Minimizing TMP Energy Consumption using a Combination of Chip Pre-treatment, RTS and Multiple Stage Low Consistency Refining

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ABSTRACT

High intensity thermomechanical pulps were produced from white spruce on the pilot scale using a combination of pressurized chip destructuring and fibration, chemical treatment, RTS primary refining and multiple stage low consistency refining. Competitive news grade TMP pulp quality was achieved with approximately 1500 kWh/ODMT using the new process configuration. The physical pulp properties using the multiple stage LCR configuration were equivalent to the HCR control pulps at a given freeness and superior at a given application of specific energy. An interesting finding was that the conditioned spruce fibers following primary refining were equally developed in a Low Consistency Refiner as compared to High Consistency Refiner; eliminating the need for a secondary high consistency refining stage. Results from this investigation shed light on the importance of pulp fiber conditioning for maximizing the displacement of HCR with less energy intensive LCR.

In a separate study using a similar process configuration, it was found that increasing the consistency of the LCR component to 5%-6% is a feasible alternative. The energy consumption and pulp quality development were similar to that obtained with multi-stage LCR at 4% consistency. The displacement of more HCR with LCR in thermomechanical pulping will continue to increase as pulp and paper producers strive to reduce operating, capital and installation costs.

INTRODUCTION

The thermomechanical pulping (TMP) process has been dominated by high consistency refining (HCR) since its proliferation in the 1970’s (1). Accompanying the growth in TMP capacity was a surge in electrical power consumption never before realized in the pulp and paper industry. Sundholm proclaimed at the IMPC in 1993 the need for a concerted effort within the industry to reduce energy consumption (2). Despite considerable efforts and success in recent years to reduce the energy consumption of thermomechanical refining, power savings to date remains short of industry expectations. New TMP systems today are expected to have 10% to 20% less energy consumption than the TMP systems of previous decades; many pulp and paper companies are now seeking higher savings in the 20%-30% range, due to a more deregulated and volatile power supply. The forecasts on electricity rates are in the upwards direction. Environmental regulations and incentives to reduce greenhouse gas emissions have also inspired more mills to reduce energy consumption (3).

During the 1990’s, developments in low consistency refining technology (LCR) led to the installation of low consistency refiners in mainline TMP applications, most commonly following the latency chest and before screening (4, 5, 6). Most of these mills installed low consistency refiners to allow for an increase in mainline production rate; increasing capacity increased the freeness following HCR refining, and the LCR was used to make up for the difference in freeness. The return on investment (ROI) was quite favorable in such applications due to the lower installed and operating cost of LC refiners relative to HC refiners. The lower operating cost is due to a reduction in specific energy consumption (SEC) arising from the displacement of energy intensive HCR with LCR.

The favorable ROI led to many TMP producers jumping on board with mainline LCR projects. Several of these projects were jointly funded by the local utility provider in an effort to curb peak power consumption and keep electricity rates in line. However, despite such efforts the pressure from many utility providers to reduce peak power consumption will continue.
Savings in specific energy consumption in mainline LCR applications has been limited to approximately 5%-10% due to inherent limitations in the loading of LC refiners. Most mills apply well less than 150 kWh/ODMT in mainline LCR refiners for pulp strength considerations; at higher SEC levels pulp strength and long fiber content drop off sharply. This limits the available displacement of HC refining with LC refining and related energy savings.

An objective of this study was to increase opportunities for displacing more energy intensive HC refining with LC refining. The approach involved modifications to both the HC and LC components of thermomechanical pulping.

**PROCESS DEVELOPMENT**

Andritz introduced a method for increasing the defibration of wood prior to mainline refining at the 2003 International Mechanical Pulping Conference (7). The method, known as RTFibration™, involves a gentle separation of fibers in wood chips using a combination of pressafining and refining actions in a moderately pressurized environment. High-intensity RTS™ TMP pulps produced using RTFibration pre-treatment had 10%-14% lower energy consumption compared to the control RTS TMP pulps (7). Further reductions in energy consumption were available when coupling RTFibration with a chemical treatment; greater than 20% energy savings was realized compared to conventionally produced TMP.

Results from these studies revealed that defibrated chips using the RTFibration technique are more amenable to an increase in refining intensity. Two explanations help rationalize this observation; 1) fiberized chips have more surface area for heat and/or chemical penetration, thereby improving the softening behavior of wood fibers and resilience to fiber breakage, and (2) fiberized chips are more pliable and less susceptible to breakage than intact or destructured chips, especially in the breaker bar and inlet section of the refining zone.

The present study involved the coupling of RTFibration-RTS with low consistency refining (LCR) to take full advantage of this phenomenon; the goal was to maximize HC refining displacement with lower energy LC refining. The premise being that if the fiber is sufficiently conditioned (softened) following RTFibration-RTS pulping in the mainline, then LC refining can commence at an elevated freeness compared to conventional TMP systems.

Ideally, the fiber is suitably conditioned for LC Refining following the primary HC refiner, hence eliminating the need for secondary refining altogether. Such was the approach taken in this investigation.

**EXPERIMENTAL**

**Study 1: HC versus LC-multi-stage refining of white spruce**

The experimental work was conducted at the Andritz Research and Development Center located in Springfield, Ohio USA. The wood furnish used in this study was white spruce from Wisconsin.

**RTFibration**

White spruce wood chips were first destructured using an Andritz pressurized RT Pressafiner™ chip press. The chips were fed via a rotary valve into a pressurized conveyor, which in turn delivered the chips to the pressurized inlet housing of the compression screw device. A moderate pressure is sufficient to maintain the integrity and axial separation of the wood chips without damage (7). The chips were then compressed and destructured in the screw device. Four hydraulic restrictor pins on the discharge side of the press further compressed the chip plug to increase the level of destructuring. The macerated chips discharging from the screw were impregnated with water in an inclined conveyor.

The destructured chips were then fiberized in an Andritz 36-1CP pressurized single disc refiner (91 cm diameter). The fiberized chips demonstrated little resistance to drainage. **Figure 1** illustrates fiberized spruce chips at a magnification of 200X.
**RTS Primary Refining**

Primary refining was conducted at RTS conditions in a 36-1CP refiner operating at a disc speed of 2300 rpm and pressure of 5.9 bar. Directional refiner plates (Durametal 36604) were operated in the feeding direction to further increase the refining intensity (See Figure 2). The fiberized spruce chips were refined to a freeness of 516 mL. A reductive chemical treatment (undisclosed) was applied at the primary refiner. An objective of the chemical treatment is to increase fiber softening such that the fiber is more receptive to downstream low consistency refining. The primary refined pulp was mixed and then split in two batches for 1) HC refining and 2) multiple-stage LC Refining.

**Batch 1: High Consistency Secondary and Tertiary Refining**

The primary refined pulp was secondary refined using a pressurized 36-1CP refiner operating at a pressure of 3.4 bar and rotational disc speed of 1800 rpm. The refiner was equipped with fine barred plates formulated to maximize pulp strength development. The secondary refined pulp was then tertiary refined using an Andritz 401 atmospheric double disc refiner (91 cm diameter) with three levels of specific energy.

**Batch 2: Multiple Stage Low Consistency Refining**

The primary refined pulp was refined using four stages of LC refining. An Andritz TwinFloIIIB dual discharge refiner (51 cm diameter) was used to conduct LC refining. The refiner was equipped with refiner plates formulated to maximize pulp strength development. The refining consistency was 4.0%. The primary refined pulp was LC refined in four passes. The fourth stage LC refining was conducted at five levels of specific energy ranging from moderate to aggressive. The TwinFloIIIB refiner was operated at a disc speed of 1100 rpm to simulate the intensity of larger 58” TwinFlo production scale machines.

All pulp samples were tested using standard Tappi test procedures. Shive analysis was conducted using a Pulmac Shive Analyzer fitted with 0.10 mm screen plate. Fiber length classification was conducted using a Bauer McNett classifier.

![Figure 1. Fiberized Spruce Chips (200X)](image1)

![Figure 2. Durametal 36604 HC Pattern](image2)

**Study 2: Multi-stage LC Refining of White Spruce at 5%-6% Consistency.**

A different shipment of white spruce chips underwent similar RTFibration pre-treatment and RTS refining as described earlier in the Experimental Section. No chemical treatment was applied to the fiber in Study 2. The primary pulp in this study was secondary refined to compensate for the lower softening level i.e. no chemical treatment in Study 2. The refined pulp was then diluted in a tank with agitation to remove latency.

The pulp in the tank was then refined using three stages of LC refining. An Andritz TwinFloIIIB dual discharge refiner (51 cm diameter) was used to conduct LC refining. The refiner was equipped with refiner plates formulated to maximize pulp strength development. In this study, the refining consistency of the LCR component was increased.
to 4.9% and 5.7%, respectively. For the multi-stage LCR series refined at 4.9% consistency, the third LCR pass was conducted at six levels of specific energy ranging from moderate to aggressive. For the multi-stage LCR series refined at 5.7% consistency, the third LCR pass was conducted at two levels of specific energy application. Additional third stage energy applications were not possible since there was not sufficient pulp.

RESULTS AND DISCUSSION

Study 1: HC versus LC-multi-stage refining of white spruce

This section presents results obtained from Study 1 entailing a comparison between HCR and multi-stage LCR of RTFibration-RTS thermomechanical pulps produced from white spruce.

Figure 3 presents the freeness as a function of specific energy consumption. The freeness-energy relationship was similar for both the HCR and LCR configurations between 516 mL (primary pulp) down to approximately 250 mL, below which the energy consumption of the LCR configuration dropped off sharply. Compared at a freeness of 125 mL, the SEC of the RTF-RTS + HCR (hereto for referred as HCR series) and RTF-RTS + LCR (hereto for referred as LCR series) were 1833 kWh/ODMT and 1476 kWh/ODMT; an energy savings of 357 kWh/ODMT.

Figure 4 presents the tensile index results as a function of specific energy consumption. The tensile index of the LCR series was higher across all levels of specific energy application. Compared at a specific energy application of 1475 kWh/ODMT, the LCR series had 5 Nm/g higher tensile index than the HCR series.

Figures 5 through 8 present several pulp properties versus freeness for the HCR and LCR refiner configurations.

The handsheet bulk was similar for both the HCR and LCR series (See Figure 5). The tensile index was similar for both series across most of the freeness range from approximately 500 mL to 100 mL. Referring to Figure 6, the tensile index of the HCR had a sharper climb at freeness levels below approximately 100 mL. The tear index relationship was similar for both refining configurations across the freeness range investigated (See Figure 7).

Referring to Figure 8, the shive content was equivalent for both the HCR and LCR series.

Table I presents a comparison of the RTFibration-RTS + HCR and RTFibration-RTS + LCR series. The pulp quality from both series was interpolated at a freeness of 125 mL.

<table>
<thead>
<tr>
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<th>RTFibration-RTS+HCR</th>
<th>RTFibration-RTS+LCR</th>
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<tr>
<td>Freeness (mL)</td>
<td>125</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>SEC (kWh/ODMT)</td>
<td>1833</td>
<td>1476</td>
<td>2276</td>
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<td>Bulk (cm$^3$/g)</td>
<td>2.14</td>
<td>2.19</td>
<td>2.22</td>
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<tr>
<td>Tensile Index (Nm/g)</td>
<td>52.1</td>
<td>50.3</td>
<td>47.9</td>
</tr>
<tr>
<td>Tear Index (mN.m$^2$/g)</td>
<td>7.8</td>
<td>8.0</td>
<td>8.8</td>
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<tr>
<td>Shive Content (%)</td>
<td>0.26</td>
<td>0.14</td>
<td>0.40</td>
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<td>Scattering Coeff. (m$^2$/kg)</td>
<td>53.5</td>
<td>53.5</td>
<td>51.7</td>
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<td>+28 Mesh (%)</td>
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<td>Tensile Index@1475 kWh/ODMT</td>
<td>44.3</td>
<td>49.3</td>
<td>34.7</td>
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</table>

*Produced from white spruce in the Andritz Pilot Plant

Results from Study 1 indicate competitive high intensity thermomechanical pulps can be produced using multiple stage mainline LCR. The pulp properties were enhanced at a given application of specific energy using multi-stage LCR. Compared to previous work on low consistency refining of spruce TMP, the primary refined fibers from this investigation are more amenable to mainline LCR. The importance of proper fiber conditioning during the steps of chip defibration, high intensity refining, and selective chemical treatment cannot be overemphasized when LCR refining a high freeness TMP pulp for mechanical printing grades.
High intensity thermomechanical pulps produced using multiple-stage LCR can achieve energy savings in the range of 30% or greater compared to conventional TMP pulping. Selective pulp properties such as bonding strength, shive content, and scattering coefficient can be enhanced in tandem with a reduced energy consumption.

**Study 2: Multi-Stage LC Refining of white spruce at 5%-6% consistency**

This section presents results obtained from Study 2 on multi-stage LCR refining of white spruce RTFibration-RTS pulps at 4.9% consistency and 5.7% consistency, respectively.

**Figure 9** presents the freeness as a function of specific energy consumption. Compared at a freeness of 125 mL, the specific energy consumption of the multi-stage LCR refined series at 4.9% and 5.7% (here-to referred as 4.9% LCR and 5.7% LCR) consistency were 1674 kWh/ODMT and 1572 kWh/ODMT, respectively.

**Figure 10** presents the tensile results as a function of specific energy consumption. The tensile-SEC relationship was similar for both series. Compared at specific energy application of 1600 kWh/ODMT, the tensile index of the 4.9% LCR and 5.7% LCR series were 46.6 N.m/g and 47.2 N.m/g, respectively.

**Figures 11 through 14** present several pulp properties versus freeness for the multi-stage LCR series refined at 4.9% and 5.7% consistency.

Referring to **Figure 11**, the handsheet bulk was similar for both the LCR series. The tensile index of the 4.9% LCR and 5.7% LCR series at a freeness of 125 mL was 47.5 N.m/g and 46.0 N.m/g, respectively (See **Figure 12**). The tear index for the 4.9% LCR and 5.7% LCR series at a freeness of 125 mL was 8.7 mN.m²/g and 8.4 mN.m²/g, respectively (See **Figure 13**). It is noted that the tensile index of the 4.9% LCR series had a peak at a freeness of approximately 100 mL, which corresponded to a third-pass LCR SEC application of approximately 200 net kWh/ODMT.

**Figure 14** presents the shive content results for both series as a function of freeness. Both the 4.9% and 5.7% consistency multi-stage LCR series had a similar trend.

Table II presents a comparison of the multi-stage LCR series at a freeness of 125 mL. The pulp quality from both series was interpolated at a freeness of 125 mL.

<table>
<thead>
<tr>
<th>Pulp Property</th>
<th>4.9% Consistency</th>
<th>5.7% Consistency</th>
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<tbody>
<tr>
<td>Freeness (mL)</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>SEC (kWh/ODMT)</td>
<td>1674</td>
<td>1572</td>
</tr>
<tr>
<td>Bulk (cm³/g)</td>
<td>2.36</td>
<td>2.38</td>
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<tr>
<td>Tensile Index (Nm/g)</td>
<td>47.5</td>
<td>46.0</td>
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<tr>
<td>Tear Index (mN.m²/g)</td>
<td>8.7</td>
<td>8.4</td>
</tr>
<tr>
<td>Shive Content (%)</td>
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<td>0.84</td>
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<tr>
<td>Scattering Coefficient (m²/kg)</td>
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<tr>
<td>+28 Mesh (%)</td>
<td>30.2</td>
<td>28.4</td>
</tr>
<tr>
<td>Tensile Index@1600 kWh/ODMT</td>
<td>46.6</td>
<td>47.2</td>
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Mainline LCR refining in the 5%-6% consistency range is a feasible alternative for the production of low energy thermomechanical pulp. The pulps demonstrated a refining behavior similar to multiple stage LCR refining at 4% consistency, however, at a considerably reduced pumping volume.

Apart from energy savings, benefits may include a reduction in the number of LC refiners and related capital equipment for high capacity TMP lines. Future work will evaluate the development of thermomechanical pulp quality and energy consumption at pumping consistencies in excess of 6%.
CONCLUSIONS

× Newsprint grade thermomechanical pulp was produced with approximately 1500 kWh/ODMT using a combination of chip fibration, high intensity primary refining and multiple-stage low consistency refining.

× The pulp fibers following primary refining were effectively developed using a multi-stage LCR sequence; the physical pulp properties were comparable to the control HCR pulps when refined to newsprint freeness levels.

× Displacing about 400 mL of HCR refining with multi-stage LCR resulted in a specific energy savings of approximately 360 kWh/ODMT.

× Increasing the refining consistency during multi-stage LCR to approximately 5%-6% is a feasible alternative for producing low energy TMP pulps at minimal operating and installed cost.

× Forecasted increases in electricity rates will continue to force paper producers to adopt lower energy TMP technologies. This study demonstrated that modifications to the front end of the thermomechanical pulping process can be used to substitute HCR refining stages with LCR and take a step reduction in specific energy consumption.

ACKNOWLEDGEMENTS

Special thanks to all personnel of the Andritz Springfield Research and Development Center for their skillful contributions to the pilot plant work and testing of pulp samples.

References

Fig. 9  Freeness versus SEC
4.9% and 5.9% Consistency

Fig. 10  Tensile Index versus SEC
4.9% and 5.9% Consistency

Fig. 11  Handsheet Bulk versus Freeness
4.9% and 5.9% Consistency

Fig. 12  Tensile Index versus Freeness
4.9% and 5.9% Consistency

Fig. 13  Tear Index versus Freeness
4.9% and 5.9% Consistency

Fig. 14  Shive Content versus Freeness
4.9% and 5.9% Consistency
Minimizing TMP energy consumption using a combination of chip pretreatment, RTS and multiple stage low consistency refining

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Energy Consumption in TMP

• Spruce newsprint: 1900 – 2400 kWh/ODMT

• Spruce LWC: 3000 – 3600 kWh/ODMT

• Demands today are for lower power consumption

• Often driven by the local power utility. High peak rate costs and rising off-peak rates
LCR Refiniers in Mainline TMP

- Low consistency refiners (LCR) installed in the mainline position (after latency chest) in a number of TMP mills. Often in conjunction with a capacity increase.

- Single stage LCR applications. Typically less than 150 kWh/ODMT.

- 5% - 8% energy savings.
RTFibration™

- RTFibration introduced at IMPC 2003
- Gentle separation of wood fibers using a combination of pressurized Pressafining and fiberizer refining actions
RTFibration Objectives

- Separating the wood into its basic constituents (*defibration*)
- Transforming the individual fibres into suitable properties for papermaking (*fibrillation*)
RTPressafined and Fiberized Chips
Magnification of Fiberized Chips
RTFibration

- Fiberized chips are more amenable to an increase in refining intensity

- Two explanations:
  - Fiberized chips have more surface area for heat and chemical penetration improving the softening behavior
  - Fiberized chips are more pliable and less susceptible to breakage during refining
RTFibration-RTS

- Combined with RTS and a chemical treatment greater than 25% energy savings are realized compared to conventional TMP

- Refined fiber is more flexible and better developed
Combining RTFibration-RTS and LCR

- The present study involved coupling RTFibration-RTS with LCR
- Multiple stage LCR
- LCR refine at a higher starting freeness
Objectives

- Maximize HCR displacement with LCR
- Commence LCR following primary refining.
- Eliminate secondary HCR refining step
- Produce spruce TMP pulp for newsprint at energy levels comparable to groundwood pulp
Experimental – Study 1

HCR versus Multiple stage LCR

- White spruce
- RTPressafiner chip pretreatment (1.4 bar)
- Fiberizer refining (1.4 bar)
- RTS primary refining (5.9 bar, 2300 rpm) to a freeness of 516 mL
- Chemical treatment (2.6%) applied
- Primary refined pulp mixed and separated in two batches
RTS Technology

(R) Low Retention Time (10 seconds)

(T) High Refiner Inlet and Case Pressure (5.9 bar)

(S) High Refiner Disc Speed (2300 rpm)
Primary Refiner Plates

Durametal 36604 - Directional Feeding
Experimental – Study 1

Batch 1 (HCR)

- Secondary high consistency refining of primary pulp (2.8 bar, 1800 rpm) to 204 mL
- Tertiary high consistency refining (atmospheric)
- Three levels of specific energy applied in tertiary refining stage (531, 734, 891 kWh/tonne)
Batch 2 (LCR)

- Primary pulp at 516 mL refined using four stages of Low Consistency Refining (LCR)
- Approx. 100 kWh/tonne net energy applied in stages 1 (412 mL), 2 (357 mL) and 3 (318 mL)
- Five levels of specific energy applied in quaternary LCR refining stage (27, 75, 129, 173, 228 kWh/tonne)
Results and Discussion – Study 1

• Comparison of RTFibration-RTS pulps produced with HCR versus multiple stage LCR refining

• Figures from both series plotted for comparison
Freeness versus Specific Energy

- RTF-RTS + LCR
- RTF-RTS + HCR

Specific Energy (kWh/ODMT)
Tensile index versus Specific Energy

Specific Energy (kWh/ODMT)

Tensile index (Nm/kg)

- RTF-RTS + LCR
- RTF-RTS + HCR
Bulk versus Freeness

- RTF-RTS + LCR
- RTF-RTS + HCR

Graph showing the relationship between Bulk [cgs/g] and Freeness (mL) with two distinct datasets.
# HCR versus Multi-stage LCR

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<td>125</td>
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<tr>
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<td><strong>Freeness (mL)</strong></td>
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<tr>
<td><strong>Bulk (cm³/g)</strong></td>
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HCR versus Multi-stage LCR

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<td>Tensile Index at 1475 kWh/tonne</td>
<td>44.3</td>
<td>49.3</td>
<td>34.7</td>
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Summary - Study 1

• Competitive high intensity TMP pulps were produced using multiple stage LCR

• The fibres were sufficiently softened following primary refining to allow effective pulp strength development using LCR
Experimental – Study 2
Multiple stage LCR at higher consistency

- White spruce
- RTPressafiner chip pretreatment (1.4 bar)
- Fiberizer refining (1.4 bar)
- RTS primary refining (5.9 bar, 2300 rpm) to a freeness of 516 mL
- No chemical treatment applied
Experimental – Study 2

- Primary refined pulp was secondary refined to a freeness of 309 mL

- Secondary refining was conducted to compensate for no chemical treatment/softening
Experimental – Study 2

- Pulp split into two batches
- Batch 1 LCR refined in three stages at a consistency of 4.9%
- Batch 2 LCR refined in three stages at a consistency of 5.7%
Freeness versus Specific Energy

Specific Energy (kWh/ODMT)

LCR 4.9%

LCR 5.7%
Bulk versus Freeness

<table>
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<th>Freeness (mL)</th>
<th>LCR 4.9%</th>
<th>LCR 5.7%</th>
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<tr>
<td>30</td>
<td>1.80</td>
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- LCR 4.9%
- LCR 5.7%
Tensile index versus Freeness

- LCR 4.9%
- LCR 5.7%
Tear index versus Freeness

LCR 4.9%

LCR 5.7%
## Multi-stage LCR at higher consistency

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<td>Freeness (mL)</td>
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<td>Tensile index (Nm/g)</td>
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## Multi-stage LCR at higher consistency

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</tr>
<tr>
<td>Shive content (%)</td>
<td>0.67</td>
<td>0.84</td>
</tr>
<tr>
<td>Scattering coeff. (m²/kg)</td>
<td>54.7</td>
<td>56.3</td>
</tr>
</tbody>
</table>
Multi-stage LCR at higher consistency

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Consistency (%)</td>
<td>4.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Tensile Index at 1600 kWh/tonne</td>
<td>46.6</td>
<td>47.2</td>
</tr>
</tbody>
</table>
Results and Discussion – Study 2

• Mainline LCR refining in the 5% - 6% consistency range is a feasible alternative for the production of thermomechanical pulps at lower energy consumption

• Pumping volumes are considerable reduced

• May reduce the number of LCR refiners for higher capacity TMP lines
Conclusions

• News grade TMP pulp was produced with approx. 1500 kWh/tonne using a combination of chip fibration, high intensity primary refining and multiple stage LCR

• The multiple stage LCR refined pulp had comparable strength properties to the control HCR refined pulp

• Displacing approx. 400 kWh/tonne of HCR refining with LCR resulted in an energy savings of 360 kWh/tonne
Conclusions

- Increasing the refining consistency during multiple stage LCR to 5% - 6% range is a feasible alternative.
- Forecasted increases in electricity rates will continue to pressure mills to reduce TMP power consumption.
- Modifications to the front end of the TMP process can be used to help substitute more HCR refining energy with LCR.
Acknowledgements

• Special thanks to the personnel at the Andritz Laboratory in Springfield for their contributions to the pilot plant work and testing of pulp samples
THANK YOU FOR YOUR ATTENTION