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Final report - SRDC project BS188S - Improving the performance of chopper systems in cane harvesters

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FINAL REPORT - SRDC PROJECT BS188S
IMPROVING THE PERFORMANCE OF
CHOPPER SYSTEMS IN CANE HARVESTERS

by
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SD99019

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CONTENTS

SUMMARY

1.0 BACKGROUND ..........................................................1

2.0 OBJECTIVES ..........................................................4

3.0 METHODOLOGY .......................................................4

3.1 Materials .................................................................4

3.1.1 Chopper test rig ......................................................4

3.1.1.1 Feed conveyor ....................................................5

3.1.1.2 Feed train rollers ..............................................5

3.1.1.3 Chopper module ..............................................6

3.1.1.4 Power unit .......................................................7

3.1.1.5 Cleaning system ..............................................7

3.2 Instrumentation .......................................................8

3.2.1 Pressure sensors ..................................................8

3.2.2 Force sensors .......................................................8

3.2.3 Speed sensors .....................................................9

3.2.4 Feed roller displacement .....................................9

3.2.5 Blade position .....................................................9

3.2.6 High-speed cine photography ..............................10

3.2.7 Billet trajectory ..................................................10

3.3 Testing protocols ....................................................11

3.3.1 Cane variety ......................................................11

3.3.2 Determination of relevant varietal characteristics ....13

3.3.3 Feed train roller speed - Chopper drum speed relationship ......15

3.3.4 Pour rate ..........................................................16

3.3.5 Cane and juice loss ...........................................17

3.3.6 Billet quality .....................................................17

3.3.7 Billet length distribution .....................................18

3.3.8 Blade sharpness ................................................18

3.4 Tested chopper systems .........................................19

3.4.1 Austoft: 12-inch ..................................................20

3.4.2 Austoft: 15-inch, differential ..................................20

3.4.3 Austoft: 12-inch, differential ..................................20

3.4.4 Westhill Engineering: 15-inch, differential ...............20

3.4.5 Massey Ferguson: 12-inch ....................................21
4.0 RESULTS AND DISCUSSION ...............................................................21
  4.1 Cane characteristics ........................................................................21
  4.2 Chopper characteristics ....................................................................24
    4.2.1 Hydraulic power consumption .................................................25
    4.2.2 Cutting forces ........................................................................29
    4.2.3 Rotational speed ....................................................................34
    4.2.4 High speed cine photography ..................................................34
    4.2.5 Cane and juice losses ...............................................................35
      4.2.5.1 Variety and pour rate .......................................................36
      4.2.5.2 Feed train roller speed and pour rate ...............................39
      4.2.5.3 Blunt blades ..................................................................42
    4.2.6 Billet quality ............................................................................43
      4.2.6.1 Varietal effects ................................................................43
      4.2.6.2 Pour rate ........................................................................45
      4.2.6.3 Feed train roller speed .....................................................46
      4.2.6.4 Blunt blades ..................................................................48
    4.2.7 Billet length distribution ............................................................48
  4.3 Sample manufacturer’s report ...........................................................52

5.0 DIFFICULTIES ENCOUNTERED DURING PROJECT .......................56

6.0 RECOMMENDATIONS FOR FURTHER RESEARCH .......................56

7.0 APPLICATION OF RESULTS TO THE INDUSTRY ............................57

8.0 PUBLICATIONS ARISING ..................................................................57

9.0 REFERENCES ....................................................................................58

10.0 ACKNOWLEDGMENTS ....................................................................59

APPENDIX A Summary of trials conducted on each chopper system
APPENDIX B Guidelines for quantifying billet quality
APPENDIX C Summary of impact and shear pendulum tests in the node and internode region
SUMMARY

From the development of the rotary pinch chop in the 1950s and the virtual universal adoption of this concept by the industry in the early 1980s, improvements in the design of chopper systems nominally kept pace with industry needs. By the mid 1990s, the major increases in harvester installed engine power and subsequent increases in harvester processing rates highlighted the choppers as a significant ‘bottleneck’ in the machine throughput. A ‘flurry’ of development followed, including the development and adoption of 15-inch over the standard 12-inch chopper systems. However the performance of harvesters in the field indicated that there were many issues relating to the chopping process which were not well understood by both the machine designers and the industry. The issue of chopper performance achieved considerable prominence in 1996, with modifications to chopper design and replacement of choppers in new harvesters occurring in the field during the crushing season. The nominated problems of billet quality, billet length (and variability of length) were exacerbated by the wide range in billet lengths which were now accepted by different sugar mills, and requests by different operators for reduced/adjustable billet length as a machine option.

Cane and juice loss during billeting in the harvester were conservatively estimated to cost the Australian industry over $M30/year in direct losses, however from the losses measured in this work the cost is at least $M35/year at currently depressed sugar prices. The quality of the chopped billets also impacts on sugar quality. This project developed from the need by the industry to achieve a greater understanding of the processes involved in the billeting of cane, as a method to allow better designs to be developed.

This has been a cooperative project conducted with the active support of harvester and chopper manufacturers. The chopper test facility, which was developed for this project with SRDC and BSES internal funding, is a significant asset for the industry. Removable chopper test modules are mounted on a replica harvester feed train system, via a two dimensional load cell system. All hydraulic circuits are fully instrumented to allow monitoring of pressure and instantaneous speed on all relevant shafts. This system allows full quantification of the processes and resultant effects that occur during the billeting process. The use of very high-speed cine photography (2000 frames/sec) allows the processes, which occur during the cutting process to be visually recorded for subsequent analysis. These features of the test rig allow it to be used for a wide range of other studies and projects.

The test program undertaken with harvester and chopper system manufacturers, tested and evaluated the performance of five different commercial chopper systems (and one non-commercial system) under differing cane variety characteristics, at different processing (pour) rates and at different feed train roller speeds (billet length settings). The results of this test program have:
• Illustrated the magnitude of losses associated with the billeting process. In series 1, losses in chopper A were up to four percent at 240 t/hr pour rate and were similar to losses with other chopper systems. In series 2, chopper A measured five percent losses at 240 t/hr pour rate and were similar to losses with other chopper systems. This demonstrates that crop condition plays an important role in the magnitude of cane and juice losses.

• Demonstrated that manipulation of feed train speed to control billet length adversely impacts on billet quality and losses.

• Demonstrated the actual energy consumption during billeting is low compared to the peak loadings experienced by choppers in machines. Typical mean power consumption at 240 t/hr is in the order of 15 kW. The dramatic difference in average power consumption during testing and the installed power in harvesters is seen to relate to the magnitude of the ‘glut feed’ events that occur during harvesting.

• Quantified that the forces induced in the cane bundle are of very significant magnitude, resulting in cyclic acceleration and deceleration of the cane bundle and the feed train rollers.

• Shown billet quality to be extremely dependent on initial cane characteristics, pour rate and relative peripheral speed of the feed train rollers and the choppers.

• Illustrated that a 100 percent increase in feed train roller speed manifests into an average increase in mean billet length of approximately 33 percent.

The results of series 1 and series 2 indicate that cane and juice losses can be decreased and billet quality improved through Best Management techniques. This is achieved by harvesting less brittle varieties at lower pour rates, with matched peripheral speeds of the feed train rollers and choppers, and ensuring the blades of the chopper system are maintained in a sharp condition. Series 2 tests also highlight the importance of crop condition on the magnitude of losses and billet quality.

The results of this work confirm that significant losses occur in the billeting process and that machine design and operation can significantly impact on the magnitude of these losses. The results also strongly indicate that losses may be of greater magnitude than indicated in this testing program.

All the chopper systems tested recorded very similar performance characteristics. The greatest impact on chopper performance is not the design or size of chopper unit but operating parameters including crop condition, pour rate and the feed train roller peripheral speed and chopper peripheral speed relationship.

It is therefore recommended that further work be undertaken to determine the relationships between losses in the chopper test rig and similar chopper units in the field.
1.0 BACKGROUND

The concept of billeting cane and incorporating cutting and loading into one operation was developed as early as the Faulkner harvester in the 1920s. It was not until Massey Ferguson developed the low cost 515 chopper harvester in the 1950s that the advantages of this harvesting system were sufficiently tangible to be accepted by the industry in the 1960s.

To billet the cane, the 515 chopper harvester incorporated a system known as the rotary pinch chop. The system was conceptualised, designed and developed by engineering staff at Massey Ferguson, and appropriate patents protected the design. The success of the chopper harvester concept spawned the development of alternative concepts for billeting cane such as the ‘swing knife’, ‘chop-throw’ and alternative drum designs. Since the expiry of the patents on the rotary pinch chop in the early 1980s, it has been the preferred system throughout the world. There has, however, been considerable evolution and development in the concept, along with a degree of ‘recycling’ of concepts.

Despite a substantial increase in harvester throughput the physical size of the chopper systems, apart from a 50 percent increase in nominal width, remained constant (12 inch drum centres) until the mid 1990s. The dramatic increase in material processing rate was further exacerbated by the significant reduction in bulk density caused by harvesting of crops green rather than burnt before harvest.

Following major increases in installed harvester engine power in the mid 1990s, the chopper system was clearly a major constraint on machine performance. Both the harvester manufacturers and after market suppliers were seeking solutions, both for retro fitting to machines in the field and for fitting as standard equipment. The adoption of chopper systems with 15-inch drum centres by harvester manufacturers in 1996 was one approach to the problem. However the field performance of these units demonstrated they were not necessarily the solution to the problem in their current form, with the poor billet quality being produced by these machines becoming a major industry issue.

Billet quality and to a lesser extent losses during billeting are issues fundamental to the maximisation of sugar quality and sugar recovery. The move from wholestalk to billeted cane had not been without problems. Deterioration of the cane because of the number of cut surfaces was exacerbated by damage to the billets. Losses of juice and fibre were also an issue.

The first documented evaluations of losses associated with chopper harvesting appear to be by Moller (1975) who measured losses by feeding topped and stripped cane into a stationary MF102 harvester. The chopper losses (juice and fine material) from this work were estimated to be in the order of four percent. Pour rates are not known, but by virtue of the experimental method used would probably have been very low and relatively uneven.
Further work (Fuelling and Henkel, 1978) examined the relationship in the field between tonnage cut, chopper blade condition and billet quality on three machines, a Toft 6000 (swing knife), MF 205 (MF rotary pinch chop) and Claas 1400 (Claas rotary pinch chop). Key findings were:

- The MF 205 ‘self sharpening’ blades, typically gave 80 percent sound billets with minimal deterioration in billet quality until badly worn (70 percent sound billets @ 4000 tonnes).
- The Class design initially gave similar billet quality results with new blades, falling to 70 percent sound billets after 1000 tonnes and 40 percent sound billets at wear-out (1500 tonnes).
- Billet quality from the swinging knife system was never competitive (70 percent max sound billets) and deteriorated rapidly as the blades dulled 40% at knife replacement at 200 tonnes.

The trials also demonstrated billet quality in lodged cane was typically 10 percent lower than billet quality in standing cane.

Further work by Fuelling (1980) attempted to quantify chopper losses as part of a major field trial program. In these trials, weighed bundles of 100 stalks were laid on the ground and driven over by the harvester as the most practical method to achieve controlled feed into the harvester at ‘realistic’ pour rates with limited facilities. A mass balance analysis was conducted to determine the magnitude of chopper losses. The results were inconsistent, but nominally in the order of two and a half percent.

Ridge (pers comms) undertook a series of trials in 1982 in conjunction with Versatile-Toft, during the development of the pinch chop system to be used in the 7000. The trials were undertaken by feeding the stationary harvester with pre-weighed, stripped and topped cane via a 12 m long conveyor. A pour rate of 60 t/hr of stripped green cane was selected. Trial results indicated losses to be in the order of three percent with a nominal billet length of 250 mm. No attempt was made to adjust billet length from the standard setting and the probable losses at differing billet lengths was calculated on the basis of the loss/cut and the number of cuts per metre of cane. A limited trial was also conducted with blunt blades fitted to the choppers, indicating an increase in losses of approximately 50 percent.

Although the rotary pinch chop has been in universal use from the early 1980s, there has been considerable evolution and development in the concept, along with a degree of ‘recycling’ of concepts. The original rotary chop was developed as an over centre chop concept where either interacting blades or blade anvil arrangements completed their engagement as they aligned between the centreline of the choppers. An alternative approach was the hoe chop where the chopper blades complete the cut well before they align between the centreline of the choppers. This design essentially superseded the over centre chop as it offered lower power consumption, lower cut losses, lower juice losses and lower billet damage. The concept had been taken to the extreme in the design of the Massey Ferguson 405 prototype in the early 1980s with high-speed cine and advanced logging techniques being used to optimise the design.
With the exhaustion of Massey Ferguson patents on the pinch chop concept, Versatile-Toft adopted this system in their 7000/7700 series harvesters. This design was based on designs developed by Massey Ferguson during the evolution from the original 515 to the 305 harvester, and was similar to their hoe chop design (12 inch nominal drum centres). This then remained the ‘industry standard design’, used by both Austoft and Cameco over the next 15 years despite significant increases in machine throughput over this period.

Perceived problems with this design led to the development of alternative designs by third party harvester component suppliers such as ‘Greaves Enterprises’, ‘Westhill Engineering’ and ‘Trail Brothers’, with a range of other alternative designs being developed by innovative farmers. Although many of these designs ‘re-invented the wheel’ the level of activity indicated a high level of dissatisfaction with the standard design. One after market conversion which reinvented the over centre chop concept, was introduced by a third party supplier in 1995. Despite the ‘reversion’ to the over centre chop concept, there was a higher level of attention to detail relating to the design of blade clamps and the fitting of rubber rather than steel thrower bars. This meant the system offered a dramatic reduction in chopper operating pressure and reduced susceptibility to overload, effectively giving a significant increase in machine capacity over the standard choppers. Whilst extremely low levels of billet damage were recorded with this arrangement in limited field trials, a fundamental analysis would indicate that billet quality would be more sensitive to the relationship between feed roller peripheral speed and chopper blade peripheral speed than hoe chop or other chopper designs. This feed roller/chopper relationship is adjusted to manipulate billet length.

After limited field trials in 1995, both harvester manufacturers introduced choppers of new design and of larger diameter into their machines in 1996. Whilst both designs appeared to reduce power consumption at high pour rates (greater ability to process glut-feed events), effectively increasing machine capacity, both manufacturers encountered billet quality as a major problem with their 1996 model machines. Data from Tully Mill, coupled with data from random assessments by BSES officers during the early stages of the crushing season, demonstrated very high levels of ‘damaged and mutilated billets’, particularly in 1996 model harvesters. This continued to drive a frenzy of further development and a heightened awareness of other factors impacting on the problem. An additional entry to the market made available during 1996 was a chopper utilising unequal drum diameters. This gave a blade entry configuration initially approximating a blade/anvil configuration, changing to a hoe chop as the cutting cycle progressed. This concept, termed the differential chop, has become the ‘industry standard’ design, on the basis of field observations which have indicated reduced billet damage and extended time between blade changes. Due partly to the incorporation in the design of the Massey Ferguson ‘self sharpening’ blade geometry concept.
2.0 OBJECTIVES

The objective of this project was to undertake a cooperative testing program with harvester and chopper system manufacturers to test and evaluate the performance of chopper systems currently available to the industry.

The testing program undertaken with each chopper system included:

- Quantifying the relationships between cane feed train nominal velocity, chopper peripheral velocity, billet length, billet length distribution and billet quality of each chopper at different pour rates. Power consumption and instantaneous torque loadings were also assessed.

- Quantifying the inherent juice and fibre losses and billet damage in the cutting process with the different designs and under different harvesting conditions (pour rate, feed train speed and cane type).

- Quantifying the impact of wear and poor adjustment on performance in a limited trial program.

The analysis of each chopper configuration incorporated:

- Logging the operation of each chopper type with high-speed loggers during test runs to determine forces induced in the cane bundle, power consumption of the choppers and feed train rollers and instantaneous speed variation in selected components.

- Capturing the actual cutting process using high-speed cine and use this information to confirm cutting/damage processes.

- Developing guidelines with the manufacturers to enhance the performance of choppers.

3.0 METHODOLOGY

3.1 Materials

3.1.1 Chopper test rig

The chopper test rig is a stationary replicate of the standard CASE IH Austoft 7000 cane harvester feed train and chopper systems. The 7000 type is the dominant harvester in the Australian industry and in many other sugarcane producing countries. The Cameco CH2500 is a close replica of this design, with components such as feed train rollers and chopper drums having a high degree of interchangeability. It was therefore assumed that the same feed train configuration could be used to represent both designs. Figure 3.1 illustrates the static chopper test rig. The fundamental components of the test rig are detailed in the following sections.
Figure 3.1 The chopper test rig with conveyor feed system and high speed cine camera.

3.1.1.1 Feed conveyor

Wholestalk cane is fed to the chopper test rig via a 12 m long (750 mm wide) rubber belt conveyor. The cane is loaded evenly on the belt in a configuration representing the ‘butt first’ feed of a normal harvester. To feed the cane, the unit is activated and has a range of speeds from 1 m/s to 2.1 m/s. To ensure even feed into the chopper test rig, the belt speed is set to match the tip speed of the lower rollers of the feed train. The conveyor feeds the wholestalk cane onto the buttlifter and under the first floating feed roller. An additional large diameter non-powered floating roller was positioned at the end of the conveyor to assist with the even transition of material from the conveyor into the feed train.

3.1.1.2 Feed train rollers

The feed train roller section of the test rig was fabricated from the sidewall sections usually reserved for commercial harvester manufacture. The standard design consists of two ‘layers’ of powered rollers, one above the other, as shown in Figure 3.3. The rollers in the top layer are free floating to allow for variations in cane swath thickness.
The bottom layer rollers are fixed. The top and bottom layers of rollers rotate in opposing directions, effectively pulling the cane swath through. In relation to Figure 3.3, the top layer rollers rotate anti-clockwise while the lower layer rollers rotate clockwise.

The feed train rollers in the test rig are hydraulically driven via three hydraulic circuits in a system which gives similar power characteristics to a conventional harvester, with the ability to vary speed of different roller groups to between 100 and 250 rpm, using pressure compensated flow control valves. This allows their speed to be set to the full range achievable on any commercial harvester.

3.1.1.3 Chopper module

The rotary ‘pinch chop’ system consists of two machined contra-rotating drums with hardened steel replaceable blades mounted parallel to the axis of the drums so as to ‘pinch’ and sever material passing between the drums. On current machines, the drums are hydraulically driven by two individual motors and are synchronised by timing gears. A flywheel running on a separate shaft driven by the top timing gear gives added inertia to reduce the pulsing which would occur if additional energy was not available during the chopping process. The flywheel is fitted with a slip clutch to protect the gears from overload in the event of a solid object being passed through the blades.

On the chopper test rig, the chopper drums are mounted in a discrete module and are secured to the feed train via load cells and tie rods. Interchangeable modules allow a quick set up of the different chopper types to be tested and measurement of forces developed by the choppers in the cane bundle being chopped. Chopper housings are dedicated to the 12-inch and 15-inch chopper systems respectively. Figure 3.2 illustrates the chopper module assembly for the 12-inch system. Care was taken to ensure the chopper/feed train relationship found in the commercial harvester was maintained with each chopper system.

After chopping, the billets are collected in a bin for assessment of billet quality and juice and cane loss.
3.1.1.4 Power unit

Power for the chopper test rig was supplied by a Toft 6000 harvester fitted with a 206 kW motor. Hydraulic supply for the chopper motor circuit and each of the three feed train circuits were taken from appropriate circuits on the harvester.

3.1.1.5 Cleaning system

A cleaning system was used to remove leaf material and small billet fragments from the billeted sample. The cleaning system used was based on an Austoft 7000 elevator and secondary extractor, modified to improve presentation of the cane to the airflow. This system was a low velocity system with air velocities less than 10 m/s to ensure that only leaf material and small billet fragments would be removed. In operation, at least three passes of material was required through this system to achieve acceptable levels of removal of these components.

Larger fragments (pieces of split and damaged billet less than 50 mm long) were not removed by this system and must realistically be still considered loss as these would normally be extracted under field conditions (Kroes, 1997). A series of tests incorporating both the fan extraction cleaning system plus additional hand sorting of the remaining sample was conducted to determine the percentage of these larger billet fragments.
3.2 Instrumentation

The test rig was instrumented to allow measurement of hydraulic pressure, displacement of first and last top floating rollers, tension and lateral force in the cane bundle, rotational speed and chopper blade position. This allowed determination of the various relationships between the feed train and choppers, and their interaction with the cane bundle.

High-speed data acquisition of the system is implemented by a 16 channel 100 kHz PCMCIA slot Analog and Digital Input/Output board. The pressure transmitters, load cells, Hall effect switch and potentiometers interface directly to an isolated mounting rack and account for 14 analogue input channels.

The operation of the computer board is controlled by proprietary windows based software DASYLab® which provides the acquired data to be recorded directly to specified files. The data acquisition was set up on a laptop computer, which allowed compactness and portability.

The actual cutting process, along with the trajectory of the billets from the choppers was recorded using a high-speed cine motion camera and Sony Hi-8 video camera respectively. This allowed the development of a better understanding and confirmation of the processes involved during the chopping cycle.

The instrumentation transducers and motion capture equipment utilised on the test rig are detailed in the following sections. The locations of these devices on the test rig are illustrated schematically in Figures 3.3 and 3.4.

3.2.1 Pressure sensors

Hydraulic pressure was measured using Genspec standard GS4200 series industrial pressure transmitters. These transmitters have accuracy in terms of stability, repeatability and non-linearity/hysteresis of less than 0.25% F.S.O. and a response time of 1 ms. The transmitters were interrogated by the data acquisition system at 7000 Hz, averaged and recorded to disk at 100 Hz.

Transmitters were located on the pressure and return circuits of the chopper drive motors and on the pressure and return circuits of the last feed rollers of the upper and lower feed train. Power consumption of the choppers and feed rollers could then be determined during processing of the cane bundle.

3.2.2 Force sensors

Five S-beam load cells with self-aligning tie-rod ends were utilised to connect the interchangeable chopper housings to the feed train. Load cells were orientated in both the axial and transverse directions to the cane bundle. Three load cells with a range of 2500 kg were orientated in the axial plane with two load cells with a range of 750 kg orientated in the transverse plane. The load cells have individual regulated power supplies and signal
amplifiers. The loadcells were interrogated by the data acquisition system at 7000 Hz, averaged and recorded to disk at 100 Hz.

The load cells enable the measurement of the instantaneous tension induced in the cane bundle and the ‘offset’ or lateral forces during the chopping process.

3.2.3 Speed sensors

Magnetic pick-up transducers were utilised to record the speed of the choppers and last top and bottom feed rollers. The transducer is a passive device and requires no external power and responds to movement of a ferrous part, past the pole-piece on the end of the unit. The transducers were setup to sense the teeth on gear wheels, each with 72 teeth.

The simple alternating waveform corresponding to movement of the teeth past the pole piece and representing a voltage-time domain was converted to a frequency-time domain using a Fast Fourier transform in the DASYLab® software. To achieve accuracy with this approach, data was acquired at a sampling rate of 7000 Hz and recorded at this frequency.

3.2.4 Feed roller displacement

The rotational position of the first and last top feed rollers was measured using a rotary position potentiometer. The potentiometers have individual regulated power supplies and provide a zero to five volt output. The potentiometers were interrogated by the data acquisition system at 7000 Hz, averaged and recorded to disk at 100 Hz.

The rotational position of the rollers recorded the thickness of the cane bundle and allowed a better understanding of the movement of cane in the feed train at different feed train roller speeds.

3.2.5 Blade position

A miniature proximity switch utilising the Hall effect to give switching when influenced by a magnetic field was used to mark the period when the corresponding blades of the two chopper shafts aligned to complete the cut. The switch was located on the chopper motor bearing housing with a magnet positioned at each blade location on the chopper drum housing.

This switch was interrogated and recorded at the same frequency as the pressure, load and position sensing transducers and therefore allowed blade crossover position to be stamped in the recorded data. This can then be correlated against the other data recorded to fully investigate the period where the chopping process is occurring.
3.2.6 High-speed cine photography

Due to the high rotational speed of the choppers, the capture of the actual cutting process was beyond the capability of conventional video and camera technology. Specialised high speed cine camera equipment was utilised to capture this process and comprised a Hitachi Model 16HM high-speed motion analysis cine camera, control pack and halogen lighting.

The camera recorded at approximately 2000 frames per second, equating to the use of a 100 ft roll in approximately two seconds. Therefore, approximately one-third to one-fifth of a typical test run is recorded, depending on feed train roller speed. The negative film is then developed and transferred to S-VHS video at a transfer rate of 25 frames per second, giving approximately three minutes of video footage.

The high-speed cine camera gives a graphic display of juice and cane loss occurring during the chopping process, as well as compression of the cane swath as it enters between the blades. The frame location for the high-speed cine camera is shown in Figure 3.4.

3.2.7 Billet trajectory

The trajectory of the billets after billeting is recorded onto videotape utilising a Sony Hi-8 video camera. A 15 cm by 10 cm grid drawn on villa board is used a backdrop to the billet path and is used to measure the range of the trajectory. The recording of the trajectory of the billets from the choppers provides a visual reference of the characteristics of the material exiting the choppers. Discussion of this qualitative data is outside the scope of this report.

![Figure 3.3 Schematic diagram of chopper test rig illustrating location of instrumentation transducers.](image-url)
3.3 Testing protocols

A testing protocol should standardise the variables in the testing program to give the most representative regime possible to simulate in-field use. The chopper test rig was a full scale replicate of a cane harvester’s feed train/chopper assembly and therefore capable of achieving the same throughput as a commercial harvester. Thus no scaling of the protocol was necessary. Detailed procedures of each test protocol are presented in the following sections.

3.3.1 Cane variety

More than 50 distinct varieties of cane grown in the Australian sugar growing regions, with all having different characteristics (Varietal Composition and Distribution, 1997) and potentially different interaction with the chopper system in the harvester. The first phase of selecting the varieties for the test program, the characteristics of eight varieties, each representing greater than one percent of the total tonnage grown were reviewed. Table 3.1 presents information on mechanical strength properties, fibre contents and information on the percentage of the total crop this variety represents.
Table 3.1: Most commonly grown varieties (Varietal Composition and Distribution, 1997) in Queensland.

<table>
<thead>
<tr>
<th>Variety</th>
<th>Distribution %</th>
<th>Impact *</th>
<th>Shear **</th>
<th>Percent Fibre</th>
<th>Percent Short Fibre</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q96</td>
<td>8.1</td>
<td>0.42</td>
<td>29.5</td>
<td>14.09</td>
<td>54.6</td>
<td>Tough</td>
</tr>
<tr>
<td>Q117</td>
<td>11.1</td>
<td>0.37</td>
<td>25.5</td>
<td>13.75</td>
<td>66.5</td>
<td>Moderate</td>
</tr>
<tr>
<td>Q124</td>
<td>39.7</td>
<td>0.42</td>
<td>23.6</td>
<td>11.54</td>
<td>57.0</td>
<td>Moderate</td>
</tr>
<tr>
<td>Q135</td>
<td>1.3</td>
<td>0.47</td>
<td>36.8</td>
<td>21.27</td>
<td>52.0</td>
<td>Moderate</td>
</tr>
<tr>
<td>Q136</td>
<td>3.1</td>
<td>0.72</td>
<td>32.2</td>
<td>14.13</td>
<td>60.5</td>
<td>Tough</td>
</tr>
<tr>
<td>Q138</td>
<td>5.3</td>
<td>0.41</td>
<td>33.2</td>
<td>10.75</td>
<td>45.8</td>
<td>Tough</td>
</tr>
<tr>
<td>Q141</td>
<td>2.6</td>
<td>0.31</td>
<td>12.9</td>
<td>10.20</td>
<td>78.4</td>
<td>Brittle</td>
</tr>
<tr>
<td>Q151</td>
<td>2.7</td>
<td>0.41</td>
<td>24.8</td>
<td>12.12</td>
<td>59.8</td>
<td>Moderate – Tough</td>
</tr>
</tbody>
</table>

* Impact values are empirical values: 0 – weak; 1 - high
* Shear values are empirical values: 0 – weak; 50 - high

To effectively test the performance of chopper systems, it was determined that two varieties should be common to tests for each system, and that all possible effort should go into test protocols to minimise differences caused by environmental and maturity factors.

The variety with the largest quantity grown and hence most cane processed by chopper systems was deemed an appropriate variety for testing. This variety is Q124, a moderate toughness cane. A brittle cane variety, Q141, was also selected to give a range in variety toughness characteristics to be tested.

Therefore, each chopper system was tested using brittle and moderate strength canes. For comparison between chopper systems, it was decided that using the same varieties when testing the brittle and moderate varieties was essential, although this was subject to availability at that period in the season.

Due to a lack of a dedicated cane source, supply of cane varieties for the testing program was selected based on availability. The most suitable varieties determined for testing were Q124 and Q141. However, at commencement of the first series of tests it was not possible to source a suitable crop of Q124. An available crop of Q135 was substituted, as the characteristics of Q135 are similar to those of Q124 (Table 3.1). As a result of these similarities, the objective to test all chopper systems with a moderate and a brittle variety was not sacrificed.

Availability of Q124, throughout the season was limited in the Bundaberg region, thus a more available variety (Q135) was used as the moderate toughness variety in early tests. The characteristics of Q124 and Q135 are very similar, as indicated by Table 3.1. To characterise the varieties tested, the mechanical strength characteristics were measured.
### 3.3.2 Determination of relevant varietal characteristics

For a valid comparison between chopper systems, each system must be tested with a cane of the same characteristics. Whilst it is considered the variation in characteristics within each variety is minimal when compared to the variation between varieties (Cox M C, 1998, pers. comm.), variations in maturity, crop class, time of year, moisture stress and other factors could be expected to impact on the physical properties of a cane variety.

Standard tests as developed by Brotherton et al (1976) are only an indication of the type and abundance of vascular bundles (the primary component of the cane pith), and hence is not a value of actual cane strength (total of pith and rind). Shear tests are currently of interest predominantly for the milling industry, as it relates to the frictional strength between cane when presented as a mat of fibres. Additionally, the values obtained from these tests are empirical values only, and as such do not give an indication of true strength. Therefore, a test system had to be designed to give a value for transverse and longitudinal impact strength of the cane stalk, both at the node and internode region.

The test system to determine the strength characteristics of varieties incorporated a pendulum device. This enabled the measurement of the constitutive behaviour of the cane stalk in the modes of failure more common to the chopping process, shown in Figure 3.5.

![Failure Modes of Crack Propagation in Sugarcane (Kroes, 1998)](image)

Due to the action of blade engagement in the chopping process, in relation to the direction of travel of the cane swath, rotary choppers subject cane predominantly to mode II failure, however mode I failure may occur and manifests itself into a splitting of the billets.
The characteristics of the node and internode regions are very different, so the test rig had to be capable of testing both. The fracture force applied had to also be dynamic to simulate the action of the chopping process. This was achieved by using the testing principles of a simple pendulum. The pendulum was designed to conform to the Australian Standards Methods for impact tests on plastics (AS 1146.1-1990) and Methods for impact tests on metals (AS 1544 – 1977). The standards for impact testing of plastics was used as the basis for design, as the strength of cane would be more similar to plastic than metals. The pendulum apparatus is shown in Figure 3.6.

![Pendulum testing apparatus](image)

**Figure 3.6: Pendulum testing apparatus**

A random cross section of cane stalks was selected from the same crop used in the chopper testing. A minimum sample size of two stalks was required to conduct transverse impact and longitudinal impact tests at the node and internode regions of the base, middle and top of the stalk of both varieties at harvest (zero days), three days and eight days after harvest.

The transverse impact tests required the pendulum to impact the stalk in a transverse direction with the stalk held vertical. The longitudinal impact tests required a small section (20 mm) of the stalk to be cut, and held in the apparatus horizontally such that the pendulum would impact the sample midpoint of the cross-section parallel to the longitudinal axis of the stalk. The average cross-sectional area of all samples was measured before testing for calculation of the impact strength of the cane. Care was taken in preparing samples to maximise the quality of the sample (no splits or growth cracks).
An important factor impacting the cane characteristics is the growth stage of the crop. For the first series of tests, the Q135 cane was a second ratoon spring plant standing crop, while the Q141 was a third ratoon Autumn plant crop, also standing. The Q124 used in series 2 was a standover autumn plant, heavily lodged and the Q141 a standover autumn plant and lodged.

As the crops of the first series were standing, the cane stalks were relatively straight. The Q141 used in the second series lodged late in the season, and therefore the stalks were still relatively straight. However, the Q124 lodged early and had sufficient growing time for the stalks to reorientate skywards, thus resulting in hooked stalks. As both crops used in the second sequence of tests were standover, the length and average diameter of the cane stalks tended to be larger than the crops used in series 1.

Therefore there are dramatic differences between the wholestalk cane used in the first series of tests and the wholestalk cane used in the second series. There were also differences in the wholestalk cane used between chopper systems in the second series.

**3.3.3 Feed train roller speed - Chopper drum speed relationship**

The nominal speed of chopper drums in commercial harvester’s range from 180 rpm to 230 rpm depending on factory setup. The manufacturers of the choppers tested nominated a nominal chopper drum speed of 200 rpm, the factory set drum speed for post 1994 model Austoft harvesters. This gives a nominal peripheral velocity of the blades of approximately 3.5 m/s and 4.6 m/s for the 12-inch and 15-inch centre chopper drum assemblies respectively.

In commercial harvesters the feed train is separated into two roller groups running at different speeds to agitate the cane and enhance dirt rejection. The first four rollers are typically set to a speed between 100 and 135 rpm, with the last six rollers running between 100 and 200 rpm, depending on model specifications. The speed of the last six rollers is adjustable on recent model machines to give an option of variable billet length.

Evenness of feed was a high priority and this was deemed to be best achieved by running all rollers (including the buttlifter) at the same peripheral speed and match the belt speed of the feed conveyor with this speed. The nominal feed train roller speeds for the first series of test rig trials were set at 135 and 185 rpm as these were the feed train roller speeds nominated in 1999 model harvesters. This was varied up to 250 rpm for a limited assessment of the impact of higher roller speeds. After wider consultation with industry the 135 rpm feed train roller speed was lowered to 100 rpm to reflect a more common setup for harvesters from both manufacturers. When operating at 100, 135 and 185 rpm and with a nominal feed train roller diameter of 220 mm, the nominal peripheral speed of the rollers are 1.2, 1.6 and 2.1 m/s respectively.
3.3.4 Pour rate

Pour rate can be described as the mean material processing rate of the harvester, and it is the primary method of benchmarking the load ‘seen’ by the harvester components. Instantaneous pour rate and mean pour rate are terms used to define the operational conditions. To determine actual harvesting rate, the mean pour rate must be further discounted by field efficiency factors. In a harvester, the gross material processing rate seen by the choppers is different to the material delivery rate from the machine because of removal of material by the cleaning system.

For the purposes of this trial program, it was decided to rate pour rate as the gross material processing rate of the chopper system. One method of estimating the maximum potential pour rate of the chopper system in a harvester is by calculating the maximum mass flow-rate along the feed-train. This is achieved by determining the volume feed rate with the rollers fully open and assuming a nominal value for the density of the cane and trash being fed. Using a bulk density of 450 kg/m³, the maximum bulk density recorded for straight stalks of green cane by Schembri & Garson (1995), a feed train roller speed of 185 rpm, and maximum roller opening of 150mm, a theoretical capacity in green cane of the harvest feed train is approximately 400 t/hr total material processing rate. Green cane harvesting trials associated with BS165 indicated higher pour rates than this are achieved for limited periods by compressing the cane bundle.

The theoretical maximum capacity of a harvester and its actual maximum capacity are typically quite dissimilar. The findings of BS165 indicate cane typically feeds in a glut-starve pattern through the harvester, with a mean roller opening of approximately 30-35 percent being the maximum which can be sustained before choking and stallout become major problems. This equates to a capacity of approximately 130 t/hr in green cane. The level of trash removal achieved and field efficiency factors then reduces this to the typical ‘on the line’ capacity figures used by the industry.

The selection of pour rates for the testing program therefore had to equate to ‘realistic’ values. The selection of 120 t/hr approximates a ‘typical’ mean processing rate for the chopper system in a modern harvester operating under commercial conditions. The selection of 240 t/hr represents a pour rate that is regularly ‘seen’ by chopper systems in harvester, by virtue of the typical ‘glut-starve’ feed pattern to the choppers, over a wide range of operating conditions.

The pour rate of the chopper test rig is determined simply by rate of material processed per unit time. The chopper test facility is fed via a belt type conveyor system, with the wholesstalk cane placed in bundles to feed butt first into the feed train. The bundles are of approximately equal mass, with the butts of successive bundles being spaced at 500 mm intervals. As previously indicated, to maximise evenness of feed to the choppers, all rollers (rather than just the rollers closest to the choppers as in the harvester) were run at the nominated feed train speed. The speed of the feed conveyor was matched to the peripheral speed of the rollers to ensure even transfer of material to the feed train and maximum evenness of feed. The target pour rate is then achieved by manipulating the mass of cane per unit length of feed conveyor,
at the nominated feed conveyor speed, for example a feed train and feed conveyor speed of 2.1 m/s and loading of 33.5 kg/m gives a pour rate of 240 t/hr. The length of the feed conveyor onto which material was placed was a function of desired duration of the test and feed conveyor belt speed. In practice, the time limit on the test was approximately five seconds at a feed conveyor speed of 2.1 m/sec. To maintain this pour rate at other feed train/feed conveyor speeds, the length of the conveyor onto which cane was loaded was reduced. The mass for each test is tabulated in Appendix A.

3.3.5 Cane and juice loss

To quantify the losses associated with the chopping process, ‘mass balance’ techniques were used, where the lost mass is determined as the initial mass of cane minus the final mass of billets and large billet pieces. To enable correct mass balance procedures to be used, the wholestalk cane from the field had to be weighed, stripped and reweighed to give the true mass of cane and trash entering the system. This separation of trash from the cane before chopping also ensured that all extraneous matter was removed during the cleaning process. As the cane is laid on the feed conveyor, approximately half of the stripped trash was placed under the cane and the remaining trash is interspersed in the bundles. This placement of trash is consistent with field observations taken during BS165 where trash was noted to be concentrated towards the bottom of the feed train.

After processing the billets and trash were collected in the collection bin and weighed. The billets and trash were then subjected to the cleaning system and the trash and small billet fragments removed. The remaining mass of clean billets and large billet fragments was then weighed. The difference between the clean wholestalk mass before processing and the billet mass after processing gave the mass of cane fibre and juice lost.

Throughout the test series, a number of the individual tests were selected for hand sorting after passing through the pneumatic cleaning system. This defined the relationship between extracted loss and true loss. This ensured the mass balance procedure for determining juice and cane loss was as accurate as possible.

3.3.6 Billet quality

The mass of material from each test was in the order of 450 kg. It was not feasible to sample every billet from this mass for billet quality purposes. Therefore billet quality was assessed through a program of subsampling the mass of billets from each test. Work by McRae et al (1998) has indicated that a sample size of 20 kg gives representative data for this assessment and was the sample size adopted for this work.

To achieve a representative sample of material from the upper, middle and lower layers of the cane swath collection devices were placed at the forward, middle and rear sections of the collection bin covering the full trajectory of cane from the choppers.
The International Society of Sugar Cane Technologists procedures for billet quality assessment was adopted as a basis for the billet quality assessments undertaken in this work (De Beer et al, 1985). A detailed account of the procedures is presented in Appendix B.

The billet quality assessment procedure included sorting the sample into billet length categories, weighing each category and then re-sorting these sub-samples into sound, damaged and mutilated for billet quality assessment. Although the procedure listed in Appendix B states the categories in 50 mm increments, the analysis technique was varied for this project by separating the categories into 25 mm increments. This provided a more detailed analysis of the samples.

The assessment of billet quality was undertaken by the same personnel in both series of tests and using the same guidelines. This ensured that the interpretation of qualitative assessment criteria was repeatable and consistent.

### 3.3.7 Billet length distribution

The procedure for determining billet length distribution was modified from the guidelines set out by De Beer et al (1985) for quantifying billet length distribution. A detailed procedure of the De Beer et al (1985) billet length distribution is presented in Appendix B.

To provide a more detailed understanding and analysis of billet length categories of 25 mm increments were used. Thus billets from the billet quality sample from each test were sorted into categories of 0-100 mm, 100-125 mm, 125-150 mm, 150-175 mm, 175-200 mm, 200-225 mm, 225-250 mm, 250-275 mm, 275-300 mm, 300-325 mm, 325-350 mm, 350-375 mm, 375-400 mm and longer than 400 mm. Each category was then weighed, and a weighted mean billet length recorded.

### 3.3.8 Blade sharpness

All trials were undertaken with new blades fitted to all chopper system drums unless otherwise stated. New blades consist of a bevel length and radius of approximately 30 mm and one millimetre respectively. To undertake tests using blunt blades, a set of discarded used blades was acquired and each blade machined to an even blade depth equivalent to the depth at the highest worn point, typically the centre of the blade. The resulting cutting edge was level but with a bevel edge similar to a worn blade and comprised a bevel diameter of approximately three millimetres.

The protocol developed in this project for quantifying chopper performance is fundamentally different from all previous work on chopper testing. Whereas all previous work used either burnt or stripped cane and at low pour rates, this test program included trashy cane at realistic pour rates for current harvesting conditions.
3.4 Tested chopper systems

Chopper systems tested in this program represented the three conceptual groups of the over centre chop, hoe chop and differential chop, as illustrated in Figure 3.7. Figure 3.8 represents the blade geometry used in the different chopper systems, namely bevel to bevel, back to bevel and back to back. With all commercial chopper systems, the system manufacturer undertook the assembly and setup of the systems in the chopper module.

Figure 3.7: Rotary chopper configurations

Figure 3.8: Blade mesh configurations
3.4.1 Austoft: 12-inch

This chopper system was the ‘industry standard’ design until 1995/96. It features 12 inch drum centres and two cutting blades per drum. The diameter of the top and bottom drums is identical. The drums were fitted with standard 65 mm blades. The cutting action of this system is a conservative hoe chop, with the blades meshing bevel to back. The setup represented the setup of identical systems in commercial operation. In the chopper test program, this unit is nominated as Chopper A.

3.4.2 Austoft: 15-inch, differential

This chopping system is fitted as standard to current model Case IH Austoft 7000/7700 machines. It features 15 inch drum centres and three cutting blades per drum (four blades/drum is available as an option). The diameters of the top and bottom drums are 435 mm and 380 mm respectively (when fitted with blades). The unequal drum diameters allow alternative blade entry dynamics and are commonly referred to as the differential chop system (Figure 3.7). The drums were fitted with standard 65 mm blades, setup bevel to bevel (Figure 3.8). The chopper system setup was undertaken by Austoft staff to represent the system in commercial operation.

3.4.3 Austoft: 12-inch, differential

This chopper system is available as a retrofit for older model machines or on special orders for current model Case IH Austoft 7000/7700 machines. It features 12 inch drum centres and three cutting blades per drum. The diameters of the top and bottom drums are 360 mm and 305 mm respectively (when fitted with blades). The unequal drum diameters allow alternative blade entry dynamics and are commonly referred to as a differential chop system. The chopper system setup was undertaken by Austoft staff to represent the system in commercial operation.

3.4.4 Westhill Engineering: 15-inch, differential

This system is manufactured by a ‘third party’ supplier and is aggressively marketed throughout the industry as a high performance alternative to the units supplied by the manufacturers. It features 15 inch drum centres and three cutting blades per drum (four is optional). The diameters of the top and bottom drums are 435 mm and 380 mm respectively (when fitted with standard blades). The unequal drum diameters allow alternative blade entry dynamics and are commonly referred to as a differential chop system. Two different blade types were tested and included standard blades of 90 mm depth which represents the systems in commercial operation and developmental 65 mm depth blades. Both blade configurations were meshed bevel to bevel. The chopper system setup was undertaken by Westhill staff to represent the system in commercial operation.
3.4.5 Massey Ferguson: 12-inch

This system was designed by Massey Ferguson for the 405 prototype. It features cast steel chopper drums with 12 inch drum centres and two cutting blades per drum. The drums were fitted with quick-change 65 mm blades. The cutting action is an aggressive hoe chop system, with extensive use of high-speed cine and high-speed data logging during its development. Field trials with the MF 405 fitted with these units have supplied billets of exceptionally high quality.

4.0 RESULTS AND DISCUSSION

Chopper test rig trials undertaken are presented in Appendix A where details of pour rates, feed train roller speed to chopper drum speed relationship, varieties of cane, the number of replications, and the quantity of sugarcane required to achieve the nominated pour rate are tabulated. Chopper systems A, B and E were tested over a short time period using cane from the same sources. Chopper systems A, C and D were tested at a later time and the cane material used was significantly different in characteristics. These two discrete testing periods are defined as series one and series two tests respectively.

4.1 Cane characteristics

To characterise the cane supplies used for testing, four of the current industry standard methods for cane characteristic testing for milling purposes were utilised on samples. A summary of the results from these tests is tabulated in Table 4.1.

<table>
<thead>
<tr>
<th>Cane</th>
<th>Impact Strength *</th>
<th>Shear Strength **</th>
<th>Short Fibre Content (%)</th>
<th>Total Fibre Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 1 Q135</td>
<td>N/A</td>
<td>35.3</td>
<td>60.5</td>
<td>13.8</td>
</tr>
<tr>
<td>Series 2 Q124</td>
<td>0.59</td>
<td>29.7</td>
<td>63.6</td>
<td>12.5</td>
</tr>
<tr>
<td>Series 1 Q141</td>
<td>N/A</td>
<td>19.6</td>
<td>77.5</td>
<td>11.5</td>
</tr>
<tr>
<td>Series 2 Q141</td>
<td>0.36</td>
<td>16.0</td>
<td>77.3</td>
<td>7.8</td>
</tr>
</tbody>
</table>

* Impact values are empirical values: 0 is weak, 1 is high
** Shear values are empirical values: 0 is weak, 50 is high
N/A Not available

Both crops of Q141 have similar short fibre and shear strength characteristics, with the exception of the total fibre content, which is four percent less for the crop used in the second series. Characteristics of Q124 and Q135 are similar, but vary to Q141. These results support the decisions to replace Q124 with Q135 (due to Q124 being unavailable) for the tests conducted with the first three chopper systems, and that Q141 was sufficiently dissimilar to Q124 and Q135 to give a valid alternative cane characteristic.
The physical characteristics of the cane used in both test series was recorded and summarised in Table 4.2. Measurements were taken of the average diameter of the stalks, average length of stalks to the dewlaps and approximate crop yield. With the exception of Q124 in series 2, the length and diameter of stalk was very consistent with the stalks of Q124 varying greatly both in length and in diameter. The crop yield was also determined with series 1 yields based on a working estimate from the weight and number of stalks in a given area. Crop yields from series 2 were actual harvest yields from the remaining cane in the block.

**Table 4.2: Cane physical characteristics for both series 1 and series 2 tests.**

<table>
<thead>
<tr>
<th>Variety</th>
<th>Series</th>
<th>Diameter (mm)</th>
<th>Nominal Stalk Length (m)</th>
<th>Crop Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q135</td>
<td>1</td>
<td>30 – 35</td>
<td>2.2</td>
<td>65</td>
</tr>
<tr>
<td>Q141</td>
<td>1</td>
<td>40 – 45</td>
<td>2</td>
<td>90</td>
</tr>
<tr>
<td>Q124</td>
<td>2</td>
<td>25 – 50</td>
<td>2.7</td>
<td>200*</td>
</tr>
<tr>
<td>Q141</td>
<td>2</td>
<td>35 – 50</td>
<td>2.3</td>
<td>150**</td>
</tr>
</tbody>
</table>

* Based on 80t/acre harvest yield
** Based on 50 and 60 t/acre harvest yield

Transverse and longitudinal impact tests were conducted on the node and internode regions at three locations (base, middle, and top) on the cane stalk. Average results of these tests conducted at the node and internode regions are shown in Figures 4.1 and 4.2 respectively. These results are a whole stalk average. Results of all transverse and longitudinal impact tests conducted are presented in Appendix C.

**Figure 4.1:** Relationship between transverse impact strength and variety, region of cane billet and age after cutting.
Figure 4.1 illustrates the relationship between transverse impact strength and variety, region of cane billet and time after cutting. The internode region has a higher transverse impact strength than the node region with this mode of failure and is independent of variety (Q141, Q124) and time after cutting. At harvest, Q124 records a high transverse impact strength at the node and internode relative to Q141. The changes in transverse impact strength are minimal in Q124 and Q141 with time after cutting.

The decreasing moisture content of the cane stalks is a plausible explanation for the increase in transverse impact strength up to three days after cutting in the node region. After this time the stalks have dried sufficiently to allow the node core to dry and for the node rind to become brittle thus reducing impact strength. The internode region continues to exhibit an increase in transverse impact strength and this can be attributed to the fibres within the core section of this region acting as moisture sink from the node region, thus remaining elastic for a longer period.

This data indicates that significant differences in chopper performance as measured by billet damage would not be expected with cane stored up to three days after harvest.

Figure 4.2 illustrates the relationship between longitudinal impact strength and variety, region of cane billet and age after cutting. Longitudinal impact strength is an order of magnitude lower than transverse impact strength. Therefore less energy is required for this mode of failure.
The node region has a higher longitudinal impact strength after zero days and is independent of variety. This trend is reversed after three days in Q141 and after eight days in Q124 when the internode longitudinal impact strength is greater than the node by approximately 0.5 $\text{kJ/m}^2$ and 2 $\text{kJ/m}^2$ respectively. After zero days, Q124 has a higher longitudinal impact strength in the order of 2 $\text{kJ/m}^2$ and 1 $\text{kJ/m}^2$ at the node and internode over that measured in Q141.

Days after cutting impacts more rapidly on longitudinal impact strength over transverse impact strength. This again can be attributed to the decreasing moisture content of the cane stalks where by the increase in strength can be accounted for in the rigidity of the rind and fibres. After sufficient drying time it is plausible that the rind becomes brittle and that the differential movement of the fibres can more easily occur in the internode region reducing impact strength.

The reduced transverse and longitudinal impact strengths of Q141 should manifest into a higher cane and juice loss and reduced billet quality when utilised in the chopper test rig.

On the basis of these tests, it was believed that the errors induced by a delay of up to four days between cutting and testing would not adversely impact on the quality of the test results.

### 4.2 Chopper characteristics

The captured raw instrumentation data is calibrated and the relevant parameters of power consumption and cutting forces calculated. An example of calibrated data is shown in Figure 4.3 and illustrates measurements taken of pressures, cutting blade position and displacement of feed rollers.

![Figure 4.3: Sample of recorded instrumentation](image-url)
4.2.1 Hydraulic power consumption

Hydraulic power consumption is a function of motor torque and speed of rotation. Direct measurement of speed of rotation was carried out using the speed sensors described in section 3.2.3. Measurement of parameters, which allow calculation of motor torque and also motor power, was undertaken including oil pressure using the pressure transmitters described in section 3.2.1. Calculation of motor torque and motor power were undertaken using the following equations.

\[ M = \frac{p \times V}{2\pi} \] .... (1)

\[ P = \frac{M \times n}{9550} \] .... (2)

Where:

- \( M \) = Torque, Nm
- \( p \) = oil pressure, MPa
- \( V \) = motor displacement ml/rev
- \( P \) = Motor power, kW
- \( n \) = speed of rotation, rpm

Chopper system motor power and last top and bottom feed roller power were calculated for each test. The data for replicates was then averaged and is presented in Tables 4.3-4.7. In addition to hydraulic power consumption, the amount of work done by the relative components during a trial was calculated. No instrumentation data was collected on chopper A series 2 due to a computer malfunction.

Table 4.3: Chopper A hydraulic power consumption and work done for series 1

<table>
<thead>
<tr>
<th>Variety</th>
<th>Nominal chopper speed (rpm)</th>
<th>Nominal feed train speed (rpm)</th>
<th>Pour rate (t/hr)</th>
<th>Chopper unit work done (J)</th>
<th>Chopper unit power (kW)</th>
<th>Last top feed roller work done (J)</th>
<th>Last top feed roller power (kW)</th>
<th>Last bottom feed roller work done (J)</th>
<th>Last bottom feed roller power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q141</td>
<td>195</td>
<td>135</td>
<td>120</td>
<td>20.2</td>
<td>3.0</td>
<td>0.23</td>
<td>0.04</td>
<td>3.0</td>
<td>0.45</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>135</td>
<td>240</td>
<td>59.9</td>
<td>9.2</td>
<td>0.40</td>
<td>0.06</td>
<td>8.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>13.8</td>
<td>2.8</td>
<td>1.7</td>
<td>0.35</td>
<td>6.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>30.9</td>
<td>5.8</td>
<td>1.0</td>
<td>0.19</td>
<td>5.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>135</td>
<td>120</td>
<td>26.8</td>
<td>4.1</td>
<td>0.21</td>
<td>0.03</td>
<td>3.4</td>
<td>0.52</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>135</td>
<td>240</td>
<td>64.0</td>
<td>10.3</td>
<td>-0.35</td>
<td>-0.04</td>
<td>6.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>16.3</td>
<td>3.1</td>
<td>0.31</td>
<td>0.06</td>
<td>3.8</td>
<td>0.73</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>46.1</td>
<td>8.5</td>
<td>0.23</td>
<td>0.04</td>
<td>5.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Table 4.3 illustrates that power consumption increases with pour rate, toughness of variety and mismatch of peripheral speed between the chopper A and feed train rollers. The average power consumption recorded for the worst case scenario is approximately 10 kW. This level is significantly less than the power consumption measured under field conditions where current choppers have in the order of 125 kW (170 Hp) available for processing material. The evenness of feed, presentation of material, levels of trash and pour rate could explain the lower levels measured in the test rig.

The power consumed by the last bottom feed roller during processing is approximately one kW with the last top feed roller consuming little power. The last bottom roller is fixed while the last top roller pivots to accommodate material. The axis of the chopper drums are aligned at the centre of the top roller displacement and this relationship causes the choppers to pull material towards the bottom roller during blade engagement at high pour rates. This action is a plausible explanation for the low power consumption of the top roller and the higher power consumption of the bottom roller.

Table 4.4: Chopper B hydraulic power consumption and work done during series 1

<table>
<thead>
<tr>
<th>Variety</th>
<th>Nominal chopper speed (rpm)</th>
<th>Nominal feed train speed (rpm)</th>
<th>Pour rate (t/hr)</th>
<th>Chopper unit work done (J)</th>
<th>Chopper unit power (kW)</th>
<th>Last top feed roller work done (J)</th>
<th>Last top feed roller power (kW)</th>
<th>Last bottom feed roller work done (J)</th>
<th>Last bottom feed roller power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q141</td>
<td>195</td>
<td>135</td>
<td>120</td>
<td>24.7</td>
<td>4.3</td>
<td>0.11</td>
<td>0.02</td>
<td>3.5</td>
<td>0.60</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>135</td>
<td>240</td>
<td>43.4</td>
<td>8.6</td>
<td>0.02</td>
<td>0.00</td>
<td>7.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>17.5</td>
<td>3.5</td>
<td>0.28</td>
<td>0.05</td>
<td>3.7</td>
<td>0.74</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>135</td>
<td>120</td>
<td>29.7</td>
<td>5.6</td>
<td>-0.43</td>
<td>-0.08</td>
<td>2.6</td>
<td>0.51</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>135</td>
<td>240</td>
<td>92.7</td>
<td>13.4</td>
<td>0.42</td>
<td>0.06</td>
<td>6.7</td>
<td>0.97</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>24.2</td>
<td>4.5</td>
<td>0.12</td>
<td>0.02</td>
<td>2.7</td>
<td>0.50</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>55.1</td>
<td>10.6</td>
<td>1.7</td>
<td>0.34</td>
<td>4.6</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Table 4.4 illustrates that power consumption increases with pour rate, toughness of variety and mismatch of peripheral speed between chopper B and feed train rollers. The average power consumption recorded for the worst case scenario is approximately 13 kW. This chopper system consumes more power during equivalent tests than chopper A. Power consumed by the last top feed roller is again negligible.
Table 4.5: Chopper C hydraulic power consumption and work done during series 2

<table>
<thead>
<tr>
<th>Variety</th>
<th>Nominal chopper speed (rpm)</th>
<th>Nominal feed train speed (rpm)</th>
<th>Pour rate (t/hr)</th>
<th>Chopper unit work done (J)</th>
<th>Chopper unit power (kW)</th>
<th>Last top feed roller work done (J)</th>
<th>Last top feed roller power (kW)</th>
<th>Last bottom feed roller work done (J)</th>
<th>Last bottom feed roller power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q141</td>
<td>195</td>
<td>100</td>
<td>120</td>
<td>40.6</td>
<td>5.7</td>
<td>-1.5</td>
<td>-0.20</td>
<td>2.6</td>
<td>0.37</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>100</td>
<td>240</td>
<td>70.2</td>
<td>11.3</td>
<td>-1.6</td>
<td>-0.26</td>
<td>2.8</td>
<td>0.45</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>19.5</td>
<td>4.0</td>
<td>0.19</td>
<td>0.06</td>
<td>3.9</td>
<td>0.82</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>41.1</td>
<td>8.6</td>
<td>-0.18</td>
<td>-0.04</td>
<td>5.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>100</td>
<td>120</td>
<td>35.7</td>
<td>5.9</td>
<td>-1.2</td>
<td>-0.19</td>
<td>2.2</td>
<td>0.36</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>135</td>
<td>120</td>
<td>29.5</td>
<td>4.2</td>
<td>-1.2</td>
<td>-0.17</td>
<td>3.6</td>
<td>0.52</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>135</td>
<td>240</td>
<td>69.7</td>
<td>10.4</td>
<td>-1.3</td>
<td>-0.20</td>
<td>4.6</td>
<td>0.69</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>21.4</td>
<td>4.5</td>
<td>0.23</td>
<td>0.05</td>
<td>3.8</td>
<td>0.80</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>71.6</td>
<td>11.9</td>
<td>0.56</td>
<td>0.09</td>
<td>6.5</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 4.5 illustrates that power consumption increases with pour rate, toughness of variety and mismatch of peripheral speed between chopper B and feed train rollers. The average power consumption recorded for the worst case scenario is approximately 12 kW. At equivalent pour rates and variety, but matched peripheral speeds of choppers and feed rollers the power consumption is approximately two thirds of the maximum recorded power consumption. This indicates that significant power reductions and savings up to one third can be made with matching peripheral speed of the chopper blades and feed train rollers.

Table 4.6: Chopper D hydraulic power consumption and work done during series 2

<table>
<thead>
<tr>
<th>Variety</th>
<th>Nominal chopper speed (rpm)</th>
<th>Nominal feed train speed (rpm)</th>
<th>Pour rate (t/hr)</th>
<th>Chopper unit work done (J)</th>
<th>Chopper unit power (kW)</th>
<th>Last top feed roller work done (J)</th>
<th>Last top feed roller power (kW)</th>
<th>Last bottom feed roller work done (J)</th>
<th>Last bottom feed roller power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q141</td>
<td>195</td>
<td>100</td>
<td>120</td>
<td>40.8</td>
<td>4.6</td>
<td>-0.12</td>
<td>-0.01</td>
<td>0.71</td>
<td>0.08</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>100</td>
<td>240</td>
<td>62.9</td>
<td>8.9</td>
<td>0.58</td>
<td>0.08</td>
<td>0.90</td>
<td>0.13</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>16.4</td>
<td>3.6</td>
<td>0.47</td>
<td>0.11</td>
<td>0.85</td>
<td>0.20</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>36.6</td>
<td>7.6</td>
<td>0.40</td>
<td>0.08</td>
<td>2.0</td>
<td>0.42</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>100</td>
<td>120</td>
<td>34.9</td>
<td>5.4</td>
<td>0.16</td>
<td>0.03</td>
<td>0.65</td>
<td>0.10</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>100</td>
<td>240</td>
<td>101.4</td>
<td>14.3</td>
<td>0.71</td>
<td>0.10</td>
<td>2.23</td>
<td>0.31</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>27.4</td>
<td>5.2</td>
<td>0.18</td>
<td>0.03</td>
<td>0.32</td>
<td>0.06</td>
</tr>
<tr>
<td>Q124</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>56.0</td>
<td>9.5</td>
<td>-0.37</td>
<td>-0.06</td>
<td>1.4</td>
<td>0.23</td>
</tr>
<tr>
<td>Q141*</td>
<td>195</td>
<td>100</td>
<td>240</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Q141*</td>
<td>195</td>
<td>100</td>
<td>240</td>
<td>75.9</td>
<td>10.6</td>
<td>0.27</td>
<td>0.04</td>
<td>1.2</td>
<td>0.17</td>
</tr>
<tr>
<td>Q141*</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>40.3</td>
<td>8.6</td>
<td>0.96</td>
<td>0.20</td>
<td>1.5</td>
<td>0.33</td>
</tr>
<tr>
<td>Q141*</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>44.6</td>
<td>8.2</td>
<td>1.7</td>
<td>0.32</td>
<td>2.5</td>
<td>0.46</td>
</tr>
</tbody>
</table>

* Developmental short blades used
Table 4.6 illustrates that power consumption increases with pour rate, toughness of variety and mismatch of peripheral speed between chopper D and feed train rollers. The average power consumption recorded for the worst case scenario is approximately 14 kW. This chopper system required the most power for processing out of all chopper systems tested, however power levels are still significantly less than the power consumption measured under field conditions.

At equivalent pour rates and variety, but matched peripheral speeds of choppers and feed rollers the power consumption is approximately two thirds of the maximum recorded power consumption. On the basis of this data, power reductions and savings up to one third can be made with matching peripheral speeds of choppers and feed rollers.

Table 4.7: Chopper E hydraulic power consumption and work done during series 1

<table>
<thead>
<tr>
<th>Variety</th>
<th>Nominal chopper speed (rpm)</th>
<th>Nominal feed train speed (rpm)</th>
<th>Pour rate (t/hr)</th>
<th>Chopper unit work done (J)</th>
<th>Chopper unit power (kW)</th>
<th>Last top feed roller work done (J)</th>
<th>Last top feed roller power (kW)</th>
<th>Last bottom feed roller work done (J)</th>
<th>Last bottom feed roller power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q141</td>
<td>195</td>
<td>135</td>
<td>120</td>
<td>25.3</td>
<td>3.7</td>
<td>0.47</td>
<td>0.07</td>
<td>3.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>135</td>
<td>240</td>
<td>66.7</td>
<td>9.8</td>
<td>0.54</td>
<td>0.07</td>
<td>7.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>16.2</td>
<td>2.9</td>
<td>0.30</td>
<td>0.05</td>
<td>3.6</td>
<td>0.63</td>
</tr>
<tr>
<td>Q141</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>45.1</td>
<td>8.2</td>
<td>0.40</td>
<td>0.07</td>
<td>6.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>135</td>
<td>120</td>
<td>30.8</td>
<td>4.7</td>
<td>0.11</td>
<td>0.02</td>
<td>2.5</td>
<td>0.39</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>135</td>
<td>240</td>
<td>65.2</td>
<td>10.6</td>
<td>-0.03</td>
<td>0.01</td>
<td>5.3</td>
<td>0.88</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>185</td>
<td>120</td>
<td>22.0</td>
<td>4.1</td>
<td>0.19</td>
<td>0.04</td>
<td>3.1</td>
<td>0.58</td>
</tr>
<tr>
<td>Q135</td>
<td>195</td>
<td>185</td>
<td>240</td>
<td>57.2</td>
<td>10.4</td>
<td>1.35</td>
<td>0.25</td>
<td>6.7</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 4.7 illustrates that power consumption increases with pour rate, toughness of variety and mismatch of peripheral speed between chopper E and feed train rollers. The average power consumption recorded for the worst case scenario is approximately 11 kW. This chopper system required the more power for processing than equivalent chopper systems tested.

These results indicate that power consumption is dependent on pour rate, toughness of variety and mismatch of peripheral speed between chopper and feed train rollers. At equivalent pour rates and variety, but matched peripheral speeds of choppers and feed rollers the trials indicate that savings of up to one third can be made in power requirements.

Power consumption levels are significantly less than the power consumption measured under field conditions where current choppers have in the order of 125 kW (170 Hp) available for processing material. The evenness of feed, presentation of material, levels of trash and pour rate are plausible explanation of the lower levels measured in the test rig.
The power consumed by the last bottom feed roller during processing is approximately one kW with the last top feed roller consuming little power. A plausible explanation for this result is relationship between the axis of the chopper drums being aligned at the centre of the top roller displacement. This relationship causes the choppers to pull material towards the bottom roller during blade engagement at high pour rates.

### 4.2.2 Cutting forces

Cutting forces developed by the chopper drums on the cane bundle were calculated from direct load cell measurements as described in section 3.2.2. Measurements were made in both axial and transverse planes to the cane bundle. The cutting process does not impact greatly on loading in the transverse plane and as such these measurements are not presented here.

The measurement of blade position as described in section 3.2.5 has allowed blade position to be correlated against cutting force during testing. Blade position has been transformed into degree rotation with 0 to 360 degrees representing one complete revolution of the chopper drums. This can represent two or three cutting cycles depending on chopper drum/blade configuration. Figures 4.4 to 4.8 illustrate the relationship between cutting forces in the axial plane (axial load) and blade position during a single test. Negative values indicate compression of the load cells and positive values tension on the load cells.

![Figure 4.4: Relationship between axial load and blade position for chopper A: Variety – Q135, Pour rate 240 t/hr, Nominal feed train speed 135 rpm.](image)

Figure 4.4: Relationship between axial load and blade position for chopper A: Variety – Q135, Pour rate 240 t/hr, Nominal feed train speed 135 rpm.
The relationship between axial load and blade position for chopper A is presented in Figure 4.4. This represents the worst case protocol with regards to chopper power consumption. The no load cutting cycle is presented as the black sinusoidal line with the negative values indicating compression on the load cells from a component of the dynamic weight of the chopper unit and is of the order of negative five kN. The sinusoidal nature of the no load cycle cannot be fully explained through out of balance chopper drums.

Blade engagement of the cane bundle commences at approximately six and 186 degrees respectively for the two cutting blades. During processing of the cane bundle into billets a marked increase in compression of the load cells occurs, indicating the resistance to cutting or the tension induced in the cane bundle. On average, compression on the load cells reaches a value in the order of negative 13 kN. Thus tension induced in the cane bundle is of the order of eight kN. Over the period of blade engagement and the projection of billets, tension is applied to the load cells to a peak value in the order of one kN. The rapid reversal of cutting force during the period of billeting indicates that some kinematics occurring which are not fully understood.

![Graph of axial load vs blade position for chopper A](image)

**Figure 4.5:** Relationship between axial load and blade position for chopper B: Variety – Q135, Pour rate 240 t/hr, Nominal feed train speed 135 rpm.

The relationship between axial load and blade position for chopper B is presented in Figure 4.5 and represents the worst case protocol with regards to chopper power consumption. The no load cutting cycle is presented as the black sinusoidal line with the negative values indicating compression on the load cells from a component of the dynamic weight of the chopper unit and is of the order of negative seven kN. This chopper unit is significantly heavier than chopper A and again exhibits a sinusoidal no load cycle which cannot be fully explained through out of balance chopper drums.
Blade engagement of the cane bundle commences at approximately 84, 204 and 324 degrees respectively for the three cutting blades. The cutting force behaviour is identical to chopper A however a greater resistance to cutting or the tension induced in the cane bundle is recorded. On average, compression on the load cells reaches a value in the order of negative 21 kN. Thus tension induced in the cane bundle is of the order of 14 kN, a 75 percent increase over chopper A. Over the period of blade engagement and the projection of billets, tension is applied to the load cells to a peak value of around zero kN. The increase in cutting force is due to chopper design and the interaction between blade/cane bundle engagement and exiting conditions. Therefore more power is required per chop to overcome the tension in the bundle or resistance to billeting.

**Figure 4.6: Relationship between axial load and blade position for chopper C: Variety – Q141, Pour rate 240 t/hr, Nominal feed train speed 100 rpm.**

The relationship between axial load and blade position for chopper C is presented in Figure 4.6 and represents the worst case protocol with regards to chopper power consumption. The no load cutting cycle is presented as the black sinusoidal line with the negative values indicating compression on the load cells from a component of the dynamic weight of the chopper unit and approximately averages negative 5 kN. This chopper unit is comparable to chopper A in weight and again the no load cycle again is sinusoidal in nature indicating and cannot be fully explained through out of balance chopper drums.
Blade engagement of the cane bundle commences at approximately 84, 204 and 324 degrees respectively for the three cutting blades. The cutting force behaviour is identical to chopper A and cutting forces are slightly greater with average compression on the load cells in the order of negative 15 kN. Thus tension induced in the cane bundle is of the order of 10 kN a 25 percent increase over chopper A. Over the period of blade engagement and the projection of billets, tension is applied to the load cells to a peak value of around zero kN. The increase in cutting force can be attributed to chopper design and the interaction between blade/cane bundle engagement and exiting conditions. Therefore more power is required than chopper A per chop to overcome the tension in the bundle or resistance to billeting.

![Graph showing relationship between axial load and blade position](image)

**Figure 4.7:** Relationship between axial load and blade position for chopper D: Variety – Q124, Pour rate 240 t/hr, Nominal feed train speed 100 rpm.

The relationship between axial load and blade position for chopper D is presented in Figure 4.7 and represents the worst case protocol with regards to chopper power consumption. The no load cutting cycle is presented as the black sinusoidal line with the negative values indicating compression on the load cells from a component of the dynamic weight of the chopper unit and approximately averages negative 8 kN. This chopper unit is the heaviest tested and again the no load cycle again is sinusoidal.

Blade engagement of the cane bundle commences at approximately 84, 204 and 324 degrees respectively for the three cutting blades. The cutting force behaviour and magnitude is similar to chopper B with cutting forces in the order of negative 23 kN. Therefore tension induced in the cane bundle is of the order of 15 kN. Over the period of blade engagement and the projection of billets, tension is applied to the load cells to a peak value of around negative one kN. The increase in cutting force can be attributed to chopper design and the interaction
between blade/cane bundle engagement and exiting conditions. Therefore power requirements per chop are similar to chopper B to overcome the tension in the bundle or resistance to billeting.

![Graph showing axial load and blade position](image)

**Figure 4.8: Relationship between axial load and blade position for chopper E: Variety – Q135, Pour rate 240 t/hr, Nominal feed train speed 135 rpm.**

The relationship between axial load and blade position for chopper E is presented in Figure 4.8 and represents the worst case protocol with regards to chopper power consumption. The no load cutting cycle is presented as the black sinusoidal line with the negative values indicating compression on the load cells from a component of the dynamic weight of the chopper unit and approximately averages negative 5 kN. The sinusoidal nature of the no load cycle again cannot be fully explained.

Blade engagement of the cane bundle commences at approximately 120 and 300 degrees respectively for the two cutting blades. The cutting force behaviour and magnitude is similar to chopper A with cutting forces in the order of negative 15 kN. Therefore tension induced in the cane bundle is of the order of 10 kN. Over the period of blade engagement and the projection of billets, tension is applied to the load cells to a peak value of around two kN. The increase in cutting force can be attributed to chopper design and the interaction between blade/cane bundle engagement and exiting conditions.

Cutting forces are dependent on chopper design and the interaction between blade/cane bundle engagement and exiting conditions. The characteristics of axial loads between cutting events can be attributed to chopper drum and thrower bar design.
4.2.3 Rotational speed

![Graph showing relationship between chopper D drum and last top feed roller speed](image)

Figure 4.9: Relationship between chopper D drum and last top feed roller speed during processing of a cane bundle: Variety – Q124, Pour rate 240 t/hr.

The relationship between chopper D speed and last top feed roller speed is presented in Figure 4.9 and represents the worst case protocol with regards to chopper power consumption. During processing the chopper speed is slowed as expected, however at times the feed roller speed is increased. This increase is due to the aggressiveness of the chopper drums and indicates the degree of control that the choppers have during feeding and the importance of matching peripheral speeds of the feed train rollers and the choppers. In this test the feed train speed is cycling through a range of 60 rpm. During processing, the feed train roller speed reduces by up to 25 percent and increases by up to 40 percent. The increase in roller speed would have implications on the fatigue life of the mechanical components in the hydraulic motors.

4.2.4 High speed cine photography

The cutting process was captured on high-speed cine film and then transferred to video as described in section 3.2.6. Figure 4.10 illustrates a 16 consecutive frame sequence of chopper A during testing. This sequence was developed from positive film and therefore is a mirror image of the actual process.
4.2.5 Cane and juice losses

The fan extraction process only removed small billet fragments, trash and juice on trash. Larger billet fragments still considered loss after Kroes (1997) were not removed by the extraction system as expected. A series of tests were conducted to fully quantify the percentage of large billet fragments remaining after the fan extraction process. These tests were subjected to a hand sort in addition to fan extraction (fan extraction/hand sorted) to determine the total cane and juice loss.
The relationship between fan extraction only losses and fan extraction/hand sorted total losses is presented in Figure 4.11. A best-fit linear regression was applied to determine a scale factor that could be applied to the fan only extracted loss data to correct for this underestimation of losses.

The equation of the regression line is:

\[
\text{Loss measured due to extraction (\%)} = 0.5 \times \text{Fan extraction/hand sorted loss (\%)}
\]

Therefore, measured losses from fan extracted tests only were corrected by a factor of two.

**4.2.5.1 Variety and pour rate**

Figure 4.12 illustrates the impact of variety and pour rate on cane and juice loss for each chopper system tested in series 1.
Figure 4.12: Effect of variety and pour rate on cane and juice losses for choppers tested in series 1.

Chopper A is the discontinued Austoft 12 inch-chopper system, used in these trials as a benchmark system. Cane and juice losses are in the order of 1.5 to 3.3 percent for Q135 and 2.5 up to 4.2 percent for Q141. Higher losses are recorded with Q141 at all pour rates and for each chopper system. The higher losses in chopper system A with Q135 at 120 t/hr over 240 t/hr can be attributed to experimental error.

Overall chopper B has the lowest losses, while choppers A and E are similar in performance, particularly at the higher pour rates where the losses range between 3 and 4.2 percent. This series of tests indicates that loss is a function of pour rate and the brittleness of variety as expected. The data also indicates that alternative chopper designs can potentially reduce losses relative to older designs.
Figure 4.13: Effect of variety and pour rate on cane and juice losses for choppers tested in series 2.

Figure 4.13 illustrates the impact of variety and pour rate on cane and juice loss for each chopper system tested in series 2. Cane and juice losses measured during this series range from 2 to 5 percent. Chopper system A was tested in this series as a benchmark for the other choppers tested in this series and to correlate with series 1 tests. Cane and juice losses in chopper A in this series are a few percent higher than in series 1. This can be attributed to the higher strength characteristics of the cane tested in series 2. At high pour rates losses measured with Q141 are higher than Q124 with the exception of chopper A where a reduction in loss was measured at the high pour rate. Choppers A and D have similar loss values with chopper C having lower losses at the high pour rate.

In summary, losses are dependent on pour rate, brittleness of variety and chopper system. Losses increase by approximately 1.5 percent when pour rate is increased from 120 t/hr to 240 t/hr. The lowest loss chopper system in series 1 is chopper B with losses ranging from 1.9 to 3.1 percent, while chopper C in series 2 recorded the lowest loss of between 2.4 and 3.6 percent. These results indicate that whilst some alternative designs perform better than the now discontinued benchmark system, the alternative designs are not automatically superior with respect to losses during billeting.
4.2.5.2 Feed train roller speed and pour rate

Figure 4.14: Effect of nominal feed train roller speed and pour rate on cane and juice losses for choppers tested in series 1.

Figure 4.14 illustrates the impact of nominal feed train speed and pour rate on cane and juice loss for each chopper system tested in series 1. With the exception of chopper B at low pour rates, the greater the mismatch between feed train roller speed and chopper drum speed the greater the losses. At 240 t/hr, choppers A and E show an increase in losses as the feedtrain speed increases from 135 rpm to 185 rpm.
Figure 4.15: Effect of variety, nominal feed train roller speed and pour rates on cane and juice losses for chopper A tested in series 2.

For series 2 tests a reduction in the minimum feed train speed setting from 135 rpm to 100 rpm was undertaken. This lower feed train roller speed was more representative of harvester feed train setups under field conditions. Chopper A, the benchmark chopper system, was then tested at three nominal feed train roller speeds 100, 135 and 185 rpm at 240 t/hr. Results from these tests are illustrated in Figure 4.15.

No differences in losses were measured in Q124 at 100 rpm and 135 rpm. On increasing nominal feed train speed to 185 rpm a small reduction in losses was measured. Q141 recorded lower losses at all feed train speeds than Q124. This result is reversed from series 1 and can be explained by cane strength characteristics resulting from crop class and time of harvest. Q141 also recorded a lower loss at 100 rpm than at 135 rpm. No plausible explanation can explain this result and indicates that further work on the measurement of losses in the testing protocols to improve the accuracy and consistency must be undertaken.
Figure 4.16: Effect of nominal feed train roller speed and pour rate on cane and juice losses for choppers tested in series 2.

Figure 4.16 illustrates the impact of nominal feed train roller speed and pour rate on cane and juice loss for each chopper system tested in series 2. In this series feed train speeds of 100 and 185 rpm were used.

All chopper systems show a lower degree of loss at 120 t/hr (2.8–3.3 percent) than at 240 t/hr (4–5.9 percent), with one exception of chopper C at 185 rpm which shows an anomaly of slightly higher losses at the lower pour rate. Choppers C and D clearly demonstrate a decrease in loss, by as much as 2.7 percent, between 100 rpm and 185 rpm.

From Figures 4.14 to 4.16, it can be assumed that the degree of loss is directly related to the feed train roller speed and pour rate. Choppers C and D have similar losses at the lower pour rate, and appear to be more highly influenced by the change in feed train roller speeds.

To further quantify the relationship between pour rate, variety and feed train speed, more extensive and detailed research is required, leading to the optimisation of the feed train roller peripheral speed/chopper drum speed relationship. Loss is a function of feed train speed and pour rate. In general terms, these factors are more important than chopper system design.
4.2.5.3 Blunt blades

The impact of blade wear on chopper system performance was investigated in a number of trials. In these trials a set of blunt blades were installed on chopper A. The degree of blade bluntness is defined in section 3.3.8. Trials were undertaken on a worst case scenario where test rig settings included a feed train roller speed of 100 rpm, pour rate of 240 t/hr and testing the more brittle variety, Q141.

![Blunt blades](image)

**Figure 4.17:** The impact of blunt blades fitted to chopper A on cane and juice losses.

Figure 4.17 illustrates the impact of blunt blades fitted to chopper A on cane and juice loss. It is evident that the use of blunt blades increases cane and juice loss as expected. Cane and juice losses were approximately three times that measured in identical tests with sharp blades. This is higher than previous estimates by Ridge *et al* (1986) but indicates the importance of concepts such as blade self-sharpening.
4.2.6 Billet quality

4.2.6.1 Varietal effects

Figure 4.18: The impact of variety on billet quality for choppers tested in series 1

Figure 4.18 illustrates the impact of variety on billet quality for choppers tested in series 1. The data presented is an average across pour rates and feed train roller speeds. Across varieties Q135 to Q141, the decrease in sound billets over the three chopper systems is approximately 15 percent and the majority of this decrease manifests itself into an increase in damaged billets with the percentage mutilated remaining constant. Chopper E produced the lowest billet quality sample with an average percentage mutilated approximately 11 percent and sound billets approximately 54 percent. Choppers A and B produced approximately 7 percent mutilated and 70 percent sound billets respectively. The quality of wholestalk cane was very high in this series of tests. The high level of sound billet quality is much higher than would be expected with similar chopper systems operating in the field (Norris et al 1998). Billet quality is dependent on variety and chopper system. Given that chopper A, the benchmark system, is a superseded system, significant gains do not appear to have been made with respect to billet quality.
Figure 4.19: The impact of variety on billet quality for choppers tested in series 2

The data presented in Figure 4.19 is an average across pour rates and feed train speeds. Figure 4.19 illustrates a dramatic increase in the percentage of mutilated billets in chopper A. There is an inconsistency with these results since the cane and juice losses are not significantly higher in this series. This may be attributed to the differences in crop class and characteristics of cane used in this series. In this series autumn plant cane was used and this has an inherently lower billet quality than spring plant cane which was used in series 1 testing due to the former being more mature and the higher probability of growth cracks (Robotham, B per. comms.).

A high percentage of the stalks in both varieties tested had growth cracks. The majority of billets classified as mutilated in this series were due to large splits in the rind. These splits are difficult to separate from growth cracks. Therefore it is plausible to assume that the high proportion of mutilated billets is partly due to growth cracks and not entirely due to damage inflicted by the chopping process.

In terms of these comments the comparison between chopper systems was limited to sound and damaged billets only. Choppers A and D do not demonstrate any relationship between variety and billet quality for the two varieties tested whereas chopper C measured lower billet quality in Q141.
4.2.6.2 Pour rate

Figure 4.20: The impact of pour rate on billet quality for choppers tested in series 1

Figure 4.20 illustrates the impact of pour rate on billet quality for choppers tested in series 1. The data presented is an average of both varieties and feed train speeds and displays a decrease in the percentage of sound billets in each chopper system as the pour rate increases. This decrease is in the range of 8 to 24 percent. At 120 t/hr pour rate all chopper systems produced similar levels of sound billets, however on increasing the pour rate to 240 t/hr the billet quality produced by chopper E fell dramatically.

Figure 4.21: The impact of pour rate on billet quality for choppers tested in series 2
Figure 4.21 presents an average of both varieties and feed train speeds for all chopper systems tested in series 2. The comparison between chopper systems was limited to sound and damaged billets only due to the potential impact of cane physical characteristics (crop class and growth cracks) exaggerating the levels of mutilated billets. Despite the overall lower levels in billet quality similar trends were measured in sound billet quality in this series and in series 1. At high pour rates a reduction in sound billet quality resulted as expected.

4.2.6.3 Feed train roller speed

Figure 4.22: The impact of nominal feed train speed on billet quality for choppers tested in series 1.

Figure 4.22 illustrates the billet quality for choppers tested in series 1, in relation to nominal feed train speed. The data presented is an average of both varieties and pour rates. There were no differences in billet quality over the range of feed train roller speeds tested and therefore billet quality was not a function of feed train speed in this series.

Chopper E has on average a 15 percent lower percentage of sound billets than the other chopper systems at both feed train speeds. Chopper B has the highest percentage of sound billets and lowest value of mutilated billets.
As expected these results show much higher levels of billet quality than similar chopper systems operating under field conditions. This is highlighted with chopper A where an average sound billet quality in the test rig of 65 percent was measured whereas this chopper under field conditions resulted in only 25 percent sound billet quality. From this series it is concluded that billet quality is a function of pour rate and variety, and is influenced by other factors such as the basecutter and extraction systems.

Figure 4.23: The impact of nominal feed train speed on billet quality for choppers tested in series 2.

Figure 4.23 illustrates the impact of nominal feed train speed on billet quality for choppers tested in series 2. The data presented is an average of both varieties and pour rates. The dramatic change in quality of wholestalk cane has overshadowed results on billet quality in this series. Therefore it is not valid to draw any conclusions between chopper systems in terms of feed train speed relationships.
4.2.6.4 Blunt blades

![Graph showing billet quality distribution](image)

**Figure 4.24: The impact of blunt blades fitted to chopper A on billet quality.**

Figure 4.24 illustrates the impact of blunt blades fitted to chopper A on billet quality. Blunt blades reduce the levels of sound billets and dramatically increase the level of mutilated billets. Blunt blades have a much larger impact on chopper performance than any other parameter.

4.2.7 Billet length distribution

The billet lengths from each test and subsequent quality assessment sample were recorded and the mean billet length and distribution determined as per section 3.3.7. Mean billet length was found to be independent of pour rate and variety and dependent on feed train roller speed as expected. Figures 4.25 to 4.30 illustrate the distribution of the percentage (by weight) of billets in each length category for the five chopper systems tested. The data presented is an average across varieties and pour rates.
Mean Billet Length (135rpm) = 264mm
Mean Billet Length (185rpm) = 304mm

Figure 4.25: Billet length distribution for chopper A in series 1.

Mean Billet Length (135rpm) = 213mm
Mean Billet Length (185rpm) = 238mm

Figure 4.26: Billet length distribution for chopper B in series 1.
Figure 4.27: Billet length distribution for chopper E in series 1.

Figure 4.28: Billet length distribution for chopper C in series 2.
Figures 4.25 to 4.30 demonstrate a reduction in the mean billet length as the nominal feed train roller speed is reduced. The average decrease in billet length between 185 rpm and 135 rpm ranged between 40 mm and 54 mm for chopper systems A and E respectively.
The average decrease in billet length recorded between 185 rpm and 135 rpm ranged between 32 mm and 25 mm for chopper systems B and C respectively. A decrease of 37 mm and 55 mm was recorded in billet length between 185 rpm and 100 rpm for chopper systems C and D.

Chopper system D recorded a worse billet length distribution at 100 rpm feed train roller speed than at 185 rpm. This was consistent when both the standard blades and short developmental blades were used.

These figures illustrate that to reduce billet length the installation of a three bladed system is a better option than to adjust feed train roller speed in terms of billet quality distribution.

4.3 Sample manufacturer’s report

A report on the performance of each chopper system was produced and presented to the respective manufacturer. For brevity, a sample of the header and contents pages for a typical report is presented herewith.
SRDC PROJECT BS188S
IMPROVING THE PERFORMANCE OF
CHOPPER SYSTEMS IN CANE HARVESTERS
MANUFACTURER’S REPORT
WESTHILL ENGINEERING
15 inch differential chopper unit
by
C P Norris, R J Davis and P R Hockings

Principal Investigators: Mr P R Hockings Mr R J Davis
Research Officer Research Officer
BSES BSES
Private Bag 4 Private Bag 4
BUNDABERG QLD 4670 BUNDABERG QLD 4670
Phone: (07) 4132 5238 Phone: (07) 41325236

This project was funded by the Sugar Research and Development Corporation during 1997-98 and 1998-99 financial years.

BSES Publication September 1999
CONTENTS

SUMMARY ................................................................................................................................. N/A

1.0 OBJECTIVES ........................................................................................................ N/A

2.0 METHODOLOGY ........................................................................................................ N/A

2.1 Materials ........................................................................................................ N/A

2.1.1 Chopper test rig ........................................................................................ N/A

2.1.1.1 Feed Conveyor ........................................................................ N/A

2.1.1.2 Feed train rollers ..................................................................... N/A

2.1.1.3 Chopper Module ....................................................................... N/A

2.1.1.4 Power unit ................................................................................ N/A

2.1.1.5 Cleaning system ......................................................................... N/A

2.2 Instrumentation ........................................................................................................ N/A

2.2.1 Pressure sensors ......................................................................................... N/A

2.2.2 Force sensors ........................................................................................... N/A

2.2.3 Speed sensors ........................................................................................... N/A

2.2.4 Feed Roller displacement ...................................................................... N/A

2.2.5 Blade position .......................................................................................... N/A

2.2.6 High-speed cine photography ..................................................................... N/A

2.2.7 Billet trajectory ........................................................................................ N/A

2.3 Testing Protocols ................................................................................................... N/A

2.3.1 Cane variety ............................................................................................. N/A

2.3.2 Determination of relevant varietal characteristics ................................ N/A

2.3.3 Feed train roller speed - Chopper drum speed ..................................... N/A

2.3.4 Pour rate .................................................................................................. N/A

2.3.5 Cane and juice loss ................................................................................ N/A

2.3.6 Billet quality ........................................................................................... N/A

2.3.7 Billet length distribution .......................................................................... N/A

2.3.8 Blade sharpness ........................................................................................ N/A

2.4 Tested Chopper Systems ......................................................................................... N/A

2.4.1 Benchmark unit ........................................................................................ N/A

2.4.2 Westhill Engineering: 15-inch, differential .............................................. N/A
3.0 RESULTS AND DISCUSSION ................................................................. N/A
3.1 Cane characteristics ................................................................. N/A
3.2 Chopper Characteristics ......................................................... N/A
   3.2.1 Hydraulic power consumption ......................................... N/A
   3.2.2 Cutting forces ................................................................. N/A
   3.2.3 Rotational Speed ............................................................. N/A
   3.2.4 High speed cine photography ........................................ N/A
   3.2.5 Cane and juice losses .................................................... N/A
      3.2.5.1 Variety and pour rate .............................................. N/A
      3.2.5.2 Feed train roller speed and pour rate ..................... N/A
   3.2.6 Billet Quality ................................................................. N/A
      3.2.6.1 Varietal effects ....................................................... N/A
      3.2.6.2 Pour rate .............................................................. N/A
      3.2.6.3 Feed Train Roller Speed ......................................... N/A

4.0 REFERENCES .................................................................................... N/A

5.0 ACKNOWLEDGMENTS ................................................................. N/A

APPENDIX A ......................................................................................... N/A

APPENDIX B ......................................................................................... N/A

APPENDIX C ......................................................................................... N/A
5.0 DIFFICULTIES ENCOUNTERED DURING PROJECT

A number of difficulties were experienced throughout the duration of this project. Firstly a decision was made to develop the chopper test rig facility to a higher standard than originally proposed so it could be used by a number of projects BS165, BS208 and by organisations and manufacturers for commercial-in-confidence work. This resulted in a very high quality chopper system testing facility.

In developing the original proposal it was believed test protocols could be developed to give valid results whilst minimising labour costs. Previous chopper trials had used burnt or prestripped cane and at low pour rates. Preliminary trials indicated that more rigorous protocols were required to achieve accurate and repeatable results. An expansion of the test protocols resulted and included prestripping trash from wholestalks and weighing components separately and hand sorting for billet quality assessments. These two processes required more labour than originally anticipated. The amount of cane required to achieve realistic pour rates was up to 450 kg and this exacerbated the problems.

The development of the test rig and the increases to testing procedures resulted in a substantial budget increase. The cost to undertake 16 replicated trials on each chopper system tested was approximately $10,000. The continuation of the testing program was funded from BSES internal funds, specifically from the low ccs initiative and represented a more significant contribution than SRDC.

Logistical problems were also encountered in accessing cane supplies. The wholestalk cane was required to be tested as soon as possible after harvest for deterioration purposes and this necessitated a cane supply close to the chopper testing facility. It was not always possible to access the protocol designated cane crop close to the facility. A dedicated crop source would be more adequate for chopper testing to ensure cane with very similar characteristics.

Difficulties in testing were also experienced with delayed supply of chopper systems from manufacturers to be tested. This was due to the seasonal demand on their chopper systems and therefore requiring two systems to be manufactured specifically for this project.

6.0 RECOMMENDATIONS FOR FURTHER RESEARCH

This project has provided baseline performance data for a range of chopper systems currently available to the industry.

While substantial gains have been made toward improving chopper performance, this project has provided only limited scientific evaluation of the geometric influence on the relationship between chopper system and cane swath. With improvements in software packages, the high speed camera footage will be useful in further understanding this relationship scientifically. The majority of harvester manufacturers have dynamic modelling packages to optimise the kinematics of the chopper drums. However additional research is necessary to fully
comprehend the fundamentals of chopper systems including differential chop, over centre, hoe chop and more importantly the interaction between the blades and the cane bundle.

7.0 APPLICATION OF RESULTS TO THE INDUSTRY

This project will supply manufacturers with quantitative information regarding the performance of their chopper systems in terms of power consumption, cane and juice loss and billet quality.

In addition, the project will enhance the awareness and provide quantitative information to manufacturers of the interactions between varietal characteristics, pour rate and chopper peripheral speed/feed train rollers peripheral speed on these performance indicators.

Enhanced understanding of these relationships on chopper systems will result in less billet damage and lower ‘cut losses’ over the range of machine throughputs and over a wider range of billet lengths than is currently achieved. Quantifying mean power consumption of the choppers leading to greater overload capacity is also anticipated.

The increased knowledge base of the chopping process will stimulate further development of chopper systems by manufacturers via the understanding of key interactions and design criteria.

Outcomes of the project for the industry will include lower harvesting chopper costs and less damage to billets. Reductions in billet damage is important for both sugar quality and when supplying feedstock for billet planters. With the application of the findings of this project, the entire sugar industry will benefit through reduced crop losses at harvest, improved strike rates in plant cane, and increased sugar quality due to reduced deterioration between harvesting and milling.

8.0 PUBLICATIONS ARISING


Feed train and chopper module presented at Bundaberg Agrotrend 1998.
Poster papers presented at Bundaberg Agrotrend 1998-1999 and 1999 Bundaberg BSES field day.

Austoft have forwarded all data from tests on their chopper systems to the CASE IH Research and Development centre in the USA. The data will be used in the development of parameters for new chopper systems undergoing preliminary concept development.

9.0 REFERENCES


10.0 ACKNOWLEDGMENTS

The funding support from Sugar Research and Development Corporation and BSES for this project is gratefully acknowledged. The authors would also like to thank Mal Baker and Tino Modesti (CASE IH Austoft) for their assistance with the supply of necessary components for the chopper test rig and the fitting and setup of tested chopper systems.

Thank you also to Yusof Mohammed (cane grower, contractor, Mulgrave) for the supply of Massey Ferguson chopper system and to Bryan Kindersley and Wayne Brown (Westhill Engineering, Mackay) for the supply of chopper systems and support during testing.

In addition, the assistance from BSES officers Les Poulsen and Peter Gaul who constructed the test rig and advising in the operation of the rig and Scott Fredericks, Jeff Blackburrow, Greg Redguard, Bernie Leary, Jeff Waters, Trevour Jenson and Phil Netz for their assistance and hard work in conducting the tests.

The assistance of BSES extension officer Julian Collins is organising cane supply and to David Lack (QDPI Horticultural Research Station, Bundaberg) and Alan Lawson (cane grower, Millaquin) for supplying cane for the trials is gratefully acknowledged.
APPENDIX A

SUMMARY OF TRIALS CONDUCTED
ON EACH CHOPPER SYSTEM
**Chopper System:** Chopper A  
**Date Tested:** 17/11/1998 to 08/12/1998

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**Date Tested:** 15/12/1998 to 21/12/1998

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* Short 65 mm blades
**Chopper System:** Chopper E  
**Date Tested:** 22/12/98 to 30/12/98

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APPENDIX B

GUIDELINES FOR QUANTIFYING
BILLET QUALITY
Current assessment of billet quality within the international sugar industry is predominantly for the purpose of comparing performance of different machines or harvesting systems in general terms (De Beer, A G \textit{et al} 1985). The funded project aims to go one step further by quantifying billet quality in relation to changes in feed train speed and pour rate. De Beer, A G \textit{et al} (1985) states that data on billet quality is based on the following:

- Billet size distribution
- Mean billet length
- Percent sound, damaged, and mutilated billets
- Percent sound billets of good length

Billet size distribution is determined by sorting the billets into categories of 0-100 mm, 100-150 mm, 150-200 mm, 200-250 mm, 250-300 mm, 300-350 mm, 350-400 mm, and longer than 400 mm lengths. Each category must then be weighed, and then the results are graphed or tabled as a percentage by weight of the total sample weight.

The mean billet length is calculated by applying to the formula following. Assumed to be the mean length of each category is the mid-length of the category (50 mm for 0-100 mm, 125 mm for 100-200 mm etc. and an estimate for the billets greater than 400 mm long):

\[
\text{Mean Billet Length} = \frac{50W_1 + 125W_2 + 175W_3 \text{ etc}}{\text{Total Weight of Sample}}
\]

where \( W_1 = \text{Weight of Billets} \) 0-100 mm \\
\( W_2 = \text{Weight of Billets} \) 100-150 mm \\
\( W_3 = \text{Weight of Billets} \) 150-200 mm

Each category is sorted into sound, damaged, or mutilated billets, and the proportions of each category expressed as a percentage (by weight) of the total sample. Identifying a billet as sound, damaged or mutilated is made easy by the following guidelines (De Beer, A G \textit{et al} 1985):
Sound Billets:

Those sections of stalk longer than 100 mm with no splits (other than growth cracks) longer than 80 mm in length through one end. Small rind cracks, less than 40 mm long are not regarded as splits. No section of rind more than 400 mm² removed exposing the pith, no squashed ends with frequent rind cracks.

Damaged Billets:

Those with splits larger than 40 mm in the rind and totalling more than 80 mm per billet or with sections of rind between 400 and 2000 mm² removed, exposing the pith. No squashed ends with frequent rind cracks. All billets less than 100 mm in length.

Mutilated Billets:

Those, which have been broken, squashed and damaged so that there are numerous rind cracks and a portion of the cane is reduced to a pulpy condition. Billets with more than 2000 mm² of rind removed are also classified as mutilated.

Percentage of sound billets of good length is simply the percentage, by weight, of sound billets in all categories greater than 250 mm (De Beer, A G et al 1985). As discussed in the following section, the length considered as a good length varies between mill areas, but 250 mm is a common value used.
APPENDIX C

SUMMARY OF IMPACT AND SHEAR
PENDULUM TESTS IN THE
NODE AND INTERNODE REGION