decreased energy requirements and linearly increased capacity. They explained that the increased power required at higher rotational speed was offset by the increase in capacity. They also found that increased rotational speed helped keep the cylinder free from plant gum.

Studies on processing mechanisms suggested that roll speeds and speed difference, minimum roll clearance and unit roll forces are parameters that could affect power requirements and the degree of processing (Jirovec et al., 1999; Roberge et al., 1999; Johnson et al., 1999).

A feasible range for speed difference seems to fall between 1 (both rolls have the same linear velocity) and 2 (linear velocity of one roll is double that of the other). Examples
can be found in studies done by Jirovec et al. (1999) and Roberge et al. (1999). Jirovec et al. (1999) tested kernel processor performance for roll speed differences from 17 to 50%. Roberge et al. (1999) studied tip speed ratios ranging from 1.08 to 1.93 on corn processing.

Roberge et al. (1999) found that roll clearance also had a significant effect on kernel damage. They investigated machine performance at minimum roll clearance of 4 and 6 mm for corn silage. They found that a kernel processor with a minimum roll clearance of 4 mm required more specific energy than one with a minimum roll clearance of 6 mm. Minimum roll clearance of 4 mm also increased kernel damage more than a minimum roll clearance of 6 mm. Jirovec et al. (1999) found that roll clearance may have a greater effect on processing than roll speed difference and recommended 1 to 3 mm roll clearance for processing whole-plant corn at 19 mm TLC. They based their recommendation on crop physical properties, harvester energy requirements and dairy cattle lactation performance. They also noted that 1 mm roll clearance produced frequent plugging at the rolls under mass-flow rates obtainable with other machine configurations.

Greater kernel damage was observed at more mature stages (Jirovec et al., 1999). They found that at higher maturity stages, increasing processing roll tip speed (the linear velocity at the tip of the roll) differential from 17 to 50% did not significantly increase kernel damage and only slightly reduced particle size.
3.7 Systems Analysis—Use of DAFOSYM

The Dairy Forage System Model, DAFOSYM, is a simulation model designed to evaluate technologies and management strategies on representative dairy farms (Rotz et al., 1999a). Utilization of DAFOSYM generally entails a review of the original model, adjustment of model parameters and description of the farm used for simulation.

The model integrates crop growth, harvest, storage, feeding, animal utilization, manure handling, and economic analysis over many years of weather. It has proven useful in evaluating the biological and economic consequences of many alternative technologies and management strategies on the dairy farm.

The model begins with input information describing the farm, available machinery and weather data for a selected location. Simulation of crop production and harvest is based on a daily time step following historical weather data. Simulation begins in early spring of the first year. Manure spreading, tillage and planting operations are performed on days when soil and weather conditions are suitable for fieldwork. Operations are done in sequence until all are completed. The crop growth models determine the accumulation of dry matter and the quality change in the crops based upon the weather of each day and moisture available in the soil profile. Growth models cycle on a daily time step until the crop is ready for harvest.

An economic analysis is performed for each weather year. The total costs of production are subtracted from the various farm incomes to obtain the net return above feed and manure costs and the overall return to management and unpaid factors for the modeled farm. Simulation results are reported for each weather year.

DAFOSYM follows a partial budgeting format which accounts for all costs associated with growing, harvesting, storing and feeding of crops to the milking herd and
young stock and the collection, storage and application of manure back to the crop land. A total feed and manure cost is determined as the sum of all costs associated with these processes. A net return over feed and manure costs is calculated as the difference between the income from milk sales and the net cost of feeding the animals and handling the manure. To estimate whole farm profit, the costs for animal housing, animal care and milking are subtracted from the incomes of milk, excess feed and animal sales to obtain the overall return to management and unpaid factors.

Production costs include capital investments in machinery and structures. Annual costs for capital investments are determined by amortizing the initial price over a given life with a given real interest rate. Annual operating costs include costs of labor, fuel and electricity, maintenance and repair of machinery, land, seed, fertilizer, chemicals, and supplemental feeds. Annual requirements for each of these categories are determined by the model and multiplied by a given price to determine annual costs.

All production costs and the net return over these costs is determined for each simulated year of weather conditions. The distribution of annual values obtained can be used to assess the risk involved in alternative technologies or strategies as weather conditions vary. A wide distribution in annual values implies a greater degree of risk for a particular alternative. The selection among alternatives can be made based upon the average net return and the probability of attaining that net return.

The major components of corn silage systems are harvest, storage, and feeding. Harvest is simulated on a daily time step according to crop, soil, and weather conditions (Rotz et al., 1989; Harrigan et al., 1996). The storage process includes aerobic deterioration from respiration during filling, storage, and removing along with chemical and biological
changes due to fermentation (Buckmaster et al., 1989). Feed allocation and animal response are related to the nutritive value of available feeds and nutrient requirements of the various animal groups in the dairy herd (Rotz et al., 1999b).

DAFOSYM must be modified to include functions for predicting the performance of a new technology. Parameters for modification include those used to describe the forage harvester, the characteristics of the processed material, the characteristics of the ensiling process (Rotz et al., 1999a), nutritive changes in feeds and feed delivery method.

When forage processing was included as a component in DAFOSYM, adjustments were made on parameters used to describe the forage chopper, characteristics of ensiling process, and characteristics of the processed forage (Rotz et al., 1999a). The refined model assumed that the kernel processor affected the harvest and storage operation as well as feed quality.

Three parameters or characteristics of the forage harvester were considered in the kernel processor model. They were initial cost, specific energy requirement, and throughput capacity. The initial cost of adding processing to a conventional pull-type forage harvester, was about $10,000 based upon commercially available equipment. Initial cost affects the depreciation, interest, repair, and maintenance costs for owning the machine.

Use of a kernel processor increases the specific energy requirement of the forage harvester. However, this increase may be partially or totally offset when processing is combined with a longer length of cut. Specific energy requirement for a standard harvester was 3.3 kWh/Mg DM (ASAE, 1999a). When added to conventional forage harvester, processing makes forage that is more easily compressed in a silo.
An important consideration in the shredding process is the effect shredding has on feed value, intake and milk production. Hong et al. (1988) suggested that the macerated crop was more digestible than conventional alfalfa forage. The increased digestibility allowed the animal to receive more energy from the forage, assuming intake did not change. Hong et al. (1988) also suggested an increase of 6% in animal intake. Harrison et al. (1998) reported an in situ study where DM disappearance over 24 to 48 h was increased by 17% with processing, and the rate of disappearance was increased 30%.
Chapter 4: Methodology

A pull-type New Holland 718 forage harvester was acquired for modification. A shredding chamber consisting of two pairs of corrugated rolls replaced the cutter head on the forage harvester. A hydraulic drive was designed to transmit tractor PTO power to the processing rolls.

Machine power usage and silage particle sizes were recorded for various conditions including machine throughput, combinations of roll speed, minimum clearance between the rolls within a pair, and the unit roll force on the rolls at various moisture levels of corn. Samples were collected to make silage in lab-scale silos for ensiling evaluation including particle size distribution and silage density. A cutting mechanism consisting of flail cutters was added behind the two pairs of rolls to further reduce particle size and blow material to a trailer. Samples were collected using the cutting mechanism to make laboratory scale silos. The investigation of the cutting mechanism belongs to a separate study and is only briefly discussed in related areas.¹

A simulation study was undertaken to evaluate the dairy producer’s benefit in adopting the novel forage harvester. DAFOSYM was used to determine the long-term costs and benefits for using shredded silage on representative dairy farms. It was also used to determine the sensitivity of costs and benefits to values assumed for major parameters used to model the effects of the novel harvester.

¹ M. L. Sword. M.S. Agricultural and Biological Engineering study.
4.1 Machine Design and Fabrication

The design of the novel harvester had two major aspects: the hydraulic drive, and the processing chamber consisting of two pairs of corrugated rolls. The machine was fabricated in the Agricultural and Biological Engineering shop with some work done by Engineering Services at Penn State.

A small basic forage harvester (Model 718) was provided by New Holland North America, Inc. (New Holland, PA). Maximum recommended PTO power for the production unit was 67.5 kW (90 hp). It had four feeding rolls and a cutting cylinder. The cutting cylinder was replaced by two pairs of processing rolls (152.4 mm diameter); crop material was crushed and shredded between the two pinch points of the two set of rolls.

The rolls were powered hydraulically for easy adjustment of roll speeds. Total power requirement of the harvester was shared among picking up, feeding, shredding, and conveying processes. The flail cutting mechanism was added after the shredding mechanism was built and tested in the field. The cutting mechanism was powered by the tractor hydraulic remote via a hydraulic motor.

4.1.1 Shredding Chamber and Hydraulic Drive

The two pairs of rolls were arranged to convey shredded material upward (Figure 2). The rolls were spring loaded; the minimum spacing between the rolls and the roll unit pressure were adjustable. Within each pair of rolls, corn plants were subjected to shear and compressive forces, caused respectively by the corrugations on the roll surface and pressure exerted by the rolls while pulling particles toward the pinch points of the rolls. The difference of speed at the pinch points created a tearing effect on the crop. Between the two
sets of rolls, the plant was subjected to the tensile stress between the two pinch points of the rolls. The magnitudes of the stress imposed on the particles during processing varied according to operational conditions. The roll speeds, the speed differences, the roll clearance, the roll spring loads, and the particle properties affected the magnitudes of each type of stress.

Figure 2. Schematic of the shredding harvester (side view).

The hydraulic circuit used to transmit tractor PTO power to the shredding rolls is shown in Figure 3. A pair of hydraulic tandem gear pumps generated flow to power four hydraulic motors—connected to each of the four rolls. Each pump powered two hydraulic motors in series that corresponded to one pair of rolls. The four fixed displacement hydraulic gear motors were identical. The flow rate to the motors was adjusted with flow control valves to obtain different roll speeds. With directional control valves, the rolls were reversed in case of plugging. Two counterbalance valves were used to set pressure load to the two motors that drove each of the two slower rolls. This ensured a speed differential within pairs to avoid overrunning situation of the slower rolls. Six pressure transducers were used to
measure the pressures before and after each motor so the pressure drop across each hydraulic motor (Figure 3) could be calculated.

**Figure 3.** Schematic of the hydraulic drive on the novel harvester.

The power demand of the shredding rolls was estimated by first meeting the power requirements of other mechanisms on the harvester. The novel harvester was designed to utilize up to 67.5 kW of PTO requirement tractor power—dictated by the harvester PTO driveline. The energy requirements of unit operations within a forage harvester have been separated roughly as follows: 40% for pneumatic conveying, 40% for the cutterhead, and 20% for material pickup and drive train losses (Srivastava et al., 1995). In order to use most of the PTO power for shredding, blowing was not counted. Therefore, 80% of the PTO
power (54 kW) should be available for shredding, with the remaining 20% needed for material pickup and drive train losses.

Major components of the hydraulic drive are listed in Table 1. Detail specifications of these components can be found in the paper by Cauffman (2002). The tandem gear pumps were driven by the tractor PTO shaft through a 1 to 4 gear increaser (more detail in the next section). The basic harvester had a 540-rpm heavy duty PTO shaft. The hydraulic pump input speed was 2160 rpm. Assuming the pressure drop on each pump to be 13.8 MPa (2000 psi), the theoretical torque required to operate each of the two pumps at 2160 rpm was:

\[
T_T(N \cdot m) = \frac{V_p(m^3/rev) \times \Delta P(Pa)}{2\pi} = \frac{6.23 \times 10^{-5}(m^3/rev) \times 13.8 \times 10^6(Pa)}{2\pi} = 137(N \cdot m)
\]

Energy losses occurred in the pump because of friction in bearings and between other mating parts and due to fluid turbulence. The actual torque delivered to each pump was found by considering mechanical efficiency \(\eta_m\):

\[
T_A(N \cdot m) = \frac{T_T(N \cdot m)}{\eta_m}
\]

Assuming an 85% mechanical efficiency of the pump (\(\eta_m\)), the actual power delivered to each of the two pumps was:

\[
Power(W) = T_A(N \cdot m) \times N(rev/min) \times \frac{2\pi(rad/rev)}{60(s/min)} = 36380(W)
\]
Therefore, a total power of 73 kW was required to run the tandem pumps at 2160 rpm with a pressure drop of 13.8 MPa (2000 psi). This exceeds the 54 kW predetermined power allowance, but will give more speed ranges.

**Table 1.** Principal components of the hydraulic drive.

<table>
<thead>
<tr>
<th>Item</th>
<th>Qt</th>
<th>Manufacture Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear Box</td>
<td>1</td>
<td>Hub City Model 95 H</td>
<td>1:4.19 increaser</td>
</tr>
<tr>
<td>Tandem Gear Pumps</td>
<td>1</td>
<td>Permco P257B</td>
<td>62.3 cm³/rev/pump, 1-1/2 in gear width, 24 MPa (3500 psi) Max.</td>
</tr>
<tr>
<td>Gear Motors</td>
<td>4</td>
<td>Permco M257A</td>
<td>62.3 cm³/rev displacement</td>
</tr>
<tr>
<td>Relief Valves</td>
<td>2</td>
<td>NACHI-FUJIKOSHI CORP, R-T06-3-E20</td>
<td>170 lpm flow rate</td>
</tr>
<tr>
<td>Flow Control Valves</td>
<td>4</td>
<td>FLUTEC SRVR12-011/5</td>
<td>½” Port</td>
</tr>
<tr>
<td>Directional Control Valves</td>
<td>2</td>
<td>Prince RD-5000</td>
<td>Pressure compensated, 53 lpm</td>
</tr>
<tr>
<td>Counter Balance Valves</td>
<td>2</td>
<td>Sun CBGA_LHN_HCM</td>
<td>0 to 226 lpm Nominal</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>1</td>
<td>American Industrial Heat Transfer</td>
<td>1 ¼” NPT, 4 fans</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MCAOMF-4-NPT</td>
<td>23.6 kW/38°C ΔT</td>
</tr>
<tr>
<td>Hydraulic Reservoir</td>
<td>1</td>
<td>Filler Breather, Sight and Temp gage</td>
<td>32” x 30” x 12”</td>
</tr>
<tr>
<td>Hydraulic Filters</td>
<td>2</td>
<td>ZinGA Industries SE-10</td>
<td>10 micron</td>
</tr>
<tr>
<td>In-line Strainers</td>
<td>2</td>
<td>ZISS-250-50</td>
<td>2 ½” port, 60 mesh</td>
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<tr>
<td>Check Valve</td>
<td>1</td>
<td>ZILRV-12-50</td>
<td>In-line Return, 1-1/4 in port</td>
</tr>
<tr>
<td>Filter Head w/Gage Port</td>
<td>2</td>
<td>ZISF-120-25-103</td>
<td>172 kPa</td>
</tr>
<tr>
<td>Shut-off Valve</td>
<td>1</td>
<td>Parker</td>
<td>Ball type</td>
</tr>
</tbody>
</table>

### 4.1.2 Machine Fabrication

The entire cutter head chamber was removed from the original harvester, two 6.35 mm (¼ in) thick steel sheets were cut and welded to the harvester frame to hold the two pairs
of shredding rolls. The shredding rolls had an outside diameter of 152.4 mm (6 in). All four rolls were dimensionally identical.

The shafts were mounted in bearing housings that were welded to the two 6.35 mm side sheets. Two bearing support brackets were welded to each of the side sheets. Each roll consisted of three segments of hollow rolls that were 124 mm long and one segment that was 90 mm long. These segments were originally from New Holland prototype kernel processors. Figure 4 illustrates a typical segment. The segments were clamped together by large lock nuts at both ends of the shaft with 1490 N·m torque. The outer surface of the roll segments was grooved longitudinally (parallel to the axis of rotation); the V-shaped grooves were spaced 6.35 mm apart (4 grooves per in.) with a 90° angle and a depth of 4 mm. Two compression springs (spring constant of 272 N/mm or 1550 lb/in) at each shaft end allowed vertical displacement of both rolls to adjust to the variable thickness of material passing between the rolls. The hydraulic motors were mounted rigidly to the rolls and moved with the rolls. Minimum spacing between the two processing rolls was adjusted with locking set bolts from 1 to 15 mm.

Figure 5 is a CAD drawing of right side sheet when looking directly at the sheets. The centerline of the front pair of rolls was at a 15° angle to the vertical line and the rear pair was at a 15° angle to the front pair so shredded silage was discharged at an angle of 30° from horizontal. A floating bridge was placed between the rear feed rolls and the front shredding rolls to assist material flow (not shown in drawing).

Figure 6 shows the actual chamber with the shaft/roll assembly. The left sheet is identical to the right sheet in design. The four large holes (159 mm or 6.25 in.) were
designed to remove and assemble the roll-shaft assembly when necessary. After the rolls were assembled to the side sheets, these holes were then covered to eliminate potential material buildup in these areas during harvesting (see label in Figure 6). The distance between the pinch points of the rolls was fixed. This distance, 330 mm (13 in), was the shortest allowed by the physical constraints of the roll and bearing support brackets (Figure 7).

Figure 4. A segment of the shredding rolls used on the novel harvester (photo).
A plate under the rolls prevents material from falling on the ground from between the two pairs of rolls (Figure 6). During the fabrication, a bridge was actually added between the two pairs of rolls, but during preliminary testing, the bridge was found to cause plugging and therefore was abandoned. The bottom plate was placed at about the same inclination as the two pairs of rolls for easy removal by sliding. A plate welded to a couple of hinges was placed behind the rear feed rolls to prevent material from falling/wedging between the rear feed rolls and the front shredding rolls. Because the hydraulic motors were mounted on the left side of the shredding chamber, the spring used to hold the front attachment were removed.
and placed on the right side of the machine together with the original right side spring (Figure 6).

The basic harvester had a 540-rpm heavy duty PTO shaft. A gearbox with a 1 to 4 ratio was coupled by keyway (9.5 mm or 3/8 in. square key) to the primary PTO shaft for an output speed of 2160 rpm (Figure 8). Since the primary PTO shaft had a diameter of 34.9 mm (1.375 in.) and the gearbox bore had a diameter of 36.5 mm (1.4375 in.), a thin bushing was made to fill the gap between the gearbox and the shaft.

The hydraulic motors were fixed onto the bearing housing of the shafts so the motors could move with the rolls when the clearance between the rolls was adjusted, either by hand or due to the material flow between the rolls. Each motor was coupled to each shaft with a chain coupler. The motors had a keyway shaft of 31.75 mm (1 ¼ in.) diameter and the shaft the rolls had a spline end of 44.45 mm (1 ¾ in.) diameter. The chain coupler is shown in Figure 9.

The hydraulic reservoir was mounted to the frame on the left side of the harvester (Figure 10). A heat exchanger was bolted to the reservoir on the tractor side and a panel was placed on the rear side of the reservoir to mount the hydraulic control components.
Figure 6. Assembled shredding chamber showing removable floor and side sheet covers for cutout (photo).

Figure 7. Right side of shredding chamber showing bearing housing configuration (photo).
Figure 8. Power transmission from tractor PTO, the hydraulic tandem gear pump, 1 to 4 ratio gearbox and tractor PTO shaft (photo).

Figure 9. Hydraulic motors connected directly to shredding rolls (photo).
Figure 10. Hydraulic reservoir and hydraulic control panel (photo).
4.2 Experiment Design

The machine was run in the field to test its functionality after fabrication. Field experiments were carried out using whole-plant corn with cooperation of the Farm Operations Unit at The Pennsylvania State University in State College, PA. Field experiments were done during two harvest seasons—Fall 2000 and Fall 2001. Three sets of experiments were done on medium to low moisture crop in fall 2000 while crops of three moistures from 70% to 60% were tested in fall 2001. Factors studied included roll speed differential, roll clearance, unit roll force, crop moisture content, and machine throughput. Measures of performance included specific energy requirement, particle size distribution, packed silage density, and silage quality.

Machine power requirements were estimated from the speeds of the hydraulic motors and pressure drops across the motors. A data logger (Campbell Scientific 21X) logged data (see Appendix B for data logger program and wiring) from the speed sensors and pressure transducers; both the pressure and speed data were recorded at 2 Hz. Machine throughput was estimated by recording tractor travel time and crop yield. Specific energy was total machine power requirement divided by the throughput.

Particle size distribution was determined using the standard ASAE particle size method (ASAE, 1999b). Silage packed density was calculated for laboratory scale silos (refer to Appendix A and Hoover, 1998). Ensiled silage from the laboratory scale silos was evaluated for pH and nutrient analysis.

During fall 2000, the first two sets of experiments focused on the effect of machine configuration on energy consumption and particle size reduction; for the third experiment, samples were collected to make silage in laboratory scale silos. The ensiled silage was
examined for particle size distribution, packed density, and visually-appraised quality. During Fall 2001 experimentation, a cutting mechanism was added to the shredder for a separate investigation. The 2001 experimentation was used to further investigate the effects of crop moisture content, throughput, and roll speed configuration on energy consumption of the shredding mechanism. For silage density and particle size evaluation, silage samples were collected with the cutting mechanism activated.

The mechanical efficiency of a hydraulic motor is reduced by friction between mating parts and due to fluid turbulence. Gear motors purchased had an estimated mechanical efficiency $\eta_m$ of 85% (Beiler Hydraulics, 1999). For each treatment, by knowing the motor displacement $V_D$ and measuring the pressure drop over the motor, the actual torque delivered by the motor $T_A$ was found as:

$$T_A (N \cdot m) = \frac{V_D (m^3/rev) \times \Delta P (Pa)}{2\pi} \times \eta_m.$$  

Using measured speed of each motor, estimated power delivered by each motor was

$$Power_E (W) = T_E (N \cdot m) \times N (rad/s).$$

It was assumed that $\eta_m$ did not change with motor speed or the pressure drop over the motor, i.e.,

$$\eta_m \neq f (N, \Delta P).$$

With this assumption, the comparison among treatments of shredding for power consumption was feasible, furthermore, and the comparison to chopping power is reasonable.
4.2.1 Machine Function Test

The first step after the completion of fabrication was to test for proper function. The machine was run with the directional control valves in their neutral position for about 10 minutes to filter the oil and flush the system.

The settings of the counter balance valve were explored during function testing. Setting was reduced or load was released by turning a setscrew on the valve clockwise. The complete adjustment range was 3 turns. When the counterbalance valve was set too high, the top rolls ran too slow. On the other hand, when the counterbalance valve was set too low, little tearing was observed on crop plants. One quarter of a turn was set on both valves.

Directional control valves were useful for reversing the rolls if plugging occurred. Plugging happened between the rear feed rolls and the front shredding rolls or between the two set of shredding rolls when feeding of crop was not smooth. The plugging between the shredding rolls was probably due to the narrow clearance on the rear rolls.

The bottom plate proved to be a good idea for bridging material between the two pairs of rolls. Pieces of cobs and grains fell after passing the first pair of rolls but relatively little piled up on the plate. After material piled up, it formed bridge to the second pair of rolls.

During function test, the rolls were first set with a 12 mm clearance for the front rolls and 4 mm for the rear rolls. It seemed that material went through these rolls with little processing. When the clearance was reduced to 9.5 mm and 1.15 mm, more processing was observed. The unit roll force was set at 15 N/mm on both pairs of rolls.

Cobs and kernels were shredded into tiny particles. Most of the stalks were crushed and torn into sections without being completely severed. Sectioned stalks measured
approximately 30 cm in length, approximately the distance between the pinch points of the two pair of rolls.

For further experimentation, it was estimated, based on visual examination of the degree of processing of stalks, that the roll clearance for the rear pair of rolls should not exceed 2 mm and the roll clearance for the front pair of rolls should be approximately 10 mm.

### 4.2.2 Roll Speed and Machine Throughput

Although the speed of each shredding roll could be adjusted hydraulically in a hydraulic drive, predictions of reasonable target roll speeds were made to obtain smooth material flow in the harvester.

The throughput through the first pair of rolls should be equal to or slightly less than that through the second pair of rolls. This throughput depends on the envelope size between the rolls, i.e., roll clearance and material width between the two rolls, the density of material, and the linear speed the material travels between the rolls. The equation for feed rate was:

\[
\dot{M} = \rho \cdot x \cdot \omega \cdot v
\]

\(\dot{M}\) = Feed Rate (kg DM/s);
\(\rho\) = Density (kg DM/m\(^3\));
\(x\) = Roll Clearance (m);
\(\omega\) = Material Width (m);
\(v\) = Material Velocity (m/s).

The rotational speed can then be calculated:

\[
N(\text{rpm}) = \frac{v(\text{m/s}) \cdot 60}{\pi \cdot D(\text{m})}
\]
From literature of processing rolls, feasible roll clearance for the two pair of rolls were found to be 10 mm and 4 mm, respectively. The material width between the rolls was estimated to be equal to the width of the removed cutterhead (460-mm). Therefore the speeds of the rolls can be estimated if the material density between two rolls is known. From the forage harvester processing study by Roberge et al. (1998), a material density of 54 kg DM/m$^3$ was estimated for 4.5 mm roll clearance under medium a feed rate (11 Mg DM/h). On our machine, the highest speed was found to be around 2080 rpm—a tip velocity of 16.6 m/s. Using the material density of 54 kg DM/m$^3$ and 16.6 m/s roll tip velocity, the throughput for a 4 mm rear roll clearance was found as:

$$ (54 \text{ kg DM/m}^3) \cdot (0.004 \text{ m}) \cdot (0.46 \text{ m}) \cdot (16.6 \text{ m/s}) = \frac{(M \text{ kg DM/h})}{(3600 \text{ s/h})} \cdot $$

$$ M = 5938 \text{ kg DM/h}. $$

Assuming a yield of 40 Mg/ha (wet basis) for a 35% dry matter crop in 0.76 m rows, the tractor ground speed was calculated:

$$ (V \text{ m/h}) \times (0.76 \text{ m}) \times (40 \text{ Mg/ha}) \times (\text{ha/10000 m}^2) \times 0.35 = (5.938 \text{ Mg DM/h}). $$

Therefore,

$$ V = 5.58 \text{ km/h} \text{ or } V = 3.5 \text{ mph}. $$

The 5.6 km/h is an estimated tractor ground speed assuming that material density was the same as Roberge et al. (1998). However, with the different roll clearance and capacity, this value could vary. In our experiments, 2 mm roll clearance on the rear was used. Assuming that the material density from Roberge et al. (1998) still applied, capacity through the rear rolls would be reduced to around 3 Mg DM/h.
For our testing, the speeds of the rolls were varied so the differences within pairs were 15% or 30% (R1). The difference between the averages of pairs was 30% or 60% (R2). Rear rolls rotated at higher speeds than the front rolls. By adjusting flow rate to the motors, the highest speed was found to be around 2080 rpm for Roll 3; using this upper limit and target speed differential, four target speed configurations were computed (Table 2). The four target speed configurations were assigned letters A, B, C, and D for future reference (Table 2). According to Table 2, the average rotational speed of the front rolls was higher than 500 rpm while that of the rear rolls was higher than 1500 rpm. In each trial, the speeds were set by adjusting flow control valves while the harvester was stationary, i.e. at no load condition.

**Table 2.** Target speed configurations of the shredding rolls used during testing.

<table>
<thead>
<tr>
<th>Speed Configuration</th>
<th>R1*</th>
<th>R2**</th>
<th>Target Speeds (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Front Pair</td>
<td>Rear Pair</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roll 1</td>
<td>Roll 2</td>
<td>Roll 3</td>
</tr>
<tr>
<td>A</td>
<td>15%</td>
<td>30%</td>
<td>1600</td>
</tr>
<tr>
<td>B</td>
<td>15%</td>
<td>60%</td>
<td>1300</td>
</tr>
<tr>
<td>C</td>
<td>30%</td>
<td>30%</td>
<td>1600</td>
</tr>
<tr>
<td>D</td>
<td>30%</td>
<td>60%</td>
<td>1300</td>
</tr>
</tbody>
</table>

* ratio within each pair.
** ratio between the averages of the two pairs.

### 4.2.3 Particle Size, Density and Quality Evaluation

Silage samples were separated by an ASAE standard separator (Figure 11). There were five screens with square holes and a bottom pan (Table 3, ASAE, 1999b).
Harvested corn was packed in a lab-scale packer (see also Appendix). The packer was developed previously (Hoover, 1998) to simulate compaction in a bunker silo due to driving over the silage pack. The unit was equipped with a 5.08 cm diameter bore and 45.7 cm stroke hydraulic cylinder to compact the silage. The cylinder extension/retract cycle was electronically controlled by a Campbell 21X data logger (program included in Appendix B). The packing tube was 28.6 cm in diameter (inside) and 43 cm tall.
In a previous study of the effects of packing time and packing pressure on packed density (Appendix A) with the same packer, it was found that packing pressure had a much greater effect (p<0.001) on density than packing time (p>0.5). Therefore a short time of 3.33 s was used as the time that pressure was applied on the silage. A pressure of 170 kPa on each layer of the silage (accomplished by 5380 kPa oil pressure) was chosen to simulate the typical tire pressure on silage found from the typical total tractor weight and tire dimensions used in bunker silo packing at Penn State farms.

During silage making, the packing tube was lined with a 1-mil plastic bag into which the silage was packed. The plastic bag was used to seal the silage sample for ensiling after the compaction process was completed. Compaction measuring procedures were adapted from those used by Hoover (1998). Sample sizes were divided equally into 3 or 4 parts by wet weight, each part was placed in the compaction tube. The hydraulic cylinder then started its compaction cycle that consisted of applying 170 kPa pressure on the silage for 3.33 s, three times with 3.33 s rest periods between each pressure application. Once the cycle was complete, the next portion of the sample was placed in the compaction tube on top of the previously compacted silage and compacted. This cycle was repeated until the total sample was compacted. Before sealing, air was drawn from the bag with a Shop Vac sweeper. The bag of silage was then placed upside down in a second bag. Again the second bag was vacuumed and sealed. The silage was dated and stored at room temperature for 21 to 50 days of fermentation (Figure 12).
The pH of the preserved silage was measured at the time of opening; selected samples were sent to a commercial laboratory for nutrient analysis. When the samples were opened, two quart-sized zip bags were filled, labeled and stored in a freezer for future nutrient analysis. Using a pH tester (pH Wand, Cole-Parmer), 2 pH values were obtained for each laboratory silo. A morsel of silage was picked from the center of a lab scale silo and immersed in distilled water before the pH meter was dipped in the solution to obtain a reading. If these two values differed by more than 20%, a third value was obtained. Among the frozen stored samples, two flail-cut and two chopped bags of each of the three moistures were randomly chosen for nutrient analysis by the Cumberland Valley Analytical Service Laboratory (CVAS) in Maryland.
4.2.4 Fall 2000—Shredding of Drier Crop

Field experiments were designed to investigate machine parameters thought to be important for the shredding mechanism. Previous studies on processing mechanisms suggest that roll speed, roll speed differential, minimum roll clearance, and unit roll force are parameters that affect power requirement and the degree of processing (Jirovec et al., 1999; Roberge et al., 1999; Johnson et al., 1999).

Three experiments were completed with whole plant moisture of 67% and drier. The first two experiments (Experiment 1 and 2) were designed to determine the effect of machine configuration on energy consumption and particle size reduction; the focus of the third experiment (Experiment 3) was to make silage in lab-scale silos. Both shredded and standard chopped silage were examined for particle size distribution and packed density.

For each moisture level, yield was estimated from three hand-harvested samples (5.31 m row length to represent 1/100th of an acre with a 76 cm row spacing). Using the yield, throughput was obtained by measuring distance and the time for the harvester. Tractor ground speed was kept at 2.5 km/h for all experiments. Moisture of the whole plant corn was also obtained from hand-harvested samples oven dried for 24 hours at 103 °C (ASAE, 1999c).

For each test condition, hydraulic motor speeds and pressures were recorded in three sessions (nominally 40 s each) and one bag of sample was collected. This was done in two steps. First, the three sessions of data were collected without stopping the machine. The machine was stopped to have a plastic bag (190 l) attached to the shredding chamber and then run for about 10 s to fill the bag. In Experiments 1 and 2, the samples were examined
visually for particle size and in Experiment 3, the samples were collected to make silage and evaluated for particle size distribution with ASAE particle size method (ASAE, 1999b).

Particle size of shredded material was measured by the ASAE particle size separator according to ASAE Standard S424.1 (ASAE, 1999a). The harvested material was very heterogeneous (Figure 13). Corn stalks were shredded and torn apart; kernels were damaged and there were no large pieces of cobs. However, leaves remained almost intact and the overall particle sizes were very long. Some sections of the stalks remained unflattened. Nearly all treatments from Experiment 1 showed such particle characteristics. In order to get a representative sample, the samples for ensiling collected in the plastic bags were hand sorted into two piles: one of long particles and one of particles that were “not long” (Figure 14). The long particle pile included stalk, leaves that are more than 2 or 3 inches long while the “not long” pile include kernels and shredded fodder. These two piles were weighed and the mass ratio was found. Using this ratio, smaller sub-samples from the more homogeneous fractions were combined in proper proportion to generate whole plant samples for compaction testing. Also using this ratio, sub-samples were made for particle size analysis in the ASAE particle separator. After about four weeks, samples from those lab-scale silos were rechecked for particle size distribution in the ASAE particle size separator.
During Experiment 1 (September 29, 2000), whole plant moisture content was 67%. The purpose of Experiment 1 was to find out the effect of unit roll force and speed configuration on energy requirement and particle size. Experiment 1 included all four speed configurations (see Table 2) and two unit roll forces (15 N/mm and 30 N/mm); the minimum
roll clearance was set at 10 mm for the front rolls and 2 mm for the rear rolls (Table 4). The two best speed configurations from Experiment 1 were selected for Experiment 2. Based on machine field performance, speed configurations A (R1=15%, R2=30%) and C (R1=30%, R2=30%) were chosen for further testing. These two speed configurations showed smoother machine operation than the other two (B: R1=15%, R2=60% and D: R1=30%, R2=60%) which allowed some machine plugging.

Table 4. Factors of Experiment 1 used to determine the effect of roll speed combination(s) on machine energy requirements.

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Roll Clearance (Front, Rear) mm</th>
<th>Roll Speed Configuration (R1, R2)*</th>
<th>Unit Roll Force (Front, Rear) N/mm</th>
<th>Tractor Ground Speed, km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>67%</td>
<td>(10,2)</td>
<td>A (15%, 30%)</td>
<td>(15, 15)</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B (15%, 60%)</td>
<td>(30,30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C (30%, 30%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D (30%, 60%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*R1=Speed difference within pairs, R2=Speed difference between pairs.

During Experiment 2 (October 6, 2000), crop moisture content was 61%. In Experiment 2, roll speed configurations A (R1=15%, R2=30%) and C (R1=30%, R2=30%; Table 2) were tested with different minimum roll clearances and unit roll forces. Three subsets of treatments were included in Experiment 2 (Table 5). In the first subset, minimum roll clearance was set to 10 mm for the front rolls and 1 mm for the rear rolls; unit roll force for both pair of rolls was 15 N/mm, 30 N/mm or 45 N/mm—total of six treatments. In the second subset, unit roll force was 45 N/mm for the rear rolls and 15 N/mm for the front rolls while the minimum roll clearance was 10 mm (front), 2 mm (rear)—total of two treatments. In the third subset of experiments, speed configuration B (R1=15%, R2=60%) and D
(R1=30%, R2=60%) were rechecked with minimum roll clearance and unit roll force set to what appeared to be “optimum”, i.e. minimum roll clearances of 10 mm (front) and 1 mm (rear) and unit roll forces of 15 N/mm (front) and 45 N/mm (rear)—also two treatments.

Table 5. Factors of Experiment 2 used to determine the effect of roll clearance and pressure on machine energy requirements.

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Roll Clearance (Front, Rear) mm</th>
<th>Roll Speed Configuration (R1, R2)*</th>
<th>Unit Roll Force (Front, Rear) N/mm</th>
<th>Tractor Ground Speed, km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>62%</td>
<td>(10,1)</td>
<td>A (15%, 30%)</td>
<td>(15, 15)</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C (30%, 30%)</td>
<td>(30, 30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(15, 45)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(10,2)</td>
<td>A (15%, 30%)</td>
<td>(15, 45)</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C (30%, 30%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(10,1)</td>
<td>B (15%, 60%)</td>
<td>(15, 45)</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D (30%, 60%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*R1=Speed difference within pairs, R2=Speed difference between pairs.

Visual examination of particle size from the above 10 treatments in Experiment 2 indicated minimum roll clearances of 10 mm (front) and 1 mm (rear) showed the most severe shredding of stalks; the stalks appeared to be shorter and thinner. Therefore the minimum roll clearances of 10 mm (front) and 1 mm (rear) were chosen for Experiment 3. The damage to kernels and cobs seemed very similar between roll clearances of 10 mm (front), 2 mm (rear) and 10mm (front), 1 mm (rear). Since no pronounced difference was shown in particle size among treatments of different speed configurations with other variables being equal, all four speed configurations (A, B, C, D) were tested in Experiment 3. Experiment 3 was done on October 11, 2000; whole-plant moisture content was 51%. In Experiment 3, samples
were collected to make silage in lab-scale silos. Samples were also collected from a standard forage harvester for comparison. The whole-plant corn was chopped to approximately 16 mm (5/8 in) theoretical length of cut.

Table 6. Factors of Experiment 3 used to fill laboratory scale silos and evaluate particle size distributions.

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Roll Clearance (Front, Rear) mm</th>
<th>Roll Speed Configuration (R1, R2)*</th>
<th>Unit Roll Force (Front, Rear) N/mm</th>
<th>Tractor Ground Speed, km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>51%</td>
<td>(10,1)</td>
<td>A (15%, 30%)</td>
<td>(15, 45)</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*R1=Speed difference within pairs, R2=Speed difference between pairs.

4.2.5 Fall 2001—Effect of Moisture and Throughput

The main goal of the fall 2001 experiment was to further evaluate the machine with different moisture crops and at different machine capacities, i.e. different tractor ground speeds. Two experiments were done in 2001. Experiment 4 consisted treatments to collect power data and Experiment 5 treatments for collecting samples for laboratory scale silos. Effects of three moisture levels: 70%, 65% and 60% and three tractor ground speeds: 2 km/h, 2.6 km/h and 3.5 km/h were examined. Crop yield was estimated for each moisture level in order to obtain a dry matter throughput for the machine. The corn crop was Dekalb 525 bty variety, which was planted on April 4, 2001 with a plant population of 69,100/ha (28,000/ac).

A cutting mechanism was added to the shredder for a separate Master’s degree study (Sword, 2002). The cutting mechanism significantly reduced particle size coming out of the
shredding rolls. In the beginning of the experiment, shredded silage was packed in lab scale silos for density evaluation. However, after the 70% moisture experiments were done, shredded-only silage was deemed less optimum compared to shred and cut silage and all later silos used silage harvested with the cutting mechanism added.

4.2.5.1 Cutting Mechanism

Figure 15 shows the flail cutters and Figure 16 illustrate the rear view of the cutting mechanism added for the fall 2001 experiment. The cutting chamber consisted of four sets of flails mounted on four bars rotating around a center shaft. The flails were powered by tractor hydraulic remote and a hydraulic motor. The rotational speed of the center shaft was changed by adjusting the flow control valve on the tractor hydraulic system.

For the purpose of this thesis, the parameters of the cutting mechanism were set at their seemingly “optimum” levels. Each of the four bars had a complete set of flails and the highest possible flail speed of 2200 rpm was set to make laboratory scale silos. The radius of the flails was 20 cm and the theoretical cut length for material leaving the rear rolls and cut by flail impact was 11 cm (Sword, 2002).
Figure 15. Dismounted flail cutter (photo).

Figure 16. Cutting mechanism powered by the tractor hydraulic remote (photo).
**4.2.5.2 Machine Power and Silage Density Evaluation**

Table 7 illustrates variables used to evaluate power requirements for shredding corn at three moisture levels and three tractor ground speeds in Experiment 4. Besides the moisture level and tractor ground speed, roll speed configuration and front roll clearance were also varied in these experiments. Two roll speed configurations were examined: A (R1=15%, 30%) and C (R1=30%, R2=30%). Roll clearance of both 15 mm and 10 mm for the front rolls were examined for 65% and 60% moisture levels. Front roll clearance was expanded to 15 mm when harvesting the 65% moisture crop in an attempt to ease material flow to the shredding rolls. Plugging between the feed rolls and the front shredding rolls occurred during the test, which was partly due to the corn head. The sickle knives on the corn head could not be timed perfectly—corn stalks could gather into a bunch before were fed into the feed rolls, which generally caused plugging on the feed rolls. Opening up the front roll clearance to 15 mm reduced plugging somewhat.

**Table 7.** Factors used to evaluate power requirements of shredding in Experiment 4.

<table>
<thead>
<tr>
<th>Target Moisture Content</th>
<th>Roll Clearance (Front, Rear) mm</th>
<th>Roll Speed Configuration (R1, R2)*</th>
<th>Unit Roll Force (Front, Rear) N/mm</th>
<th>Throughput Mg DM/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>(10,1)</td>
<td>A (15%, 30%) C (30%, 30%)</td>
<td>(15, 45)</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>65%</td>
<td>(10,1) (15,1)</td>
<td>A (15%, 30%) C (30%, 30%)</td>
<td>(15, 45)</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.7</td>
</tr>
<tr>
<td>60%</td>
<td>(10,1) (15,1)</td>
<td>A (15%, 30%) C (30%, 30%)</td>
<td>(15, 45)</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.4</td>
</tr>
</tbody>
</table>

*R1=Speed difference within pairs, R2=Speed difference between pairs.
Table 8 lists factors varied in Experiment 5 for collecting samples to make lab-scale silos—total of four conditions. Four silos were packed for each experimental condition. In the beginning of the experiment, both shredded only and shred and cut samples were collected to fill lab-scale silos. This was done for the 70% moisture level crop—therefore two experimental conditions were done for the 70% moisture level. Later, the shredded only samples were deemed too long in particle size and therefore only samples through the cutting flails were used to fill lab-scale silos. For the 70% moisture level, the rear set of rolls had a 2 mm roll clearance when the flail cutter was used. Later experiments showed that the 2 mm rear roll clearance produced very coarse particles so the 2 mm setting was eliminated for 65% and 60% moisture levels. With the 1 mm clearance for the rear rolls, sample particles looked smaller; the lower part of the stalks was sliced into thin sections. Figure 17 illustrates the particles left on the top screen of the ASAE separator. The 1 mm clearance appeared more ideal for processing corn silage.

Samples were also collected from a conventional forage harvester to make laboratory scale silos for comparison with samples from the novel harvester. Theoretical length of cut for the conventional chopper was set at 9.5 mm (3/8 in) for all experiments. Four silos were packed for each moisture level.
Table 8. Treatments used to collect corn silage to fill lab-scale silos (tractor ground speed @ 2.0 km/h) in Experiment 5.

<table>
<thead>
<tr>
<th>Target Moisture Content</th>
<th>Roll Clearance (Front, Rear) mm</th>
<th>Roll Speed Configuration (R1, R2)</th>
<th>Unit Roll Force (Front, Rear) N/mm</th>
<th>Flail Cut @Full flails and 2200 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>(10,1)</td>
<td>(15%, 30%)</td>
<td>(15, 45)</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>(10,2)</td>
<td>(15%, 30%)</td>
<td>(15, 45)</td>
<td>Yes</td>
</tr>
<tr>
<td>65%</td>
<td>(10,1)</td>
<td>(15%, 30%)</td>
<td>(15, 45)</td>
<td>Yes</td>
</tr>
<tr>
<td>60%</td>
<td>(10,1)</td>
<td>(15%, 30%)</td>
<td>(15, 45)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*R1=Speed difference within pairs, R2=Speed difference between pairs.*

Figure 17. Larger particles (> 26.9 mm, 70% moisture) from samples collected from experiments with rear rolls set at 1 mm clearance (photo).
4.3 DAFOSYM Analysis of the Shredding System

A simulation study was undertaken to evaluate the dairy producer’s benefit in adopting the novel forage harvester. DAFOSYM was used to determine the long-term costs and benefits for using shredded silage on two representative dairy farms. The two farms represented a small farm with 100 cows and a larger farm with 250 cows. Comparisons made across the simulated systems included feed production and use, operating costs, milk production, and farm profit. DAFOSYM was also used to determine the sensitivity of costs and benefits to values assumed for major parameters used to model the effects of the novel harvester.

4.3.1 Adjustment of the Model

Modifications were needed on several components of DAFOSYM to model the use of the novel harvester. These included parameters used to describe the forage harvester, nutritional value, and the ensiling process of the processed forage.

Three parameters of the forage harvester were affected: initial cost, specific energy requirement, and throughput capacity. Initial cost of the machine was assumed to be the same as a medium size conventional forage harvester. Specific energy requirements and throughput capacities were quantified after experiment results were obtained.

Assumptions on nutritional values were mainly made through literature data. Crop processing was assumed to provide forage that was more easily compressed in the silo. With processed corn silage, increases in silage density of 0 to 20% have been measured with an average being about 10% (Harrison et al., 1998). Shinners et al., (1988) found an 11% increase in initial density with macerated alfalfa silage compared to that harvested with a
The primary feed benefit from processing is an increase in the digestibility of the forage. Like kernel processing, shredding can affect digestibility in two ways. First, it cracks and/or crushes corn kernels. With broken kernels, microbes in the rumen can more readily enter the kernel, thus improving digestion of the grain. Second, shredding of the stalk and crushing of the cob also allows rumen microbes easier access to forage fibers for digestion. The effects of shredding on forage fiber and grain digestion was assumed the same as the effect of processing.

In DAFOSYM, the available energy from corn silage is a function of the NDF concentration in the forage (Rotz, et al., 1999a). As the crop matures, NDF content decreases and the predicted energy content increases. However, as the crop approaches full maturity, whole plant corn becomes less digestible, whole kernels may pass through the animal undigested and the fodder may not be consumed. With lower digestibility, the animal does not receive all the energy contained in the silage. This effect was modeled by adding a second function that reduced available energy with increasing dry matter content. As the crop matured, a peak occurred where available energy began to decrease with maturity (Rotz, et al., 1999a).

The effect on fiber was reflected by 10% increase in stover digestibility over chopped silage as assumed for processed silage (Rotz, et al., 1999a). The effect of shredding on
mature grains was modeled by adjusting the limit imposed by decreasing available energy with increasing dry matter content. When shredding was used, the reduction in available energy with increasing dry matter imposed by the maturing crop was halved (Rotz, et al., 1999a).

Changes in particle size and digestibility from processing can also affect animal intake. The effect of processing on intake was modeled by manipulating the fill and roughage factors in DAFOSYM. These factors adjust the effect that the NDF content of each feed has on the fill and roughage constraints used to balance rations. The fill constraint can limit the intake of feed. The roughage factor represents the ability of the forage to provide proper mat formation in the rumen to stimulate rumination. In the model, fill units were feed NDF weighted by particle size and rumen degradability of those particles. Roughage units were NDF weighted by particle size and the effectiveness of fiber in stimulating chewing (Rotz et al. 1999b).

In the original model (Rotz et al. 1999b), corn silage was divided into two pools according to particle size—large and small. Large and small particle fractions in forages were related to physical characteristics of the crop. For corn silage, 85% of the stover was defined to be large particles, and the remainder of the plant was small particles (Rotz et al., 1999b). The large particle pool consists primarily stover and the small particle pool primarily grain. Fill and roughage factors were determined assuming that the portion of large particles was 50% for corn silage. The longer stover in shredded silage was reflected by changing values of fill and roughage factors. In DAFOSYM, (Rotz et al., 1999b), default fill factors are 1.45 and 0.4 for large particles and small particles in chopped corn silage. When shredding technology was evaluated the definition of large and small particles was carried
over, i.e. 85% of the stover was defined to be large particles, and the remainder of the plant was small particles. Rather, the fill and roughage factors of large particles were considered to represent the feed characteristics expected of flail-cut silage. The shredded stover should digest more quickly than chopped stover, hence it should have a lower fill effect with a similar chemical NDF characteristic; however, since the shredded particles were significantly different from chopped silage, the fill factor for the large particles was kept unchanged. The fill factor for small particles remained the same. The roughage factors were set to 1.0 for large particles and 0.7 for small particles in chopped silage. Flail-cut silage has a look of hay—longer than chopped but very thin in section and therefore may have more mat-forming effect in the rumen than chopped silage. The roughage factor for large particles was increased by 5% for flail-cut silage and the roughage factor for small particles was kept the same.

Model modifications for shredded silage were reflected by adjusting multiplicative coefficients. Table 9 summarizes the multiplicative adjustments for evaluating chopped, processed (rolled at longer TLC) and shredded silage. The values for chopped and processed silage were taken from the original DAFOSYM model (Rotz et al., 1999a and 1999b). The multiplicative adjustments for shredded silage were compared to those used for chopped and processed silage. The assumed (or to be determined) values are used for the baseline analysis for shredded silage. Simulations were done with an upper bound on the milk production of 9670 L (22,000 lb)/cow for both farms.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Chopped</th>
<th>Processed (longer TLC)</th>
<th>Shredded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 9.** Model parameter multiplicative adjustments for shredded silage in comparison to standard chopped and processed silage—baseline analysis for the novel harvester.
### Simulation Procedures

Simulations were run to conduct a baseline analysis (most likely scenario) and a sensitivity analysis (effects of improper assumptions). In the baseline analysis, silage shredding was compared to both standard harvesting procedures and corn silage processing on two representative farms. The two farms represented a small farm with 100 cows and a larger farm with 250 cows. Comparisons were made on feed production and use, operating costs, milk production, and farm profit. The sensitivity analysis tested the assumptions made to describe the shredded silage. A single management scenario for using corn silage shredding was assumed for the two farms—a farmer owned a medium-sized pull-type forage harvester.

Sensitivity analysis was done by changing model parameters one at a time and determining the sensitivity of the analysis to the change. If changing a parameter leads to large impacts, that parameter may be selected as an important variable in the study. The sensitivity analysis was done on both farms. The parameters studied were PTO power requirement, stover digestibility, fill and roughage factors of large particles and machine initial price. Table 10 shows the multiplicative adjustments for sensitivity analysis. Sensitivity on machine power requirement was done by increasing 20% from baseline value.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Adjusted</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTO Power Requirements</td>
<td>1</td>
<td>1</td>
<td>TBD*</td>
</tr>
<tr>
<td>Silage Initial Density</td>
<td>1</td>
<td>1</td>
<td>TBD</td>
</tr>
<tr>
<td>Digestibility of Stover</td>
<td>1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Fill of Large Particles</td>
<td>1</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>Roughage of Large Particles</td>
<td>1</td>
<td>1</td>
<td>1.05</td>
</tr>
<tr>
<td>Fraction of Large Particles</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
</tr>
</tbody>
</table>

* to be determined—based on experimental results.
Flail-cutting may produce a stover more digestible than kernel processed silage, so a 5% increase was done in sensitivity analysis. The flail-cut silage could affect intake both positively and negatively so fill effect of large particles was reduced and increased in sensitivity analysis. Similarly, the flail-cut silage may not provide more mat-forming effect in rumen than chopped silage; therefore one evaluation was performed with the same roughage factor of large particles. The novel forage harvester might cost more (at least in the early stage of production) so machine price was increased by 20% to determine the impact of machine price on whole farm profitability. This was done by changing the input file of DAFOSYM windows version—without having to change parameter in the simulation program. Finally, the percentage of large particles in stover was increased by 10% and 5% to represent the likely increase of large particles in flail-cut silage. The increase of large particles is possible because mass percentage of “long” may not change, but mean length of the “long” portions is longer.

<table>
<thead>
<tr>
<th>Table 10. Model parameter multiplicative adjustments for sensitivity analysis for the novel harvester (bold numbers are changed comparing to baseline values).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>Baseline</td>
</tr>
<tr>
<td>Greater power requirement</td>
</tr>
<tr>
<td>More stover digestibility</td>
</tr>
<tr>
<td>Less fill for large particles</td>
</tr>
<tr>
<td>More fill for large particles</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Same roughage</td>
</tr>
<tr>
<td>Higher machine price</td>
</tr>
<tr>
<td>10% more large particles</td>
</tr>
<tr>
<td>5% more large particles</td>
</tr>
</tbody>
</table>

* to be determined—based on experimental results.

4.3.3 Representative Farms

The modeled farms reflected typical dairy farms in central Pennsylvania that use confined feeding systems. The soil on both farms was a silt loam of medium depth. The smaller farm included 100 mature animals plus replacement stock on 100 ha (247 acre) of land. Alfalfa was grown on 43 ha (106 acre) and corn on 57 ha (141 acre). The larger farm included 250 cows on 250 ha (618 acre) of land consisting of 101 ha (267 acre) of alfalfa and 122 ha (351 acre) of corn. The corn crop was a 110-day variety with a population of 69,000 plants/ha (28,000 plants/acre). Alfalfa was harvested using a four cutting harvest plan with the first two cuttings harvested at a bud stage of development and the last two harvested at an early bloom stage. Since there was no chopper on these farms, alfalfa was harvested as baled baled silage for the first and fourth cuttings and as hay for the second and third cuttings. The forage harvester used on both farms was of medium size.

Machinery and facilitates used on the two farms are listed in Table 11. Other economic parameters and prices are listed in Table 12. Facilities included bunker silos for storing corn silage and a tower silo for high moisture corn. Cost for storing alfalfa silage (balage) was assumed to be $15,000 for the smaller farm and $30,000 for the larger farm. These numbers included cost for plastic, machine and labor (Garthe and Hall, 1992), cost of inflation was considered. Most equipment used on the farm was purchased new, but a used
price was assumed for smaller utility tractors, silage dump trucks, and manure spreading tank trucks. To reduce harvest cost, corn grain was harvested as a custom-hire operation.

For the smaller farm, the herd included 100 Holstein cows plus replacement stock. Replacements included 40 cows over one year old and 45 under one year old. For the large farm, animal numbers were 250 cows, 100 older heifers, and 113 younger heifers. Simulations were done with the milk production level assumed to be about 9670 l (22,000 lb)/cow for both farms. Simulations were done using State College, Pennsylvania, weather data from 1973 to 1998.
Table 11. Machines and structures used for the analysis of two representative dairy farms.

<table>
<thead>
<tr>
<th>Machine or Storage Type</th>
<th>Small (100-cow) Farm</th>
<th>Medium (250-cow) Farm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size</td>
<td>No.</td>
</tr>
<tr>
<td>Tractors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 kW, used</td>
<td>1</td>
<td>10,000</td>
</tr>
<tr>
<td>55 kW</td>
<td>1</td>
<td>43,100</td>
</tr>
<tr>
<td>80 kW</td>
<td>1</td>
<td>53,500</td>
</tr>
<tr>
<td>Skid steer loader</td>
<td>25 kW</td>
<td>1</td>
</tr>
<tr>
<td>Mower-conditioner</td>
<td>2.7 m</td>
<td>1</td>
</tr>
<tr>
<td>Tandem Rake</td>
<td>5.4 m</td>
<td>1</td>
</tr>
<tr>
<td>Round baler</td>
<td>6.0 Mg DM/h</td>
<td>1</td>
</tr>
<tr>
<td>Bale wagon</td>
<td>5.0 Mg</td>
<td>1</td>
</tr>
<tr>
<td>Forage Harvester</td>
<td>Medium, 14 Mg DM/h</td>
<td>1</td>
</tr>
<tr>
<td>Forage hauling</td>
<td>Dump wagons, 6 Mg</td>
<td>2</td>
</tr>
<tr>
<td>Feed mixer wagon</td>
<td>Small, 4.5 Mg</td>
<td>1</td>
</tr>
<tr>
<td>Manure pump</td>
<td>450 Mg</td>
<td>1</td>
</tr>
<tr>
<td>Manure spreader</td>
<td>12.5 Mg</td>
<td>1</td>
</tr>
<tr>
<td>Coulter-chisel plow</td>
<td>2.7 m</td>
<td>1</td>
</tr>
<tr>
<td>Tandem disk harrow</td>
<td>3.7 m</td>
<td>1</td>
</tr>
<tr>
<td>Field cultivator</td>
<td>3.7 m</td>
<td>1</td>
</tr>
<tr>
<td>Corn planter</td>
<td>6 row</td>
<td>1</td>
</tr>
<tr>
<td>Grain drill</td>
<td>2.4 m</td>
<td>1</td>
</tr>
<tr>
<td>Hay shed</td>
<td>100 Mg</td>
<td>1</td>
</tr>
<tr>
<td>Alfalfa balage handling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn silage bunker</td>
<td>7.6x38x3.7m</td>
<td>1</td>
</tr>
<tr>
<td>High moisture corn silo</td>
<td>6.0x18.3m stave</td>
<td>1</td>
</tr>
<tr>
<td>Manure storage</td>
<td>Tank, 38x3m</td>
<td>1</td>
</tr>
<tr>
<td>Machinery shed</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Milking center</td>
<td>Double six</td>
<td>1</td>
</tr>
<tr>
<td>Free stall barn</td>
<td>---</td>
<td>1</td>
</tr>
<tr>
<td>Replacement housing</td>
<td>---</td>
<td>1</td>
</tr>
<tr>
<td>Commodity shed</td>
<td>---</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 12. Economic parameters and prices assumed for various system inputs and outputs for the analysis of the representative dairy farms.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor wage rate</td>
<td>$10.50/h</td>
<td>Selling price of feeds/animals</td>
<td></td>
</tr>
<tr>
<td>Diesel fuel price</td>
<td>$0.29/liter</td>
<td>-Alfalfa hay</td>
<td>$120/Mg DM</td>
</tr>
<tr>
<td>Electricity price</td>
<td>$0.08/kWh</td>
<td>-Corn Silage</td>
<td>$70/Mg DM</td>
</tr>
<tr>
<td>Corn drying price</td>
<td>$1.18/pt./Mg DM</td>
<td>-Corn grain</td>
<td>$115/Mg DM</td>
</tr>
<tr>
<td>Milk price</td>
<td>$30/hL</td>
<td>-Cull cow</td>
<td>$0.88/kg</td>
</tr>
<tr>
<td>Milk marketing/hauling fees</td>
<td>$2/hL</td>
<td>-Heifer</td>
<td>$1200/animal</td>
</tr>
<tr>
<td>Total of livestock expenses</td>
<td>$238/cow/y</td>
<td>-Calf</td>
<td>$20/animal</td>
</tr>
<tr>
<td>Custom rates</td>
<td></td>
<td>Buying price of feeds/bedding</td>
<td></td>
</tr>
<tr>
<td>-Corn grain harvest</td>
<td>$64/ha</td>
<td>-Corn grain</td>
<td>$120/Mg DM</td>
</tr>
<tr>
<td>-Corn silage harvest</td>
<td>$7/Mg</td>
<td>-Alfalfa hay</td>
<td>$135/Mg DM</td>
</tr>
<tr>
<td>-Charge for processing</td>
<td>$1/Mg</td>
<td>-Soybean meal</td>
<td>$250/Mg DM</td>
</tr>
<tr>
<td>-Alfalfa silage harvest</td>
<td>$10/Mg</td>
<td>-Protein mix</td>
<td>$396/Mg DM</td>
</tr>
<tr>
<td>Fertilizer prices</td>
<td></td>
<td>-Mineral/vitamin</td>
<td>$325/Mg DM</td>
</tr>
<tr>
<td>-Nitrogen</td>
<td>$0.35/kg</td>
<td>-Straw bedding</td>
<td>$110/Mg DM</td>
</tr>
<tr>
<td>-Phosphorous</td>
<td>$0.44/kg</td>
<td>Economic life</td>
<td></td>
</tr>
<tr>
<td>-Potassium</td>
<td>$0.27/kg</td>
<td>-Storage structure</td>
<td>20 y</td>
</tr>
<tr>
<td>Annual cost of seed/chemicals</td>
<td></td>
<td>-Machinery</td>
<td>10 y</td>
</tr>
<tr>
<td>-New alfalfa</td>
<td>$200/ha</td>
<td>Salvage value</td>
<td></td>
</tr>
<tr>
<td>-Established alfalfa</td>
<td>$15/ha</td>
<td>-Structure</td>
<td>0%</td>
</tr>
<tr>
<td>-Corn following alfalfa</td>
<td>$135/ha</td>
<td>-Machinery</td>
<td>30%</td>
</tr>
<tr>
<td>-Corn following corn</td>
<td>$155/ha</td>
<td>Property tax rate</td>
<td>2.3%/y</td>
</tr>
<tr>
<td>Land charge</td>
<td>$250/ha</td>
<td>Real interest rate</td>
<td>6.0%/y</td>
</tr>
</tbody>
</table>
Chapter 5: Experiment Results

5.1 Fall 2000 Experiments—Shredding of Drier Crop

Good particle size reduction was achieved with certain machine configurations; corn stalks were shredded and torn apart, kernels were damaged, and there were no large cobs. Specific energy requirements for shredding ranged from 2.5 to 3.4 kW h/Mg DM with an overall average of 3.1 kW/h/DM Mg. Minimum roll clearances of 10 mm (front rolls) and 1 mm (rear rolls), along with unit roll forces of 15 N/mm (front) and 45 N/mm (rear) produced more processed material with thinner stalks and shorter pieces than the minimum roll clearance of 10 mm (front) and 2 mm (rear) or unit roll forces of 30 N/mm (front) and 30 N/mm (rear). Specific energy increased slightly with increased unit roll force for minimum roll clearances of 10 mm (front) and 1 mm (rear). The shredded particles ensiled well in lab-scale silos. Significant difference were found in dry matter silage density among roll speed configurations or compared to chopped silage.

5.1.1 Experiment 1—Roll Speed Combinations

Machine power and specific energy requirements from Experiment 1 are listed in Table 13. Crop moisture was 67% and machine throughput was 2.76 Mg DM/h for all treatments in Experiment 1. At unit roll force of 15 N/mm (front and rear), the difference in power requirements among different roll speed configurations was large, the average specific energy requirement for shredding (sum of four rolls) ranged from 2.5 to 3.4 kW h/Mg DM. Tukey’s analysis of multiple comparison showed that roll speed configuration A (R1=15%, R2=30%) and B (R1=15%, R2=60%) had significant higher (p<0.05) energy consumption
than roll speed configuration C (R1=30%, R2=30%) and D (R1=30%, R2=60%) while no significant difference was found either between roll speed configuration A and B or C and D.

At unit roll force of 30 N/mm (front and rear), the difference in power requirements among different roll speed configurations was smaller than the treatments at unit roll force of 15 N/mm (front and rear). Average specific energy requirement for shredding (sum of four rolls) ranged from 2.9 to 3.4 kW h/Mg DM. Statistical analysis showed no significant difference (p=0.67) between treatments at this unit roll force setting. Specific energy requirement for shredding at roll speed configuration D was lowest at unit roll forces of 15 N/mm (front and rear) but highest at unit roll force of 30 N/mm. Overall average specific energy increased from 3.0 to 3.14 kW h/Mg DM as the unit roll force increased from 15 to 30 N/mm (front and rear). During Experiment 1, roll speed configurations B and D caused plugging on the rolls while roll speed configurations A and C ran smoothly. The large differences between the average speeds of the two pair of rolls (60%) in speed configuration B and D mandated the low speeds in the front rolls and this might have hampered material flow. Roll speed configurations A and C were therefore chosen for further test.

Peak power requirement (95 percentile value) ranged from 12.8 to 15.4 kW at unit roll force of 15 N/mm (front and rear). At unit force of 30 N/mm (front and rear), peak power requirement remained in the same range (13.5 kW to 17.3 kW) among different speed configurations.

For treatments at both unit roll forces, the rear pair of rolls required about 20% to 60% more specific energy than the front pair of rolls among all treatments in Experiment 1. Figure 18 contains the specific energy requirements for the 8 trials in Experiment 1. Average
specific energy requirements were similar between unit roll force settings of 30 N/mm (front), 30 N/mm (rear) and 15 N/mm (front), 15 N/mm (rear).
Table 13. Energy requirements to shred corn silage (67% w.b., Experiment 1) at four different roll speed configurations and two different unit roll forces. Minimum roll clearance was set at 10 mm and 2 mm for front and rear sets of rolls, respectively.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Roll Speed</th>
<th>Roll Speed Differential Target (Actual)</th>
<th>Roll Tip Velocity (m/s) Target (Actual)</th>
<th>Mean Specific Energy (kW h/Mg DM)</th>
<th>Power (kW)</th>
<th>Data Points (1Point=2 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R1* R2*</td>
<td>Roll #1 Roll #2 Roll #3 Roll #4 4 Rolls 1st Pair 2nd Pair Mean Peak**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>0.15 (0.26) 0.3 (0.35)</td>
<td>12.8 (12.2) 11.1 (9.1) 16.6 (15.7) 14.4 (13.2) 3.4 1.3 2.1 9.2 15.4 52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>0.15 (0.28) 0.6 (0.75)</td>
<td>10.4 (9.4) 9.0 (6.4) 16.6 (14.3) 14.4 (12.9) 3.3 1.2 2.0 9.0 14.0 47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>0.3 (0.22) 0.3 (0.37)</td>
<td>12.8 (11.0) 9.8 (8.9) 16.6 (14.8) 12.8 (12.5) 2.8 1.2 1.6 7.7 14.4 57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>0.3 (0.38) 0.6 (0.73)</td>
<td>10.4 (8.6) 8.0 (5.8) 16.6 (14.0) 12.8 (11.0) 2.5 0.9 1.6 7.0 12.8 52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit force: 15 N/mm (front), 15 N/mm (rear)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>0.15 (0.14) 0.3 (0.30)</td>
<td>12.8 (10.7) 11.1 (8.9) 16.6 (13.2) 14.4 (2.2) 2.9 1.3 1.6 7.9 13.5 51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>0.15 (0.28) 0.6 (0.75)</td>
<td>10.4 (9.2) 9.0 (6.3) 16.6 (14.3) 14.4 (12.9) 3.0 1.4 1.6 8.3 15.4 56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>C</td>
<td>0.3 (0.34) 0.3 (0.40)</td>
<td>12.8 (9.8) 9.8 (6.7) 16.6 (12.7) 12.8 (10.4) 3.3 1.4 1.9 9.1 17.2 52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>D</td>
<td>0.3 (0.30) 0.6 (0.71)</td>
<td>10.4 (9.0) 8.0 (6.4) 16.6 (14.4) 12.8 (12.0) 3.4 1.3 2.1 9.4 17.3 20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* R1=Speed difference within pairs, R2=Speed difference between pairs.
** 95th percentile of recorded data.
Figure 18. Specific energy requirement for shredding at four different roll speed configurations (A, B, C, D, see Table 13) with minimum roll clearance at 10 mm (front) and 2 mm (rear) and two different unit roll forces. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

5.1.2 Experiment 2—Roll Clearance and Pressure

Crop moisture was 62% and machine throughput was 2.76 Mg DM/h for all treatments in Experiment 2. The minimum roll clearance of pair 10 mm (front) and 1 mm (rear), along with unit roll forces of 15 N/mm (front) and 45 N/mm (rear) produced more processed material with thinner stalks and shorter pieces than the roll clearance of pair 10 mm (front) and 2 mm (rear) or unit roll forces of 30 N/mm (front and rear) (Figure 19).

No plugging in the rolls was experienced in Experiment 2. Speed configurations B (R1=15%, R2=60%) and D (R1=30%, R2=60%) ran as smoothly as speed configurations A (R1=15%, R2=30%) and C (R=30%, R2=30%). The actual speeds of the rolls were closer to target speeds than they were in Experiment 1; most of the actual speeds were within 100 rpm
(0.8 m/s tip velocity) of target speeds which may explain the smoothness of the operation in Experiment 2.

Figure 19. The silage processed at 1 mm (rear) minimum clearance (a) and that processed at 2 mm (rear) minimum clearance (b). Unit roll forces were 15 N/mm (front) and 45 N/mm (rear) (photo).

Table 14 lists the energy, power, requirements for shredding 62% moisture content corn. Average specific energy requirements for shredding ranged from 2.8 to 3.3 kW h/Mg DM with an overall average of 3.12 kW h/Mg DM, which is slightly less the overall average of treatments at 67% moisture. No significant difference exists between treatments. Figure 20 illustrates energy requirements for trials with minimum roll clearance of 10 mm (front) and 1 (rear) (trials #9-14, 17-18). It shows the effect of unit roll force and roll speed configuration on energy consumption. Unit roll force of 30 N/mm (front) and 30 N/mm (rear) had the lowest mean specific energy requirement among three unit roll force settings. All four roll speed configurations had similar effects on energy.
Considering all the treatments from Experiments 1 and 2, specific energy requirements were similar among all minimum roll clearances and unit roll force combinations tested. Figure 21 shows the trials with unit roll forces of 15 N/mm (front) and 45 N/mm (rear) (trial #11, 14-18) with different minimum roll clearances. Again, the effect of minimum roll clearance on specific energy requirement is ambiguous and small. But minimum roll clearance of 10 mm (front) and 1 mm (rear) produced more processed material with thinner and shorter sections of stalk. Minimum roll clearances larger than 1 mm on the rear pair produced a fodder which seemed too coarse to be acceptable. Therefore minimum roll clearance of 10 mm (front) and 1 mm (rear) was considered “the best” roll clearance. Unit roll force of 15 N/mm (front) and 45 N/mm (rear) also had more shredding effect on the material and was considered to be the best unit roll force setting. Figure 22 illustrates the effect of roll speed configuration under the best roll clearance (10 mm and 1 mm for front and rear, respectively) and best unit roll force (15 N/mm and 45 N/mm for front and rear rolls, respectively) (trials #13, 14, 17, 18). It further shows that roll speed did not greatly affect specific energy consumption. Average power requirement for trials in Experiment 2 was around 9 kW and peak power requirement was 18 kW.

The 2.5 to 3.4 kW h/Mg DM specific energy was low compared to related data. In a study with kernel processing, Roberge et al. (1999) found that the specific energy for corn silage chopping, processing and blowing was 6.58 kW h/Mg DM with 1.18 kW h/Mg DM required for processing. With this shredding harvester, some power for cutting and blowing could be added and energy requirements would still be comparable or lower than that of conventional harvesters.
Table 14. Energy requirements to shred corn silage (62% w.b.) at four roll speed configurations and three unit roll forces. Minimum roll clearance was (10 mm and 2 mm) and (10 mm and 1 mm) for front and rear sets of rolls, respectively.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Roll Speed</th>
<th>Target Speed (Actual)</th>
<th>Tip Velocity (m/s)</th>
<th>Specific Energy, Mean (kW h/Mg DM)</th>
<th>Power (kW)</th>
<th>Data Points (1 Point= 2 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roll #1</td>
<td>Roll #2</td>
<td>Roll #3</td>
<td>Roll #4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R1*</td>
<td>R2*</td>
<td>Roll #1</td>
<td>Roll #2</td>
<td>Roll #3</td>
<td>Roll #4</td>
</tr>
<tr>
<td>9</td>
<td>A</td>
<td>0.15 (0.19)</td>
<td>0.30 (0.33)</td>
<td>12.8 (11.1)</td>
<td>11.1 (9.2)</td>
<td>16.6 (14.5)</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
<td>0.30 (0.33)</td>
<td>0.30 (0.32)</td>
<td>12.8 (11.6)</td>
<td>9.8 (8.4)</td>
<td>16.6 (14.8)</td>
</tr>
<tr>
<td>11</td>
<td>A</td>
<td>0.15 (0.13)</td>
<td>0.30 (0.30)</td>
<td>12.8 (12.3)</td>
<td>11.1 (10.5)</td>
<td>16.6 (15.4)</td>
</tr>
<tr>
<td>12</td>
<td>C</td>
<td>0.30 (0.31)</td>
<td>0.30 (0.30)</td>
<td>12.8 (12.0)</td>
<td>9.8 (8.9)</td>
<td>16.6 (15.3)</td>
</tr>
<tr>
<td>13</td>
<td>A</td>
<td>0.15 (0.12)</td>
<td>0.30 (0.30)</td>
<td>12.8 (12.2)</td>
<td>11.1 (10.5)</td>
<td>16.6 (15.3)</td>
</tr>
<tr>
<td>14</td>
<td>C</td>
<td>0.30 (0.30)</td>
<td>0.30 (0.31)</td>
<td>12.8 (11.9)</td>
<td>9.8 (8.7)</td>
<td>16.6 (14.9)</td>
</tr>
<tr>
<td>15</td>
<td>A</td>
<td>0.15 (0.14)</td>
<td>0.30 (0.30)</td>
<td>12.8 (12.6)</td>
<td>11.1 (10.6)</td>
<td>16.6 (15.7)</td>
</tr>
<tr>
<td>16</td>
<td>C</td>
<td>0.30 (0.29)</td>
<td>0.30 (0.29)</td>
<td>12.8 (12.6)</td>
<td>9.8 (9.4)</td>
<td>16.6 (15.7)</td>
</tr>
<tr>
<td>17</td>
<td>B</td>
<td>0.15 (0.12)</td>
<td>0.60 (0.72)</td>
<td>10.4 (9.0)</td>
<td>9.0 (7.8)</td>
<td>16.6 (15.0)</td>
</tr>
<tr>
<td>18</td>
<td>D</td>
<td>0.30 (0.27)</td>
<td>0.60 (0.60)</td>
<td>10.4 (9.9)</td>
<td>8.0 (7.4)</td>
<td>16.6 (15.2)</td>
</tr>
</tbody>
</table>

* R1=Speed difference within pairs, R2=Speed difference between pairs. ** 95th percentile of recorded data
Figure 20. Specific energy requirements for different unit roll forces and roll speed configurations at minimum roll clearance of 10 mm (front) and 1 mm (rear). Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box). See Table 13 and Table 14 for letter definitions.

Figure 21. Specific energy requirements for shredding for different minimum roll clearances and roll speed configurations (see Table 14) at unit roll forces of 15 N/mm (front) and 45 N/mm (rear). Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).
5.1.3 Experiment 3—Laboratory Scale Silos

The silage ensiled well in the lab-scale silos; only small spots of mold were noticed on the outer surface of the silo. Minor molding such as this is common even with conventionally prepared samples. Both the smell and the color of silage were normal. Table 15 lists the dry and wet matter densities of the laboratory scale silos. Figure 23 illustrates the average dry matter density and standard deviation for each treatment.
Table 15. Silage densities of the lab scale silos (4 silos for each treatment) of silage at 51% moisture content.

<table>
<thead>
<tr>
<th>Roll Speed Configuration</th>
<th>Replications (kg DM/m³)</th>
<th>Avg. DM density (kg DM/m³)</th>
<th>Stdev (kg DM/m³)</th>
<th>Wet density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (15%,30%)</td>
<td>156 144 121 125</td>
<td>137&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.4</td>
<td>279</td>
</tr>
<tr>
<td>B (15%,60%)</td>
<td>151 162 152 155</td>
<td>155&lt;sup&gt;abc&lt;/sup&gt;</td>
<td>4.9</td>
<td>316</td>
</tr>
<tr>
<td>C (30%,30%)</td>
<td>149 141 152 149</td>
<td>148&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>4.7</td>
<td>302</td>
</tr>
<tr>
<td>D (30%,60%)</td>
<td>156 156 173 158</td>
<td>161&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>8.0</td>
<td>328</td>
</tr>
<tr>
<td>Chopped (16 mm TLC)</td>
<td>162 173 182 180</td>
<td>170&lt;sup&gt;c&lt;/sup&gt;</td>
<td>9.1</td>
<td>347</td>
</tr>
</tbody>
</table>

<sup>abc</sup> Similar lowercase superscript letters indicate values among treatments which were not significantly different by Tukey’s multiple comparisons (p<0.05).

Figure 23. Average dry matter densities with standard deviation for laboratory scale silos.

An analysis of variance for silage densities listed in Table 15 showed that there was significant difference among treatments. Tukey’s procedure was used to determine which of the means of silage densities are different from one another (Devore, 1999). Analysis
indicated that treatments A, C and B do not differ; treatments C, B, and D do not differ; treatments B, D, and Chopped silage do not differ. Yet treatments A and D differ; treatments A and Chopped silage differ and treatments C and Chopped silage differ. Chopped silage had significantly higher density than silage shredded at roll speed configurations A and C. Silage shredded at roll speed configuration D (R1=30%, R2=60%) had significantly higher density than silage shredded at roll speed configuration A while there is no significant difference among the densities of silage shredded at roll speed configurations A, C, and B. Roll speed configurations A and C yield lower density than roll speed configuration B and D but B and D had more operational problems than A and C during the experiments done in year 2000.

The highest packed density was found in chopped silage (170 kg DM/m$^3$). An extensive study on silage density showed that typical packed densities range from 106 to 434 kg DM/m$^3$ (Muck and Holmes, 2000). The lower densities of our silage were likely due to the low moisture level and longer than usual length of cut; however, the crop ensiled well because of good air exclusion.

Particle size distribution in each laboratory scale silo is illustrated in Figure 24. Particle size distributions for shredded samples from the four roll speed treatments follow a similar pattern, especially for fine particles. The distribution curves coincide in the fine particle region (<10mm). The curves split on larger particles (around 15 mm). Chopped samples yielded an entirely different particle size distribution. Compared to chopped silage, shredded silage had less fine particles (on the left side of the curves) and more large particles (on the right side of the curves). It seems that shredding eliminated some fine particles while producing more large particles. If these significantly large particles can be reduced in size,
then shredding would produce a desired feed that has effective fiber and digestible grains and fiber.

Figure 24. Particle size distributions for laboratory scale silos of 51% moisture silage.
5.1.4 Brief Summary of Fall 2000 Experiments

- Difference in specific energy was small among different roll speed configurations.
- Average specific energy requirement did not change largely with the decrease of crop moisture content averaging 3.1 kW h/Mg DM for 67 and 62% moisture.
- Minimum roll clearance of 1 mm at the rear rolls, along with unit roll forces of 15 N/mm (front) and 45 N/mm (rear), produced more processed material than configurations with minimum roll clearance of 2 mm the rear rolls.
- Silage packed density of 51% moisture crop ranged from 137 to 170 Mg DM/m$^3$ for shredded and chopped silage. Silage densities were significantly affected by roll speed configurations and method of harvesting (shredding vs. chopping).
- Further experiments are needed to determine the effect of crop moisture content and throughput.
5.2 Fall 2001 Experiments—Effect of Moisture and Throughput

Fall 2001 experiments were a continuation of studies from the previous harvesting season. Primarily, the effects of moisture content and machine throughput on energy requirement for shredding and silage quality were investigated. Table 16 lists the actual moisture levels of samples and yields at these moistures.

Power and specific energy requirements for shredding were analyzed in terms of average, standard deviation, 5% percentile and 95% percentile. The 95% percentile power requirements were considered represent peak power requirements since some machine inertia can be used to power through short duration power demands.

Particle size distributions and packed densities for all the laboratory silos were measured for each moisture level. Packed silage from laboratory scale silos was also analyzed for pH and chemical content by commercial laboratory CVAS².

Table 16. Actual moisture content of whole-plant (WP) and parts of the corn plant and yields at three moistures of whole-plant.

<table>
<thead>
<tr>
<th>Date</th>
<th>Aug. 28, 2001</th>
<th>Sept. 6, 2001</th>
<th>Sept. 23, 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>% DM of Plant</td>
<td>Moisture</td>
<td>% DM of Plant</td>
</tr>
<tr>
<td>Kernel</td>
<td>55.2</td>
<td>31.4</td>
<td>44.1</td>
</tr>
<tr>
<td>Fodder</td>
<td>76.8</td>
<td>46.7</td>
<td>76.4</td>
</tr>
<tr>
<td>Cob</td>
<td>69.4</td>
<td>21.8</td>
<td>51.2</td>
</tr>
<tr>
<td>WP</td>
<td>70.3</td>
<td>65.3</td>
<td>59.5</td>
</tr>
<tr>
<td>Yield</td>
<td>11.9</td>
<td>13.9</td>
<td>16.4</td>
</tr>
</tbody>
</table>

²Cumberland Valley Analytical Service, Inc. Cumberland, MD.
Analysis procedure: the samples were dumped, mixed, hand chopped, and a large sub-sample was placed on a pan and dried and the whole subsample was ground.
5.2.1 Machine Energy Consumption

Specific energy and power requirements for shredding corn at three moisture levels are tabulated in Table 17 through Table 21. Average specific energy for four rolls generally decreased with increasing moisture content and machine throughput. Power requirement ranges remained consistent across moisture levels and machine throughputs. Average power requirements ranged from 7.8 to 14 kW and peak power requirements were around 30 kW for all conditions tested.

Figure 25 through Figure 29 illustrate the average specific energy requirements for shredding at conditions done in Experiment 4. Average specific energy requirements ranged from 3.5 to 5.9 kW h/Mg DM. Peak specific energy requirements for shredding ranged from 8.9 to 14.0 kW h/Mg DM.

Two different roll clearances were examined for 65 and 60% moisture levels: 10 mm (front), 1 mm (rear) and 15 mm (front), 1 mm (rear). Figure 26 illustrates specific energy of four rolls for shredding 65% moisture corn at roll clearance 10 mm (front), 1 mm (rear) and roll speed configurations A (R1=15%, R2=30%) and C (R1=30%, R2=30). At 65% moisture level, frequent plugging was experienced between the feed rolls and the front processing rolls at higher throughputs with minimum roll clearance of 10 mm at the front rolls. Therefore a treatment with a minimum roll clearance of 15 mm at the front rolls was added at this moisture level and the next one (60%). Figure 27 shows the values for minimum roll clearance of 15 mm (front) and 1 mm (rear). At both moisture levels (65 and 60%), the opening of the minimum clearance in the front rolls (with other conditions the same) increased the average energy requirement for shredding numerically but the changes were not statistically significant. Average specific energy ranged from 3.0 to 5.3 kW h/Mg DM for
shredding 65% moisture corn. High peak values were observed—reaching 13.8 kW h/Mg DM at the lowest machine throughput (2.1 Mg DM/h) (Figure 26).

Figure 28 and Figure 29 illustrate values of specific energy requirements for 60% moisture content at three throughput levels with roll speed configuration A (R1=15%, R2=30%) and C (R1=30%, R2=30%). Tests at this moisture level ran surprisingly smooth compared to the other two moistures, i.e. 70 and 65% moisture—no plugging was experienced. Peak specific energy requirements were lower than those at the other two moisture levels. Average specific energy ranged from 2.8 to 4.7 kW h/Mg DM at 60% moisture. Peak specific energy requirements for shredding ranged from 6.1 to 9.2 kW h/Mg DM.

In Figure 30, the average specific energy requirements for shredding at various conditions are placed side by side. A general trend is seen: the average specific energy decreased with the increase of dry matter and the increase of machine throughput capacity.

ANOVA (2 factors with replication) analysis on specific energy requirement for shredding showed that at 70% moisture, there was no interaction effect between capacity and roll speed configuration and no significant effect of roll speed configuration. However, the average specific energy requirement was significantly lower (p<0.05) at high throughput (2.9 Mg DM/h) than that at low and medium throughput capacities (1.6 and 2.1 Mg DM/h).

Statistical analyses on the specific energy requirements at other two moisture contents showed a similar trend: the average specific energy requirement was significantly lower at high throughput capacity than that at low or medium throughout capacity. It seems that machine was running more efficient at higher throughput capacities.
The rear pair of rolls consistently required more energy than the front pair of rolls. For all conditions tested, the front pair of rolls required 40 to 80% as much energy as the rear pair of rolls. This is due to the higher roll speeds and narrower clearance in the rear pair of rolls. As the moisture increased and the roll clearance of the front pair decreased, the energy requirement of the front pair increased. For treatments with a minimum roll clearance of 10 mm at the front rolls, shredding crop of 70% moisture, the front rolls required 70 to 80% as much power as the rear rolls; at 65% moisture, 50 to 80% with 70%; at 60%, 50 to 70%. For treatments with a minimum roll clearance of 15 mm at the front rolls, the front rolls required about 40 to 50% of the energy requirement of the rear at both 60 and 65% moisture levels.

Average power requirements stayed within consistent ranges over all experiments. Average power requirement for shredding ranged from 9 to 13 kW. Generally, within each moisture level and roll configuration, the average power requirement increased as tractor ground speed increased. The range in the 95-percentile power requirement was also fairly consistent—ranging between 15 to 30 kW.
Table 17. Energy requirements to shred corn silage (70% w.b.) at three different throughput capacities. Minimum roll clearance was set at 10 mm and 1 mm for front and rear rolls, respectively.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Roll Speed</th>
<th>Difference Target (Actual)</th>
<th>Tip Velocity (m/s) Target (Actual)</th>
<th>Specific Energy, Mean (kW h/Mg DM)</th>
<th>Power (kW)</th>
<th>Data Points (1 point=2 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R1* R2*</td>
<td>Roll #1 Roll #2 Roll #3 Roll #4</td>
<td>4 Rolls 1st Pair 2nd Pair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 A</td>
<td>Roll #1</td>
<td>12.8 11.1 16.6 14.4</td>
<td>4.4 2.0 2.8</td>
<td>Power Mean Peak**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 A</td>
<td>Roll #2</td>
<td>12.8 11.1 16.6 14.4</td>
<td>4.0 1.6 2.3</td>
<td>Power Mean Peak**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 A</td>
<td>Roll #3</td>
<td>12.8 11.1 16.6 14.4</td>
<td>3.5 1.6 2.0</td>
<td>Power Mean Peak**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 C</td>
<td>Roll #4</td>
<td>12.8 11.1 16.6 14.4</td>
<td>4.4 1.8 2.5</td>
<td>Power Mean Peak**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 C</td>
<td>Roll #1</td>
<td>12.8 11.1 16.6 14.4</td>
<td>5.9 2.6 3.3</td>
<td>Power Mean Peak**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 C</td>
<td>Roll #2</td>
<td>12.8 11.1 16.6 14.4</td>
<td>3.5 1.5 2.0</td>
<td>Power Mean Peak**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* R1=Speed difference within pairs, R2=Speed difference between pairs.

** 95th percentile of recorded data.
Table 18. Energy requirements to shred corn silage (65% w.b.) at three different throughput capacities. Minimum roll clearance was set at 10 mm and 1 mm for front and rear rolls, respectively.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Roll Speed</th>
<th>Difference Target (Actual)</th>
<th>Tip Velocity (m/s) Target (Actual)</th>
<th>Specific Energy, Mean (kW h/Mg DM)</th>
<th>Power (kW)</th>
<th>Data Points (1 point=2 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R1* R2*</td>
<td>Roll #1   Roll #2   Roll #3   Roll #4</td>
<td>4 Rolls 1st Pair 2nd Pair Mean Peak**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>0.15 (0.19) 0.30 (0.37)</td>
<td>12.8 (12.5) 11.1 (10.1) 16.6 (16.6) 14.4 (14.5)</td>
<td>5.3 2.1 3.2</td>
<td>11.1 19.5</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>0.15 (0.22) 0.30 (0.42)</td>
<td>12.8 (12.1) 11.1 (9.3) 16.6 (16.2) 14.4 (14.1)</td>
<td>4.3 1.7 2.6</td>
<td>11.1 21.2</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>0.15 (0.21) 0.30 (0.35)</td>
<td>12.8 (12.3) 11.1 (9.8) 16.6 (16.1) 14.4 (13.8)</td>
<td>3.8 1.3 2.5</td>
<td>14.1 21.4</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>0.30 (0.28) 0.30 (0.33)</td>
<td>12.8 (12.5) 9.8 (9.6) 16.6 (16.4) 12.8 (13.0)</td>
<td>4.9 2.1 2.8</td>
<td>10.3 25.5</td>
<td>51</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>0.30 (0.28) 0.30 (0.33)</td>
<td>12.8 (12.5) 9.8 (9.6) 16.6 (16.3) 12.8 (13.0)</td>
<td>3.5 1.4 2.1</td>
<td>9.5 20.0</td>
<td>86</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>0.30 (0.28) 0.30 (0.32)</td>
<td>12.8 (12.4) 9.8 (9.6) 16.6 (16.2) 12.8 (12.9)</td>
<td>3.4 1.3 2.0</td>
<td>12.6 30.4</td>
<td>34</td>
</tr>
</tbody>
</table>

* R1=Speed difference within pairs, R2=Speed difference between pairs.
** 95th percentile of recorded data.
Table 19. Energy requirements to shred corn silage (65% w.b.) at three different throughput capacities. Minimum roll clearance was set at 15 mm and 1 mm for front and rear rolls, respectively.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Roll Speed</th>
<th>Difference Target (Actual)</th>
<th>Tip Velocity (m/s) Target (Actual)</th>
<th>Specific Energy, Mean (kW h/Mg DM)</th>
<th>Power (kW)</th>
<th>Data Points (1 point= 2 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1*</td>
<td>R2*</td>
<td>Roll #1</td>
<td>Roll #2</td>
<td>Roll #3</td>
<td>Roll #4</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>0.15 (0.19) 0.30 (0.34)</td>
<td>12.8 (12.2) 11.1 (10.1) 16.6 (16.1) 14.4 (13.8)</td>
<td>4.3 1.4 2.9</td>
<td>8.9 18</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>0.15 (0.20) 0.30 (0.35)</td>
<td>12.8 (11.9) 11.1 (9.6) 16.6 (15.6) 14.4 (13.4)</td>
<td>4.8 1.2 3.5</td>
<td>12.8 28.5</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>0.15 (0.22) 0.30 (0.37)</td>
<td>12.8 (11.3) 11.1 (8.9) 16.6 (14.9) 14.4 (12.8)</td>
<td>2.7 0.7 2.0</td>
<td>10.1 22.2</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>0.30 (0.25) 0.30 (0.27)</td>
<td>12.8 (12.6) 9.8 (10.3) 16.6 (16.3) 12.8 (12.8)</td>
<td>4.8 1.4 3.5</td>
<td>10.2 21.4</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>0.30 (0.23) 0.30 (0.25)</td>
<td>12.8 (12.9) 9.8 (10.8) 16.6 (16.6) 12.8 (13.1)</td>
<td>3.4 1.7 1.2</td>
<td>9.1 16</td>
<td>79</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>0.30 (0.28) 0.30 (0.32)</td>
<td>12.8 (12.4) 9.8 (9.6) 16.6 (16.3) 12.8 (12.8)</td>
<td>3.0 1.5 1.1</td>
<td>10.7 20.9</td>
<td>20</td>
</tr>
</tbody>
</table>

* R1=Speed difference within pairs, R2=Speed difference between pairs.
** 95th percentile of recorded data.
Table 20. Energy requirements to shred corn silage (60% w.b.) at three different throughput capacities. Minimum roll clearance was set at 10 mm and 1 mm for front and rear rolls, respectively.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Roll Speed</th>
<th>Difference Target (Actual)</th>
<th>Tip Velocity (m/s) Target (Actual)</th>
<th>Specific Energy, Mean (kW h/Mg DM)</th>
<th>Power (kW)</th>
<th>Data Points (1 point= 2 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Roll #1 Roll #2 Roll #3 Roll #4</td>
<td>4 Rolls 1&lt;sup&gt;st&lt;/sup&gt; Pair 2&lt;sup&gt;nd&lt;/sup&gt; Pair</td>
<td>Mean Peak**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>0.15 (0.14) 0.30 (0.27)</td>
<td>12.8 (12.5) 11.1 (10.5) 16.6 (15.1) 14.4 (14.0)</td>
<td>3.6 1.2 2.4</td>
<td>9.0 14.8</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>0.15 (0.13) 0.30 (0.26)</td>
<td>12.8 (12.1) 11.1 (10.0) 16.6 (14.3) 14.4 (13.5)</td>
<td>3.1 1.2 2.0</td>
<td>10.1 15.9</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>0.15 (0.12) 0.30 (0.25)</td>
<td>12.8 (11.6) 11.1 (9.8) 16.6 (13.7) 14.4 (13.1)</td>
<td>2.9 1.0 1.8</td>
<td>12.6 23.4</td>
<td>57</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>0.30 (0.19) 0.30 (0.21)</td>
<td>12.8 (12.8) 9.8 (10.4) 16.6 (15.0) 12.8 (13.0)</td>
<td>4.0 1.7 2.4</td>
<td>10.1 19.8</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>0.30 (0.18) 0.30 (0.20)</td>
<td>12.8 (12.4) 9.8 (10.2) 16.6 (14.4) 12.8 (12.8)</td>
<td>3.3 1.2 2.1</td>
<td>10.6 23.4</td>
<td>66</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>0.30 (0.18) 0.30 (0.20)</td>
<td>12.8 (12.1) 9.8 (9.8) 16.6 (13.9) 12.8 (12.4)</td>
<td>2.8 1.1 1.6</td>
<td>12.1 24.1</td>
<td>35</td>
</tr>
</tbody>
</table>

* R1=Speed difference within pairs, R2=Speed difference between pairs.
** 95<sup>th</sup> percentile of recorded data.
Table 21. Energy requirements to shred corn silage (60% w.b.) at three different throughput capacities. Minimum roll clearance was set at 15 mm and 1 mm for front and rear rolls, respectively.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Roll Speed</th>
<th>Difference Target (Actual)</th>
<th>Tip Velocity (m/s) Target (Actual)</th>
<th>Specific Energy, Mean (kW h/Mg DM)</th>
<th>Power (kW)</th>
<th>Data Points (1 point= 2 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R1* R2*</td>
<td>Roll #1</td>
<td>Roll #2</td>
<td>Roll #3</td>
<td>Roll #4</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>0.15 (0.15) 0.30 (0.33)</td>
<td>12.8 (12.1) 11.1 (10.7) 16.6 (16.2) 14.4 (14.1)</td>
<td>4.7 1.5 3.2</td>
<td>11.9</td>
<td>21.3</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>0.15 (0.15) 0.30 (0.33)</td>
<td>12.8 (12.1) 11.1 (10.5) 16.6 (16.0) 14.4 (14.0)</td>
<td>4.0 1.2 2.8</td>
<td>12.9</td>
<td>21.6</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>0.15 (0.14) 0.30 (0.30)</td>
<td>12.8 (11.8) 11.1 (10.1) 16.6 (15.1) 14.4 (13.5)</td>
<td>3.1 0.9 2.2</td>
<td>13.5</td>
<td>29.6</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>0.30 (0.23) 0.30 (0.25)</td>
<td>12.8 (13.0) 9.8 (10.4) 16.6 (16.1) 12.8 (13.2)</td>
<td>4.2 1.3 2.9</td>
<td>10.4</td>
<td>21.6</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>0.30 (0.20) 0.30 (0.20)</td>
<td>12.8 (12.6) 9.8 (10.0) 16.6 (14.4) 12.8 (12.7)</td>
<td>3.2 1.0 2.2</td>
<td>10.1</td>
<td>19.9</td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>0.30 (0.19) 0.30 (0.18)</td>
<td>12.8 (12.6) 9.8 (9.9) 16.6 (13.9) 12.8 (12.5)</td>
<td>2.8 0.8 2.0</td>
<td>12.2</td>
<td>23.8</td>
</tr>
</tbody>
</table>

* R1=Speed difference within pairs, R2=Speed difference between pairs.
** 95th percentile of recorded data.
**Figure 25.** Total specific energy of four rolls for shredding 70% moisture corn with roll clearance at 10 mm (front), 1 mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

**Figure 26.** Total specific energy of four rolls for shredding 65% moisture corn at a roll clearance of 10 mm (front), 1 mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).
Figure 27. Total specific energy of four rolls for shredding 65% corn at a roll clearance of 15 mm (front), 1 mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

Figure 28. Total specific energy of four rolls for shredding 60% moisture corn at a roll clearance of 10mm (front), 1mm (rear) and roll speed configurations A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).
**Figure 29.** Total specific energy of four rolls for shredding 60% moisture corn with a roll clearance of 15 mm (front), 1 mm (rear) and roll speed configuration A and C. Shown are the mean (dotted box), 90 percentile range (line), and standard deviation (box).

**Figure 30.** Average specific energy requirements for shredding silage at various moisture and roll clearance conditions.
5.2.2 Particle Size Distribution and Packed Densities

Figure 31 illustrates the particle size distribution of samples collected for lab-scale silos with a silage moisture content of 70%. Between the two samples of shredded (without flail cutting) silage, the roll speed configuration C (R1=30%, R2=30%) produced more short particle mass than the roll speed configuration A (R1=15%, R2=30%) but the two particle size distributions followed a very similar trend. The particle size distribution curve for flail-cut silage was similar to the curve for shredded silage with speed configuration C (R1=30%, R2=30%). Chopped silage and flail-cut silage had about the same amount of fine particles—about 10% of sample mass smaller than 5.6 mm. About 20% of sample mass was smaller than 9 mm in both chopped and flail-cut silage. For particle larger than 9 mm, flail-cut samples had more very large particles than chopped samples. About 45% of the sample mass was smaller than 26.9 mm in flail-cut silage versus about 90% in chopped silage.

Figure 31 shows that chopped silage had the largest portion of small particles while the particle size distributions of flail-cut silage and shredded silage were similar. In reality, the flail cutter significantly reduced large particles coming from the shredding rolls, the reason that the data failed to show this reduction was that, due to the hole size design of the ASAE separator (ASAE, 1999c), about the same amount of large particles were left on the top feeder and the first screen for both flail-cut and shredded silages. A different separation method was needed to better illustrate the difference in particle size between flail-cut and shredded (no flail) silage. For 65 and 60% moisture content silage, samples were first separated by the ASAE particle size separator; then the particles left on the top screen and the top feeder pan were hand sorted into two groups: particles longer than 152 mm (6 in) and particles shorter than 152 mm. Figure 32 shows the results of the separation for silage of
three moisture levels. Particle size distribution of chopped samples was also included in the chart for comparison; in chopped samples all particles were smaller than 50 mm.

Chopped samples yielded very similar particle size distributions at all three moisture levels. Particle size distributions of flail-cut samples were similar between the 60 and 65% moistures, but the 70% moisture crop was most coarse. Compared to chopped silage, shredded silage produced fewer particles smaller than 9 mm and more particles larger than 9 mm (Figure 31) while flail-cut silage had more fine particles and more large particles (Figure 32). Experiment results on 51% moisture crop in year 2000 also showed that shredding produced less fine particles and more large particles compared to chopping. Fine particles include grains, shredded cobs and leaves. Apparently, the use of a flail cutter increased the amount of fines while still producing a large amount of large particles.

Figure 31. Particle size distribution of chopped samples and samples processed without a flail cutter with a minimum roll clearance of 10 mm (front) and 1 mm (rear) (70% moisture content).
Silage densities from laboratory scale silos are shown in Table 22. Average densities and standard deviations for each treatment are also shown pictorially in Figure 33. Analysis of variance was done on densities of both chopped and flail-cut samples to find the difference among treatments. Shred samples (without flail cutting) were only available for 70% moisture level and were therefore not included in the comparison. Analysis of variance showed that the interaction effect between moisture content and harvesting method is not significant at a level of 0.05. For the main effects, both moisture content and harvesting method affected silage density. Since the no-interaction hypothesis was not rejected and at least one of the two main effect null hypotheses was rejected, Tukey’s method was used to identify significant differences in levels (Devore, 1999). There was no significant difference of silage densities between 60 and 70% moisture; samples obtained at 65% moisture had significantly higher average density than those obtained at 60 and 70% moistures.
Comparison between harvesting methods showed a significant difference between flail cutting and chopping. Chopped silage had significantly (p<0.05) higher densities (199 kg DM/m³) than flail-cut silage (168 kg DM/m³). It seems to be ideal to harvest at 65% moisture content, which yielded the highest silage density in both chopped and flail-cut silage.

Table 22. Silage densities of laboratory scale silos.

<table>
<thead>
<tr>
<th>Moisture</th>
<th>Harvesting Method</th>
<th>Average (kg DM/m³)</th>
<th>Standard Deviation</th>
<th>Average Wet Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chop</td>
<td>197(^{aA})</td>
<td>4.4</td>
<td>656</td>
</tr>
<tr>
<td>70%</td>
<td>Flail-cut</td>
<td>163(^{bA})</td>
<td>6.2</td>
<td>544</td>
</tr>
<tr>
<td></td>
<td>Shredded</td>
<td>142</td>
<td>3.5</td>
<td>472</td>
</tr>
<tr>
<td></td>
<td>Chop</td>
<td>206(^{aB})</td>
<td>6.0</td>
<td>589</td>
</tr>
<tr>
<td>65%</td>
<td>Flail-cut</td>
<td>176(^{bB})</td>
<td>3.6</td>
<td>502</td>
</tr>
<tr>
<td></td>
<td>Chop</td>
<td>195(^{aA})</td>
<td>7.6</td>
<td>486</td>
</tr>
<tr>
<td>60%</td>
<td>Flail-cut</td>
<td>163(^{bA})</td>
<td>8.7</td>
<td>408</td>
</tr>
</tbody>
</table>

\(^{ab}\) Similar lowercase superscript letters indicate values between harvesting method (chop vs. flail-cut) were not significant different by Analysis of Variance (p<0.05).

\(^{AB}\) Similar uppercase superscript letters indicate values among moisture levels were not significant different by Tukey’s multiple comparisons (p<0.05).
Figure 33. Silage densities for the lab-scale silos for each test with standard deviation shown as an error bar.

5.2.3 Silage Quality Evaluation

Silage in the laboratory scale silos fermented well (Figure 34). Relatively little mold appeared on the outer surfaces of the silo. More mold spots were noticed on chopped samples of 70 and 65% moisture content than on shredded samples. Silage pH value was checked for each treatment before samples were sent to a commercial laboratory for chemical analysis. Table 23 lists the pH values obtained using a pH meter but there were no statistical differences in pH among treatments. There was more visible mold on chopped samples than flail shredded samples (Figure 35) at 65% moisture content.
Figure 34. Fermented shredded samples of 65% moisture content silage.

Table 23. Silage pH values for laboratory scale silos.

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Chopped Silage</th>
<th>Flail-cut Silage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Deviation</td>
</tr>
<tr>
<td>70%</td>
<td>3.62</td>
<td>0.05</td>
</tr>
<tr>
<td>65%</td>
<td>3.77</td>
<td>0.06</td>
</tr>
<tr>
<td>60%</td>
<td>3.79</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Figure 35. Mold spots in chopped silage of 65% moisture content.

Major nutrients analyzed by commercial laboratory CVAS on flail-cut and chopped silage samples are listed in Table 24. Listed values were averages of two samples for chopped and flail-cut silage respectively. The differences between flail-cut and chopped samples were also listed.

All values listed in Table 24 are within the ranges of feed compositions for corn silage documented in NRC (2001). However, there was a consistent increase of NDF in flail-cut samples compared to chopped samples for all three moisture levels. The difference in NDF was more pronounced in the 60% moisture samples when the silage NDF was 32.7% DM for chopped silage and 51.3% DM for flail-cut samples. In order to check the accuracy of the analysis, 2 samples from different silos of chopped and flail-cut samples were sent to CVAS for a re-check. The results are listed in Table 24. This time the NDF was 35.6% DM for chopped silage and 45.9% DM for flail-cut samples. Samples at each moisture level were harvested at about the same time and packed in the same day of harvest. The significantly
(p=0.005) large increase of NDF in flail-cut silage at 60% moisture might be attributable to sub-sampling errors with heterogeneous samples. Nonetheless, no significant difference in NDF was found between chopped and flail-cut samples for silage at 65% and 70% moisture.

Flail-cut samples had numerically more protein than chopped samples (not statistically significant). Except for the results in the second analysis of the 60% moisture samples, flail-cut samples showed higher crude protein, soluble protein and degradable protein than chopped samples (0.45 to 1.1% DM in difference). No significant differences were found in mineral nutrients between chopped and flail-cut samples. Flail-cut samples showed marginally lower net energies (NEL, NEM and NEG) than chopped samples for three moisture levels. For moisture contents of 65 and 70%, the differences between flail-cut and chopped silage for three net energies ranged from 0.002 to 0.007 Mcal/kg and for 60% moisture level, these differences were up to 0.4 Mcal/kg. All energy contents for both flail-cut and chopped samples were within the normal range for corn silage listed in NRC (2001) feed composition tables.
Table 24. Major nutrients of lab-scale silage analyzed by commercial laboratory*.

<table>
<thead>
<tr>
<th>Nutrients</th>
<th>Units</th>
<th>70%</th>
<th>65%</th>
<th>60%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Chop</td>
<td>Flail-cut</td>
<td>Chop</td>
</tr>
<tr>
<td>Dry Matter</td>
<td>%</td>
<td>26.7</td>
<td>27.6</td>
<td>29.2</td>
</tr>
<tr>
<td>Crude Protein (CP)</td>
<td>% DM</td>
<td>9.55</td>
<td>10</td>
<td>8.8</td>
</tr>
<tr>
<td>Soluble Protein</td>
<td>% DM</td>
<td>4.35</td>
<td>4.8</td>
<td>3.95</td>
</tr>
<tr>
<td></td>
<td>% CP</td>
<td>45.1</td>
<td>48</td>
<td>45.5</td>
</tr>
<tr>
<td>Degradable Protein</td>
<td>% DM</td>
<td>6.95</td>
<td>7.4</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>% CP</td>
<td>72.6</td>
<td>74</td>
<td>72.8</td>
</tr>
<tr>
<td>Total Digestible Nutrients</td>
<td>% DM</td>
<td>70.7</td>
<td>69</td>
<td>71.5</td>
</tr>
<tr>
<td>Net Energy for Lactation</td>
<td>Mcal/kg</td>
<td>1.63</td>
<td>1.54</td>
<td>1.67</td>
</tr>
<tr>
<td>Net Energy for Maintenance</td>
<td>Mcal/kg</td>
<td>1.65</td>
<td>1.54</td>
<td>1.67</td>
</tr>
<tr>
<td>Net Energy for Gain</td>
<td>Mcal/kg</td>
<td>1.06</td>
<td>1.10</td>
<td>1.06</td>
</tr>
<tr>
<td>Acid Detergent Fiber</td>
<td>% DM</td>
<td>24.6</td>
<td>27</td>
<td>23.3</td>
</tr>
<tr>
<td>Neutral Detergent Fiber</td>
<td>% DM</td>
<td>42.2</td>
<td>46</td>
<td>41</td>
</tr>
<tr>
<td>Non-Fiber Carbohydrate</td>
<td>% DM</td>
<td>40.3</td>
<td>36</td>
<td>42.6</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>3.75</td>
<td>3.95</td>
<td>3.9</td>
</tr>
</tbody>
</table>

* Cumberland Valley Analytical Service, Inc. Cumberland, MD
5.2.4 Brief Summary of Fall 2001 Experiments

- The novel forage harvester using shredding and flail cutter functioned well in the field with different crop moisture levels and machine throughputs.

- Average specific energy requirements for shredding varied significantly among different roll speed treatments at unit roll force of 15 N/mm (front and rear). Roll speed configurations C (R1=30%, R2=30%) and D (R1=30%, R2=60%) yielded significantly lower specific energy than roll speed configurations A (R1=15%, R2=30%) and B (R1=15%, R2=30%) did. However, at other unit roll forces, no significant effect of roll speed configuration was found.

- Average specific energy for shredding generally decreased with increasing moisture content and machine throughput. Average specific energy requirement for shredding ranged from 2.5 kW h/Mg DM to 3.4 kW h/Mg DM for shredding 62 and 67% moisture corn; from 3.5 to 5.9 kW h/Mg DM for 70% moisture, from 2.7 to 5.3 kW h/Mg DM for 65% moisture and 2.8 to 4.7 for 60% moisture.

- Peak specific energy for shredding decreased with increasing moisture content. Peak specific energy was 13.0 kW h/Mg DM when shredding 70% moisture corn, 13.5 kW h/Mg DM for 65% moisture, and 9 kW h/Mg DM for 60% moisture.

- Average power requirements ranged from 7 to 14 kW for all conditions tested. Maximum peak power requirement among the conditions tested was around 30 kW.

- The shredded particles ensiled well in lab-scale silos with pH values ranging from 3.8 to 4.1. Chemical analysis showed that nutrients were within the normal range documented for corn silage.
• There was no significant difference in silage density between 60 and 70% moisture level (both chopped and flail silage); samples obtained at moisture level 65% had significantly higher average density than those obtained at 60 and 70% moisture levels for both chopped and flail silage.

• The use of a flail cutter increased the amount of fines while producing plenty of large particles. Particle sizes were overall larger for the 70% moisture samples than those for 65 and 60% moisture samples.
5.3 DAFOSYM Simulation Results

5.3.1 Baseline Analysis

The power requirement of the novel harvester was adjusted according to experiment results and data from literature. ASAE standard (1999a) lists a specific energy consumption of 3.3 kW h/Mg DM for standard forage harvester while a higher value of 6.58 kW h/Mg DM was found by Roberge et al. (1998). A somewhat medium value of 4.5 kW h/Mg DM was assumed for standard forage harvester for comparison with the novel harvester. The energy requirement of the head for cutting and gathering material was assuming as 20% of the total power requirement of a standard harvester. The energy requirement for cutting/blowing was assumed as about a third of what for shredding. With an average specific energy of 3.0 kW h/Mg DM for shredding, the total energy consumption of the novel harvester could be obtained as 4.9 kW h/Mg DM. Therefore the PTO power requirement for the novel harvester was about 10% more than the assumed 4.5 kW h/Mg DM for a standard harvester. Table 25 shows the model parameter multiplicative adjustments for baseline analysis. In the sensitivity analysis, the PTO power requirement for the novel harvester was increased 30% over that for a standard harvester. Table 26 is the complete list of parameter multiplicative adjustments for sensitivity analysis. These adjustments were made based on values assumed for both chopped and processed silage by Rotz et al. (1999a and 1999b).
Table 25. Model parameter multiplicative adjustments for shredded silage in comparison to standard chopped and processed silage—baseline analysis for the novel harvester.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Chopped</th>
<th>Processed (longer TLC)</th>
<th>Shredded</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTO Power Requirements</td>
<td>1</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>Silage Initial Density</td>
<td>1</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>Digestibility of Stover</td>
<td>1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Fill for Large Particles</td>
<td>1</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>Roughage for Large Particles</td>
<td>1</td>
<td>1</td>
<td>1.05</td>
</tr>
<tr>
<td>Fraction of Large Particles</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 26. Model parameter multiplicative adjustments for sensitivity analysis for the novel harvester (bold numbers are changed comparing to baseline values).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PTO</th>
<th>Stover digestibility</th>
<th>FL</th>
<th>RL</th>
<th>Large particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>Greater power requirement</td>
<td><strong>1.3</strong></td>
<td>1.1</td>
<td>1.0</td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>More stover digestibility</td>
<td>1.1</td>
<td><strong>1.15</strong></td>
<td>1.0</td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>Less fill for large particles</td>
<td>1.1</td>
<td>1.1</td>
<td><strong>0.95</strong></td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>More fill for large particles</td>
<td>1.1</td>
<td>1.1</td>
<td><strong>1.05</strong></td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>Same roughage</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
<td><strong>1.0</strong></td>
<td>0.85</td>
</tr>
<tr>
<td>Higher machine price</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
<td>1.05</td>
<td>0.85</td>
</tr>
<tr>
<td>10% more large particles</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
<td>1.05</td>
<td><strong>0.95</strong></td>
</tr>
<tr>
<td>5% more large particles</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
<td>1.05</td>
<td><strong>0.90</strong></td>
</tr>
</tbody>
</table>

The novel harvester was compared with both a standard chopper and a chopper with kernel processing (Table 27) for both representative farms. For kernel processing, a longer TLC was set. Under the assumptions of this analysis, milk production increased 2.4% (212 l/cow) with the use of shredded silage compared to standard chopping and increased 0.4% (42 l/cow) comparing to kernel processing. Use of the novel harvester increased farm net
return $8610 ($86/cow/y) compared to the use of kernel processing and $9950 ($100/cow/y) compared to standard chopping. The large increases in net return with shredding came from both savings from the increase of milk production and the use bagged alfalfa silage. Analysis by Rotz (1996) on alternative silage methods showed that bagged silage method was the most economic silage system for a 100-cow farm. The machinery cost was lower (about $3000 less) in the shredding option than in the processing option; machine prices for the shredding harvester were assumed the same as those for the standard chopper while kernel processing required additional cost in equipment.

The increase in milk production and farm profit relative to processing had to do with the assumptions of roughage effect made for shredded silage. Stover digestibility of both processed silage and shredded silage was assumed to be 10% more digestible than chopped silage. Shredded silage was assumed to have the same fill in large particles compared to chopped silage—processed silage was assumed 5% less in fill factor; the roughage factor of large particles was assumed 5% higher in shredded silage than both chopped silage and processed silage. The 5% increase in the roughage factor increased in milk production, even with the fill factor unchanged.

The relative effects of the novel harvester on farm performance and economics were similar between the two farms. When corn silage was harvested by the novel harvester on the 250-cow farm, shredding gave the same trend of higher milk production and net profit relative to kernel processing and standard chopping (Table 28). Shredding provided an increase in milk production of about 2.6% over standard chopping and 0.1% over processing on the 250-cow farm. Use of shredding resulted in $74/cow/y improvement in farm profit over the use of the standard chopper and $27/cow over the use of a chopper with kernel
processing. Though the trend of benefit of shredding is similar between the two farms but the benefit of is more pronounced on the smaller farm.

At fixed milk production (8700 L/cow or 19794 lb/cow), the use of the shredding harvester outperformed the standard chopper by $10 per animal ($63,680 for shredding and $62,680 for kernel processing) and was $49 per animal more profitable than standard chopping (Table 29). The savings in machinery (compared to kernel processing) and purchased feed and bedding (compared to standard chopping) contributed to the profitability of the shredding technology when milk production was fixed.

Table 27. Effect of corn silage shredding on annual feed production, feed use, costs, and net return of a 100-cow dairy farm in central Pennsylvania.

<table>
<thead>
<tr>
<th>Units</th>
<th>Chop</th>
<th>Process</th>
<th>Shred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn silage production t DM</td>
<td>222</td>
<td>224</td>
<td>217</td>
</tr>
<tr>
<td>Forage purchased t DM</td>
<td>101</td>
<td>112</td>
<td>81</td>
</tr>
<tr>
<td>Average milk production L/cow</td>
<td>8,947</td>
<td>9,117</td>
<td>9,159</td>
</tr>
<tr>
<td>Income from milk sales $</td>
<td>284,980</td>
<td>290,400</td>
<td>291,730</td>
</tr>
<tr>
<td>Machinery cost $</td>
<td>44,600</td>
<td>47,680</td>
<td>44,700</td>
</tr>
<tr>
<td>Purchased feed/bedding cost $</td>
<td>36,110</td>
<td>37,480</td>
<td>34,630</td>
</tr>
<tr>
<td>Net return to management $</td>
<td>64,670</td>
<td>66,010</td>
<td>74,620</td>
</tr>
</tbody>
</table>

Table 28. Effect of corn silage shredding on annual feed production, feed use, costs, and net return of a 250-cow dairy farm in central Pennsylvania.

<table>
<thead>
<tr>
<th>Units</th>
<th>Chop</th>
<th>Process</th>
<th>Shred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn silage production t DM</td>
<td>679</td>
<td>685</td>
<td>665</td>
</tr>
<tr>
<td>Forage purchased t DM</td>
<td>1,052</td>
<td>1,062</td>
<td>1,047</td>
</tr>
<tr>
<td>Average milk production L/cow</td>
<td>9,026</td>
<td>9,253</td>
<td>9,262</td>
</tr>
<tr>
<td>Income from milk sales $</td>
<td>665,660</td>
<td>682,410</td>
<td>683,100</td>
</tr>
<tr>
<td>Machinery cost $</td>
<td>67,410</td>
<td>70,550</td>
<td>67,360</td>
</tr>
<tr>
<td>Purchased feed/bedding cost $</td>
<td>205,300</td>
<td>207,280</td>
<td>206,910</td>
</tr>
<tr>
<td>Net return to management $</td>
<td>121,200</td>
<td>133,010</td>
<td>139,770</td>
</tr>
</tbody>
</table>
Table 29. Effect of corn silage shredding on annual feed production, feed use, costs, and net return of a 100-cow dairy farm in central Pennsylvania. Comparisons are made with the same milk production (8700 L/cow).

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>Standard</th>
<th>Process</th>
<th>Shred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn silage production</td>
<td>t DM</td>
<td>222</td>
<td>224</td>
<td>217</td>
</tr>
<tr>
<td>Forage purchased</td>
<td>t DM</td>
<td>102</td>
<td>76</td>
<td>84</td>
</tr>
<tr>
<td>Machinery cost</td>
<td>$</td>
<td>44,570</td>
<td>47,150</td>
<td>44,640</td>
</tr>
<tr>
<td>Purchased feed and bedding cost</td>
<td>$</td>
<td>35,310</td>
<td>31,350</td>
<td>32,920</td>
</tr>
<tr>
<td>Average Milk Production</td>
<td>l/cow</td>
<td>8,700</td>
<td>8,700</td>
<td>8,700</td>
</tr>
<tr>
<td>Net return to management</td>
<td>$</td>
<td>58,780</td>
<td>62,680</td>
<td>63,680</td>
</tr>
</tbody>
</table>

5.3.2 Sensitivity Analysis

Table 27 lists the responses in milk production and net farm return of the 100-cow farm when changing one of the major assumptions for the novel harvester. Table 31 lists the results of the sensitivity analysis on the 250-cow farm.

For the 100-cow farm, an increase in PTO power requirement (+20%) and machine initial cost (+20%) did not change milk production but affected farm profitability. The 20% increase in machine power requirement reduced net farm return by about $200/y—$2/cow/y. The 20% increase in machine initial cost brought down the net farm return by $460/y—$4.6/cow/y. The results were moderately sensitive to the assumption on machine initial cost but fairly insensitive to machine power requirement.

The simulation results were very sensitive to changes in stover digestibility, fill and roughage factor of large particle size and the amount of large particles in stover. When stover digestibility was increased by 5%, milk production increased 0.2% (18 l/cow) and net farm return increased about $7 per animal. The 5% decrease in the fill of large particles brought milk production up by 1.3% (125 l/cow) and net annual farm profit increased by
about 3% ($22/cow). On the other hand, the 5% increase in the fill of large particles reduced milk production and farm profit, milk production was down 1.5% (134 l/cow) and farm profit down by about $25 per animal. When the roughage factor of the large particles was changed back to the standard value, milk production was reduced by 1.7% (153 l/cow). The annual farm net return was therefore reduced by $36/cow. Increasing the amount of large particles in stover had negative effect on milk production and farm profit. When the amount of large particles in stover was increased by 10% to 95%, milk production reduced by 96l/cow and farm profit by about $11 per animal. However, all scenarios in the sensitivity analysis produced much higher annual profit than kernel processing (>50/cow/y) on the 100-cow farm (see Table 27 and 30).

Similar sensitivities were observed in changes in milk production and farm profit on the 250-cow farm. However, not all scenarios were profitable compared to the use of kernel processing on the 250-cow farm. Reducing the roughage factor of large particles and increasing the fill factor of large particles resulted in lower profitability than the use of kernel processing.

The simulation results showed that when higher roughage effect of large particles was assumed for the flail-cut silage, the novel harvester would be more profitable than a standard chopper with kernel processor even though the milk production might not be always higher. In all situations evaluated, flail-cut silage improved milk production and farm profitability compared to the standard chopper. Whether we have achieved such a feed yet with the harvester is unclear, but the shredding harvester does generate a feed fitting this general description of higher roughage yet as or more digestible.
Table 30. Milk Production and net return by changing major input parameters for the 100-cow farm when using the novel forage harvester.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Milk Production l/cow</th>
<th>Net Return $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>9,159</td>
<td>74,620</td>
</tr>
<tr>
<td>20% more PTO Power</td>
<td>9,159</td>
<td>74,410</td>
</tr>
<tr>
<td>5% more stover digestibility</td>
<td>9,177</td>
<td>75,311</td>
</tr>
<tr>
<td>5% less fill for large particles</td>
<td>9,284</td>
<td>76,880</td>
</tr>
<tr>
<td>5% more fill for large particles</td>
<td>9,025</td>
<td>72,110</td>
</tr>
<tr>
<td>Same roughage for large particles</td>
<td>9,006</td>
<td>70,980</td>
</tr>
<tr>
<td>20% higher machine price</td>
<td>9,159</td>
<td>74,160</td>
</tr>
<tr>
<td>10% more large particles</td>
<td>9,063</td>
<td>73,470</td>
</tr>
<tr>
<td>5% more large particles</td>
<td>9,114</td>
<td>74,130</td>
</tr>
</tbody>
</table>

Table 31. Milk Production and net return by changing major input parameters for the 250-cow farm when using the novel forage harvester.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Milk Production l/cow</th>
<th>Net Return $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>9,262</td>
<td>139,710</td>
</tr>
<tr>
<td>20% more PTO Power</td>
<td>9,262</td>
<td>139,450</td>
</tr>
<tr>
<td>5% more stover digestibility</td>
<td>9,290</td>
<td>142,233</td>
</tr>
<tr>
<td>5% less fill for large particles</td>
<td>9,444</td>
<td>148,160</td>
</tr>
<tr>
<td>5% more fill for large particles</td>
<td>9,089</td>
<td>131,700</td>
</tr>
<tr>
<td>Same roughage for large particles</td>
<td>9,073</td>
<td>129,760</td>
</tr>
<tr>
<td>20% higher machine price</td>
<td>9,262</td>
<td>139,280</td>
</tr>
<tr>
<td>10% more large particles</td>
<td>9,203</td>
<td>134,030</td>
</tr>
<tr>
<td>5% more large particles</td>
<td>9,119</td>
<td>137,560</td>
</tr>
</tbody>
</table>
5.3.3 Brief Summary of Evaluation by Simulation

- When shredded corn silage was fed to high producing Holstein cows, simulation analyses showed that the treatment provided up to 2.6% increase in milk production over standard chopping and slight increase (<0.4%) in milk production over processing on the two representative farms.

- Shredding provided an improvement in the net return of about $100/cow/y over standard chopping and $86/cow/y over kernel processing on the smaller farm.

- Annual profit increased by $74/cow and $27/cow compared to the use of standard chopping and kernel processing, respectively on the larger farms.

- Both the increase in milk production and the use of bagged alfalfa silage contributed to the improvements in farm profitability of the shredding technology.

- Simulation results were moderately sensitive to the assumption on silage density but fairly insensitive to machine power requirement.

- Simulation results were very sensitive to the assumptions on the fill and roughage factors for the large particles and the stover digestibility.

- From DAFOSYM analyses, all scenarios evaluated showed economic benefit with the use of the novel harvester compared to standard chopping on both representative farms. All scenarios evaluated were at least $50/cow/y more profitable than the use of kernel processing.

- A feed with higher stover digestibility, lower fill effect, and higher roughage effect would generally improve farm profitability. The shredding harvester generates a feed fitting this general description.
Chapter 6: Conclusions

The conclusions of this research were:

1. The novel forage harvester using shredding worked successfully in the field under various crop and machine conditions.

2. Average specific energy requirements for shredding varied significantly among different roll speed treatments at unit roll force of 15 N/mm (front and rear). Roll speed configurations C (R1=30%, R2=30%) and D (R1=30%, R2=60%) yielded significantly lower specific energy than roll speed configurations A (R1=15%, R2=30%) and B (R1=15%, R2=30%) did. However, at other unit roll forces, no significant effect of roll speed configuration was found.

3. Average specific energy was not affected significantly by different minimum roll clearance settings for the unit roll forces tested.

4. Minimum roll clearances of 10 mm (front) and 1 mm (rear), along with unit roll forces of 15 N/mm (front) and 45 N/mm (rear) produced more processed material than minimum roll clearances of 10 mm (front), 2 mm (rear) and unit roll forces of 15 N/mm (front and rear) or unit roll forces of 30 N/mm (front and rear).

5. Total specific energy requirement for shredding ranged between 2.5 kW h/Mg DM and 6.6 kW h/Mg DM for the conditions tested during two harvesting seasons. Average specific energy decreased with a decrease in corn crop moisture content or an increase of machine throughput. Average power requirements ranged from 7 to 14 kW while peak power requirement was less than 30 kW.
6. Flail-cut silage at 65% moisture had higher densities than flail-cut silage at the 70 and 60% moistures. The shredded particles ensiled well in lab-scale silos with pH values ranging from 3.8 to 4.1.

7. Shredding alone (without flail cutting) produced less fine particles and more large particles compared to chopping. Compared to chopped samples, flail-cut samples had more fine particles and more large particles. Fine particles included grains, shredded cobs and leaves. The use of a flail cutter increased the amount of fines while still producing a large amount of large particles. Particle sizes were overall larger for the 70% moisture samples than those for 65 and 60% moisture samples.

8. Flail-cut silage at 65% moisture had higher densities than flail-cut silage at the 70 and 60% moistures.

9. From DAFOSYM analyses, all scenarios evaluated showed economic benefit with the use of the novel harvester compared to standard chopping on both representative farms. All scenarios evaluated were at least $50/cow/y more profitable than the use of kernel processing.

10. The simulation results were very sensitive to the increase of stover digestibility. The results were relatively insensitive to the assumptions on machine parameters, packed density in the silo, and fill and roughage factors. The novel harvester has great potential to produce a feed that leads to milk improvement on dairy farms due to the higher stover digestibility and roughage effect.
Chapter 7: Recommendations

Since the flail cutter/blower reduced particle sizes to desired ranges (Sword and Buckmaster, 2002), future work on the harvester should be done with the flail cutter/blower added on the machine. In this research the effects of moisture content, roll configurations, and machine throughput capacity on machine energy requirements for shredding were studied. The next step is to conduct similar experiments with flail cutter on to determine the total energy requirement for harvesting corn silage at various conditions.

All of the four roll speed configurations were studied for the effects on the densities (lab scale) of the shredded silage. But only two roll speed configurations (A: R1=15%, R2=30%, and C: R1=30%, R2=30%) were studied for the effects on the densities of flail-cut silage. Studies on particle size distribution of flail-cut silage were limited to one roll speed configuration (A: R1=15%, R2=30%) in current research. Effects of roll speed configuration on silage density and particle size distribution should be studied for all four configurations with the flail cutter activated. Density studies using lab scale silos can provide useful guidelines, but experiments on a larger scale may be conducted with selected conditions using the information gained from lab scale studies.

The chemical analysis of sample silage showed questionable results in this research making it impossible to find the effects of shredding the quality of silage. In future experiments, chemical analysis of silage should be done before and after storage to help obtain a more accurate account of the changes in storage. Sampling errors should also be minimized during the chemical analysis.

Future investigation should also include full-scale lactation and digestion trials on dairy animals. The first trials were already done by Sword and Buckmaster (2002) on dairy
heifers on the responses of voluntary intake and sorting. More work may be done on changes in milk production and milk composition with lactating animals.

Finally, a machine with mechanical belt drive is desired for mass production. The power requirement for such a machine is around 100 kW with 35 kW required for the shredding rolls, 15 kW for the head, 20 kW for locomotion and 30 kW for flail cutting. Design with larger shredding rolls may allow more throughput. Rolls with 200 mm (8 in.) or 254 mm (10 in.) diameters could be used with existing bearing support designs. Shredding chamber could be widened beyond the 460 mm used in this prototype to increase machine throughput. The recommended minimum roll clearance ranges are 10 to 15 mm for the front rolls and 1 to 5 mm for the rear rolls. The larger minimum roll clearance on the rear rolls is meant mainly for unplugging jammed material. A reliable reversing mechanism on the rolls is desired. The speed ranges for the rolls should between 1500 and 2100 rpm for the rear rolls and between 1200 and 1600 rpm for the front rolls with 15 to 30% speed ratios within each pair of rolls and 30% speed ratio between the pairs.
Bibliography


(h) Proc. of the Seminar on “Maize as basic feed for beef production”. FAL, Braunschweig, Germany. pp.32-41.


Appendix A—Validation of Laboratory Scale Silage Packer

Harvested corn was packed in a lab-scale packer (Figure 36). The packer was developed previously (Hoover, 1998) to simulate compaction in a bunker silo due to driving over the silage pack. The unit was equipped with a 5.08 cm diameter bore, 45.7 cm stroke hydraulic cylinder to compact the silage. The cylinder extension/retract cycle was electronically controlled by a Campbell 21X datalogger. The packing tube was 28.6 cm in diameter and 43 cm tall.

The tube was lined with a plastic bag into which the silage was packed. The plastic bag was used to seal the silage sample for ensiling after the compaction process was completed. Compaction measuring procedures were adapted from those used by Hoover (1998). A certain sample size from each replicate was used for the test. One quarter of the sample, by wet weight, was placed into the compaction tube. The hydraulic cylinder then started its compaction cycle that consisted of applying pressure to the silage for a set amount of time three times with a 3.33 s rest periods between the pressure applications. Once the cycle was complete, the next quarter of the sample was placed in the compaction tube on top of the previously compacted silage and compacted. This cycle was repeated four times until the total sample was compacted. Then the bag was vacuumed using a shop vacuum and tied with wire tie while still in the packer tube. This bag was then removed from the packer and placed in another bag upside down. Again the second bag was vacuumed and sealed with wire tie.
Figure 36. Front view of assembled compactor unit (from Hoover, 1998).
In an effort to validate that the compaction unit simulate the packing in a bunker silo, packing time was varied from 20 to 90 s. The pressure on silage was chosen to match tractor tire data and typical total tractor weights used in bunker silo packing at The Pennsylvania State University. In this case, it was found that typical tire pressure (a tractor weighing 10170 kg used at the Pennsylvania State Farm Operations) on silage was 69 kPa. This pressure and higher pressures (186 kPa and 310 kPa) were tested with different packing time on each layer of silage. After the completion of packing, the height of the silage in the tube was measured and packed density was derived.

Chopped corn silage was brought to the lab and processed by an Automatic Roller Mill. The Automatic Roller Mill had a pair of grooved rolls with adjustable roll clearance. The rolls have the same diameter of 229 mm. The speeds of the rolls were 780 rpm and 1300 rpm, respectively. Roll clearance was set at a minimum 0.38 mm. After processing through this roller mill, silage was packed in the compactor according to the procedure described earlier.

Figure 37 is a summary of data showing the relationship of packed density vs. packing pressure and pressing time (moisture level 67% wet basis). Dry matter densities were between 176 kg/m$^3$ and 270 kg/m$^3$. Results from these preliminary tests showed that packing pressure had a much greater effect ($p<0.001$, t test) on compaction than packing time ($p>0.5$). Therefore, in later tests, shorter packing time was used to save time. (what statistical analysis)
As a pilot test to the shredder, whole plant corn was also brought to the lab and put through the roller mill at minimum roll clearance (0.38 mm). Corn ears were mashed into small pieces and stalks were crushed. However, stalks and leaves were not reduced into short pieces. Overall, particle sizes were very long. The particle sizes were not significantly reduced even after running the processed material through the roller mill four times. The explanation for this was that there was basically only maceration and no tearing on the material. As a result, whole plant corn was manually cut into 30 cm (one foot) long pieces and run through the roller mill again.

After processing four times through the roller mill, the material was compacted in the lab compactor and ensiled in mini silos, using the same procedure as chopped material. The packing pressure was 188 kPa and each layer of silage was pressed 20 s. Packing densities were near 170 kg DM/m$^3$. While this density value is still acceptable in real world, it is
much lower than those obtained with chopped material. This was because only 9 kg of silage, instead of 10.5 kg could be pressed in the compactor tube.

During these preliminary lab tests, it was noticed that rolls had to be spinning before material was fed into the rolls. Otherwise, material would jam between rolls. Roll clearance greater than the minimum could also result in material jam.
Appendix B—Data logger Programs

Laboratory Scale Packer Program

: {CR10}
: Program: PACK2000 by DRB @ PSU A&BE
: Modified somewhat in 10/00
: For controlling the bunker packer simulator device
: Flag Usage:
: Input Channel Usage:
: 1: for cap end pressure measurement
: Excitation Channel Usage:
: 1: for pressure transducer on cap end of cylinder
: Control Port Usage:
: 1: MAIN "START & KEEP GOING" SWITCH -- an input
: 8: MAIN SOL SWITCH -- an output -- C2 is bad on the CR10
: 3: SOL FOR REGENERATION (keep off for now) -- an output
: Pulse Input Channel Usage: none
: Input Locations
: 1 ON_COUNTR 0 0 0
: 2 OFF_COUNT 0 0 0
: 3 CYCLES 0 0 0
: 4 Press_bottom 0 0 0
: 5 OUTPUT_FR 0 0 0
: 6 LOOPCNT 0 0 0
: 7 SMPL_CODE 0 0 0
:
: Program notes & usage:
: target A is "ON TIME"
: target B is "OFF TIME"
: target C is # of repeats in packing cycle

*Table 1 Program
  01: .0625 Execution Interval (seconds)

1: If Flag/Port (P91); IF MAIN GO SWITCH IS ON
1: 41   Do if Port 1 is High; THEN CONSIDER LOTS OF STUFF
2: 30   Then Do

2: Full Bridge (P6)
  1: 1   Reps
  2: 12  7.5 mV Fast Range
  3: 1   DIFF Channel
  4: 1   Excite all reps w/Exchan 1
  5: 1000 mV Excitation
6: 4  Loc [ Press_psi ]
7: 1000  Mult
8: 0.0  Offset

3:  If (X<=F) (P89); IF PRESSURE
1: 4  X Loc [ Press_psi ]; IS HIGH (>650 psi) -- max exerted is 780
2: 3  >=
3: 400  F
4: 30  Then Do; THEN

4:  Z=X+F (P34); INCREMENT ON COUNTER
1: 1  X Loc [ ON_COUNTR ]
2: .0625  F
3: 1  Z Loc [ ON_COUNTR ]

5:  End (P95); END (IF PRESSURE HIGH)

6:  If Flag/Port (P91); IF (MAIN SOL IS OFF)
1: 58  Do if Port 8 is Low
2: 30  Then Do

7:  Z=X+F (P34); INCREMENT OFF COUNTER
1: 2  X Loc [ OFF_COUNT ]
2: .0625  F
3: 2  Z Loc [ OFF_COUNT ]

8:  End (P95); END (IF MAIN SOL IS OFF)

9:  If Flag/Port (P91); IF (MAIN SOL IS ON)
1: 48  Do if Port 8 is High; set output flag high
2: 10  Set Output Flag High

10:  If (X<=F) (P89); IF (ON COUNTER > target A)
1: 1  X Loc [ ON_COUNTR ]
2: 3  >=
3: 3.333  F; target A value goes here
4: 30  Then Do; THEN

11:  Do (P86); TURN MAIN SOL OFF
1: 58  Set Port 8 Low

12:  Z=F (P30); RESET ON COUNTER
1: 0  F
2: 0  Exponent of 10
3: 1  Z Loc [ ON_COUNTR ]
13: End (P95); END (IF ON COUNTER > targetA)

14: If (X<=F) (P89); IF (OFF COUNTER > target B)
1: 2 X Loc [ OFF_COUNT ]
2: 3 >=
3: 3 F; target B value goes here
4: 30 Then Do; THEN

15: If (X<=F) (P89)
1: 3 X Loc [ CYCLES ]
2: 4 <
3: 3 F; target C value goes here
4: 30 Then Do

16: Do (P86)
1: 48 Set Port 8 High ; TURN MAIN SOL ON

17: Z=Z+1 (P32)
1: 3 Z Loc [ CYCLES ]

18: End (P95); END (# CYCLES < TARGET C)

19: Z=F (P30); RESET OFF COUNTER
1: 0 F
2: 00 Exponent of 10
3: 2 Z Loc [ OFF_COUNT ]

20: End (P95); END (IF OFF COUNT > targetB)

21: Z=F (P30); SET OUTPUT FREQUENCY
1: 1 F; (# of loops)
2: 0 Exponent of 10
3: 5 Z Loc [ OUTPUT_FR ]

22: Z=Z+1 (P32); INCREMENT LOOP COUNT
1: 6 Z Loc [ LOOP_CNT ]

23: If (X<=Y) (P88); IF LOOP COUNT = OUTPUT FREQ
1: 6 X Loc [ LOOP_CNT ]
2: 3 >=
3: 5 Y Loc [ OUTPUT_FR ]
4: 30 Then Do; THEN

24: Real Time (P77); SAVE TIME
1: 211 (Same as 221) D,Hr/Mn,Sec
25:  Average (P71); SAVE AVERAGE PRESSURE
    1:  1    Reps
    2:  4    Loc [ Press_psi ]

26:  Sample (P70)
    1:  1    Reps
    2:  7    Loc [ SMPL_CODE ]

27:  Z=F (P30); RESET LOOP COUNTER
    1:  0    F
    2:  0    Exponent of 10
    3:  6    Z Loc [ LOOP_CNT ]

28:  End (P95); END (IF LOOP COUNT > OUTPUT FREQ)

29:  Else (P94); ELSE (HEY, THE MAIN SWITCH IS OFF)

30:  Z=F (P30); RESET CYCLE COUNTER
    1:  0    F
    2:  0    Exponent of 10
    3:  3    Z Loc [ CYCLES ]

31:  Z=F (P30); RESET LOOP COUNTER
    1:  0    F
    2:  0    Exponent of 10
    3:  6    Z Loc [ LOOP_CNT ]

32:  End (P95); END (IF MAIN SWITCH IS ON ELSE IT'S OFF BLOCK)

*Table 2 Program
   02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
  1 ON_COUNTR 0 0 0
  2 OFF_COUNT 0 0 0
  3 CYCLES 0 0 0
  4 Press_psi 1 0 0
  5 OUTPUT_FR 0 0 0
  6 LOOP_CNT 0 0 0
  7 SMPL_CODE 0 0 0
Shredder Data Collection Program

;{CR23X}
.Flag Usage:
.Input Channel Usage:
; 1 Pressure transducer A1 right before lower front motor A1
; 2 Pressure transducer A2 between two front motors A1 and A2
; 3 Pressure transducer AR after upper front motor A2-return line
; 4 Pressure transducer B1 right before lower rear motor B1
; 5 Pressure transducer B2 between two rear motors B1 and B2
; 6 Pressure transducer BR after upper rear motor B2--return line
; 8 switch on
.Pulse Input Channel Usage:
; 1 speed sensor for motor A1
; 2 speed sensor for motor A2
; 3 Speed sensor for motor B1
; 4 Speed sensor for motor B2
;
.Input location labels:
;1 psi_A1    1 1 1
;2 psi_A2    1 1 2
;3 psi_AR    1 1 1
;4 psi_B1    1 1 1
;5 psi_B2    1 1 1
;6 psi_BR    1 1 1
;7 battV     1 1 1
;8 RPM1_1    5 1 1
;9 RPM1_2    9 1 1
;10 RPM1_3   9 1 1
;11 RPM1_4   17 1 1
;12 Switch_on 1 1 1
;13 psi_cutpr 1 0 0
;14 psi_cutre 1 0 0
;15 psi_c2   1 1 1
;16 psi_c1   1 1 1
;17 counter 1 2 3

*Table 1 Program
  01: .25000  Execution Interval (seconds)

;A1
1: Full Bridge (P6) ;
  1: 1  Reps
2: 11 10 mV, Fast Range ;3mV/V full scale * 5V excitation
3: 1  DIFF Channel
4: 1 Excite all reps w/Exchan 1
5: 3000 mV Excitation
6: 1 Loc [ psi_A1 ]
7: 1667 Mult;5000 psi sensor with 3 mV/V at full scale
8: 15 Offset

:A2
2: Ex-Del-Diff (P8)
1: 1 Reps
2: 12 50 mV, Fast Range
3: 2 DIFF Channel
4: 1 Excite all reps w/Exchan 1
5: 1 Delay (units 0.01 sec)
6: 5000 mV Excitation
7: 2 Loc [ psi_A2 ]
8: 60 Mult
9: -27 Offset

:AR
3: Ex-Del-Diff (P8)
1: 1 Reps
2: 12 50 mV, Fast Range
3: 3 DIFF Channel
4: 1 Excite all reps w/Exchan 1
5: 1 Delay (units 0.01 sec)
6: 5000 mV Excitation
7: 3 Loc [ psi_AR ]
8: 60 Mult
9: -6 Offset

:B1
4: Full Bridge (P6)
1: 1 Reps
2: 11 10 mV, Fast Range;3 mV/V full scale * 5 V excitation
3: 4 DIFF Channel
4: 1 Excite all reps w/Exchan 1
5: 3000 mV Excitation
6: 4 Loc [ psi_B1 ]
7: 1667 Mult;5000 psi sensor with 3 mV/V full scale
8: 14 Offset

:B2
5: Ex-Del-Diff (P8)
1: 1 Reps
2: 12 50 mV, Fast Range
3: 5 DIFF Channel
4: 2 Excite all reps w/Exchan 2
5: 1 Delay (units 0.01 sec)
6: 5000 mV Excitation
7: 5 Loc [ psi_B2 ]
8: 60 Mult
9: 5 Offset

;BR
6: Ex-Del-Diff (P8)
1: 1 Reps
2: 12 50 mV, Fast Range
3: 6 DIFF Channel
4: 2 Excite all reps w/Exchan 2
5: 1 Delay (units 0.01 sec)
6: 5000 mV Excitation
7: 6 Loc [ psi_BR ]
8: 60 Mult
9: -17 Offset

;C1
7: Ex-Del-Diff (P8)
1: 1 Reps
2: 12 50 mV, Fast Range
3: 7 DIFF Channel
4: 2 Excite all reps w/Exchan 2
5: 1 Delay (units 0.01 sec)
6: 5000 mV Excitation
7: 16 Loc [ psi_c1 ]
8: 100 Mult
9: -5 Offset

;C2
8: Full Bridge (P6)
1: 1 Reps
2: 11 10 mV, Fast Range
3: 9 DIFF Channel
4: 2 Excite all reps w/Exchan 2 ;
5: 3000 mV Excitation
6: 15 Loc [ psi_c2 ]
7: 1000 Mult
8: -11 Offset

*Table 2 Program
  02: 2 Execution Interval (seconds)

1: Batt Voltage (P10)
1: 7  Loc [ battV  ]

2:  Do (P86)
   1: 41  Set Port 1 High ;Power to the switch

3:  Pulse (P3) ; READ SPEEDS ON 4 SHAFTS w/ output in RPM
   1: 4    Reps
   2: 1    Pulse Input Channel
   3: 20   High Frequency, Output Hz
   4: 8    Loc [ RPM1_1  ]
   5: 60   Mult
   6: 0.0  Offset

4:  Z=Z+1 (P32)
   1: 17   Z Loc [ counter  ]

5:  If Flag/Port (P91)
   1: 52   Do if Port 2 is Low
   2: 30   Then Do

   6:  If (X<=F) (P89)
      1: 17   X Loc [ counter  ]
      2: 1    =
      3: 2    F
      4: 30   Then Do

       7:  Set Port(s) (P20)
           1: 0000  C8,C7,C6,C5 Options
           2: 0029  C4..C1 = low/low/toggle/nc

       8:  Z=F (P30)
           1: 0    F
           2: 0    Exponent of 10
           3: 17   Z Loc [ counter  ]

5:  End (P95)

10:  Else (P94)

   11:  If (X<=F) (P89)
      1: 17   X Loc [ counter  ]
      2: 1    =
      3: 3    F
      4: 30   Then Do

       12:  Set Port(s) (P20)
1: 0000 C8,C7,C6,C5 Options
2: 0029 C4..C1 = low/low/toggle/nc

13: Z=F (P30)
1: 0 F
2: 0 Exponent of 10
3: 17 Z Loc [ counter ]

14: End (P95)

15: End (P95)

16: Volt (Diff) (P2) ; CHECK FOR "save data" SWITCH ON?
1: 1 Reps
2: 15 5000 mV Fast Range
3: 8 DIFF Channel
4: 12 Loc [ Switch_on ]
5: 1.0 Mult
6: 0.0 Offset

17: If (X<=>F) (P89) ; SWITCH IS ON, so save data
1: 12 X Loc [ Switch_on ]
2: 03 >=
3: 3500 F
4: 10 Set Output Flag High

18: Real Time (P77) ; read time with seconds
1: 0111 Day,Hour/Minute,Seconds (midnight = 0000)

19: Sample (P70) ; report battery voltage for debugging purposes
1: 1 Reps
2: 7 Loc [ battV ]

20: Average (P71) ; 6 averages of pressure
1: 6 Reps
2: 1 Loc [ psi_A1 ]

21: Average (P71)
1: 2 Reps
2: 15 Loc [ psi_c2 ]

22: Sample (P70) ;4 samples of shaft speeds
1: 4 Reps
2: 8 Loc [ RPM1_1 ]

*Table 3 Subroutines
End Program

-Input Locations-
1 psi_A1   1 1 1
2 psi_A2   1 1 2
3 psi_AR   1 1 1
4 psi_B1   1 1 1
5 psi_B2   1 1 1
6 psi_BR   1 1 1
7 battV    1 1 1
8 RPM1_1   5 1 1
9 RPM1_2   9 1 1
10 RPM1_3  9 1 1
11 RPM1_4  17 1 1
12 Switch_on 1 1 1
13 psi_cutpr 1 0 0
14 psi_cute 1 0 0
15 psi_c2   1 1 1
16 psi_c1   1 1 1
17 counter  1 2 3
Instrumentation and Wiring Specifications

The specifications of the proximity speed sensor are shown in Figure 38. Specifications of the Omega pressure transducer are listed in Table 32. Two different kinds of pressure transducers were used—four with lower range (PX602-3KGV) for pressures on the reservoir side and between two motors while two with higher range (PX300-5KGV) for motor pressure sides. Figure 39 illustrates the wiring schematic of the instrumentation.

![Figure 38. Specification of proximity speed sensor.](image)

Table 32. Specifications of the pressure transducers (Omega).

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Qty</th>
<th>Pressure Range</th>
<th>Sensitivity</th>
<th>Wiring</th>
</tr>
</thead>
</table>
| PX300-5KGV  | 2   | 0-5000 psig    | 3 mV/V      | Red— +Excitation
|             |     |                |             | Black— -Excitation
|             |     |                |             | Green— +Output
|             |     |                |             | White— -Output             |
| PX602-3KGV  | 4   | 0-3000 psig    | 10 mV/V     | Red— +Excitation
|             |     |                |             | Green— +Output
|             |     |                |             | Black— -Output
|             |     |                |             | White— -Excitation
Figure 39. Schematic of instrumentation on the shredder.
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**Publications:**
