Kraft Pulp and Paper Mill Utilization Options for Grey-Stage Wood

Theodore Radiotis, Richard Berry,
Ian D. Hartley* and Tara M. Todoruk*

Mountain Pine Beetle Working Paper 2008-09

MPBI Project # 8.50

Pulp and Paper Research Institute of Canada,

570 St. John's Blvd, Pointe-Claire, QC, Canada, H9R 3J9

*University of Northern British Columbia,

3333 University Way, Prince-George, BC, Canada V2N 4Z9

Natural Resources Canada
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5

2008

Library and Archives Canada Cataloguing in Publication

**Kraft Pulp and Paper Mill : utilization options for grey-stage wood /
Theodore Radiotis ... [et al.].**

**(Mountain Pine Beetle Initiative working paper 2008-09)
"MPBI Project # 8.50".
"Mountain Pine Beetle Initiative, Canadian Forest Service".
Includes bibliographical references: p.
Includes abstract in French.
ISBN 978-0-662-48889-7
Cat. no.: Fo143-3/2008-9E**

1. Wood chips--British Columbia--Quality control. 2. Wood-pulp--British Columbia--Quality control. 3. Pulping--British Columbia--Quality control. 4. Lodgepole pine--Diseases and pests--Economic aspects. 5. Mountain pine beetle--Economic aspects. I. Radiotis, Theodore, 1965- II. Pacific Forestry Centre III. Series.

SB945.M78K72 2008 676'.121 C2008-980188-1

Abstract

Lodgepole pine (*Pinus contorta*) that is attacked and killed by mountain pine beetle (*Dendroctonus ponderosae*) goes through several stages (red and grey) following the attack. Wood moisture content decreases rapidly, typically to below fibre saturation point. As a consequence, the wood responds differently in both the chipping and pulping processes. Research on beetle-attacked wood has shown that many physical properties are not affected, however wood-water interactions have not been studied in detail. In the two parts of this study, we examine the sorption behaviour of beetle-killed wood in comparison to green wood; and explore the influence of utilization of dry beetle-killed wood on kraft pulping operations and pulp quality.

In the first part, it was found that the sorption of red and grey pine wood was slightly higher than of non-attacked logdepole pine for both the adsorption and desorption cases. The fibre saturation point was considerably higher for the beetle-killed wood: 0.331 for non-attacked lodgepole pine, 0.365 for red wood, and 0.394 for grey wood. The hysteresis was found to be similar over a humidity range between 20 and 80%. Based on the nuclear magnetic resonance studies, the red and grey wood had a higher $T_{2,}$ indicating a looser environment for the molecular motion of the water. This may be a result of the fungi changing the cell-wall structure, demonstrated by a higher fibre saturation point, as well as a higher T_2 compared to non-attacked wood.

In the second part, kraft pulping of green-attack, grey and kiln-dried lodgepole pine wood was compared. The dry wood, during chipping, produced a higher proportion of fines and lower fraction of accepts than the wetter green-stage chips. Pre-treatment of the chips with a steam/soak process prior to pulping reduced screening rejects from 1 to 2% (no pre-treatment) to less than 0.5% (on oven-dried. wood basis). Green-stage chips cooked faster, had a 3-4% higher pulp yield, consumed less EA, and had a 3-point higher tear index than grey-stage or kiln-dried chips. These differences were explained through differences in wood composition and are likely caused by tree-to-tree variability rather than mountain pine beetle infestation. In LoSolids® pulping of green/dry chip mixture cooks, tear index decreased linearly by 0.03 mN m^2/g for every 1% of dry chips added to the mixture. Furthermore, the liquor circulation flows decreased as the proportion of dry chips increased in the mixture cooks, a consequence of the higher pins and fines content in the dry chips. The changes in pins and fines content have the potential to affect pulping uniformity and cause screen plugging in industrial systems.

Keywords: Mountain pine beetle, lodgepole pine, green-stage, grey-stage, kiln-dried, kraft pulping, pre-steaming, pulp quality, dry wood, wood-water interaction, sorption, NMR, fibre saturation point, LoSolids® pulping

Résumé

Le pin tordu (*Pinus contorta*) attaqué et détruit par le dendroctone du pin ponderosa (*Dendroctonus ponderosae*) passe par plusieurs stades (rouge et gris) après l'attaque. Le degré d'humidité du bois diminue rapidement, généralement au-dessous du point de saturation des fibres. Par conséquent, le bois répond différemment aux processus de déchiquetage et de réduction en pâte. Selon les recherches réalisées sur du bois attaqué

par le dendroctone, bon nombre des propriétés physiques du bois ne sont pas touchées. Les chercheurs n'ont toutefois pas étudié en détail les interactions bois-eau. Dans les deux parties de l'étude, nous examinons la capacité de sorption du bois détruit par le dendroctone par rapport au bois vert. De plus, nous explorons les répercussions de l'utilisation de bois sec détruit par le dendroctone sur les procédés kraft et la qualité de la pâte.

Dans la première partie de l'étude, nous expliquons que la capacité de sorption du bois de pin au stade rouge et gris était légèrement supérieure à celle du bois du pin tordu non attaqué, qu'il s'agisse de l'adsorption ou de la désorption. Le point de saturation des fibres était considérablement plus élevé pour le bois détruit par le dendroctone : 0,331 pour le pin tordu non attaqué, 0,365 pour le bois au stade rouge et 0,394 pour le bois au stade gris. Selon les résultats obtenus, l'hystérésis était similaire, si le degré d'humidité se situait entre 20 et 80 %. Selon les études sur la résonance magnétique nucléaire, le T_2 du bois au stade rouge et gris était supérieur, ce qui indique que les molécules de l'eau peuvent se déplacer plus facilement. L'une des explications possibles est que les champignons modifient la structure de la paroi cellulaire, comme le démontrent l'accroissement du point de saturation des fibres et l'augmentation du T_2, par rapport au bois non attaqué.

Dans la deuxième partie de l'étude, nous avons comparé le procédé kraft du bois de pin tordu au stade vert, au stade gris et séché au séchoir. À l'étape du déchiquetage, le bois sec a produit plus de fines et moins d'acceptés que les copeaux humides obtenus au stade vert. Le prétraitement des copeaux à la vapeur ou à l'aide du trempage, avant la réduction du bois en pâte, a permis de réduire les rejets de 1 à 2 % (sans prétraitement) à moins de 0,5 % (pour le bois anhydre). Les copeaux au stade vert cuisaient plus rapidement, avaient un rendement en fibres de 3 à 4 % supérieur, consommaient moins d' alcali effectif et leur indice de déchirement était de 3 points supérieur à celui des copeaux au stade gris ou séchés au séchoir. Ces différences s'expliquent par les différences dans la composition du bois. Elles sont probablement attribuables à la variabilité entre les différents arbres plutôt qu'à une infestation par le dendroctone du pin ponderosa. Dans la cuisson LoSolids® utilisée pour réduire les copeaux au stade vert et secs en pâte, l'indice de déchirement a diminué linéairement de 0,03 mN m^2/g pour chaque pour cent de copeaux secs ajoutés au mélange. Qui plus est, les flux de circulation de l'eau de brassage ont diminué au fur et à mesure que le pourcentage de copeaux secs augmentait dans le mélange, car les copeaux secs contiennent davantage de pins et de fines. Le changement en teneur de pins et de fines pourrait avoir des répercussions sur l'uniformité de la réduction du bois en pâte et entraîner le bouchage des cribles dans les systèmes industriels.

Mots-clés : Dendroctone du pin ponderosa, pin tordu, stade vert, stade gris, séché au séchoir, procédé kraft, prévaporisage, qualité de la pâte, bois séché, interaction bois-eau, sorption, RMN, point de saturation des fibres, cuisson LoSolids®.

Contents

List of Tables

List of Figures

PART I Wood-water interaction of lodgepole pine (*Pinus contorta*) wood chips affected by the mountain pine beetle (*Dendroctonus ponderosae*)

By Ian D. Hartley and Tara M. Todoruk

I-1 Introduction

In British Columbia, the mountain pine beetle (*Dendroctonus ponderosae*) has been attacking millions of cubic meters of standing timber of lodgepole pine (*Pinus contorta*). After the attack, the tree goes through "time-since-death" (*tsd*) stages: the red stage, where the tree shows characteristics of dying (i.e., red needles) in the stand for 2-4 years, and the grey-stage, where the tree has been dead in the stand for 5 or more years (Thrower et al. 2004; Lewis and Hartley 2006). This classification is used in British Columbia to characterize the wood that comes from the dead tree.

The wood from the infested tree has been examined by many researchers to determine the effect of the blue fungi stain produced from the attack and its impact on the physical properties. Summary research (Lewis and Hartley 2006) on wood from the beetle-attacked tree has shown that many physical properties are not affected. However, there has been no detailed study of the wood-water interaction, especially sorption behavior of the wood, based on the stages of time-since-death of the tree. Therefore, the objectives of the work were to determine the sorption isotherm for the wood, both adsorption and desorption behavior, and to characterize the wood-water interaction using nuclear magnetic resonance (NMR).

I-2 Materials and Methods

Lodgepole pine logs from the central interior of British Columbia were obtained by Paprican based on *tsd*-stages, red and grey-stage (denoted as MPB-R and MPB-G, respectively) as well as a non-attacked lodgepole pine (denoted as LP) which was used as a control. The logs were chipped whole with no difference made between sapwood and heartwood; therefore, sapwood and heartwood chips were present in each sample set. The average size of the wood chips (n=30) was 2.77 mm (standard error s.e.= 0.20 mm) in thickness, 17.52 mm (s.e. = 1.15 mm) perpendicular to the grain, and 21.41 mm (s.e. = 0.46 mm) along the grain.

For the purpose of this study, the wood chips were conditioned for different moisture contents below the fibre saturation point that established the sorption isotherm and were used for the NMR experiments.

I-2.1 Moisture Content Conditioning

Approximately 25.00 g (±0.01 g) of wood chips was used as a sample set comprised of randomly selected chips, ensuring that there was a sufficiently random sample chosen for the *tsd*-stages. Each sample set had a variety of blue-stained wood indicated as beetle-attacked wood, except for the LP set.

The moisture content of the wood chips was attained by conditioning the chips in dessicators of various salt solutions, providing steady humid environment. The salts used were: lithium chloride (LiCl, Humidity H = 20%); calcium chloride ($CaCl_2$, H = 35%); sodium dichromate ($Na_2Cr_3O_7 \cdot 2H_2O$, H = 66%); sodium nitrite ($NaNO_2$, H = 73%); and sodium sulfate anhydrous (Na_2SO_4, H = 93%). The humidity was measured during the experiment to the nearest 0.1% to ensure specific and constant relative humidities in each dessicator. A stir bar was added to the salt solution in each dessicator to ensure uniform mixing of the solution for a stable humidity.

For desorption, the freshly chipped samples were put directly into the dessicators with no conditioning. Following the desorption experiments, the samples were oven-dried in a convection oven for 24 hr at 103°C (± 1°C) and used for adsorption experiments. Once they were dried, the samples were moved into a dessicator of anhydrous calcium sulfate (Drierite) to allow the samples to cool to room temperature without allowing any gain in moisture before being used in the first humidity step.

Each sample was weighed daily as quickly as possible on a digital scale (to an accuracy of 0.01 g), as to not upset the equilibrium humidity in each desiccator. The weighing continued until the mass remained constant, within 0.01 g for 48 hrs, indicating equilibrium. These measurements were done at constant room temperature, 22 ± 2°C.

The dry-basis moisture content fraction, *m*, was calculated using the following equation:

$$m = \left(\frac{w - w_{od}}{w_{od}} \right) \qquad (1)$$

where *w* was the weight of the sample at each specific humidity condition and w_{od} was the weight of the sample at the oven-dry condition.

The procedure outlined above was used to gather the data for the sorption isotherm. The GAB isotherm model (Hartley 2000) was used to analyze the data; the results are presented in Todoruk and Hartley (2006).

I-2.2 NMR Studies

NMR relaxation measurements were performed on a modified Bruker SXP 60 pulse NMR spectrometer, operating at 26 MHz. All experiments were conducted at room temperature (23°C). The free induction decay (FID) data curves were obtained through the application of a single 90° pulse, and 1000 accumulations were obtained. The work was done at the University of Waterloo.

The data were fitted to the following equation:

$$y = B \cdot \frac{\sin\left(\frac{x}{u}\right)}{\left(\frac{x}{u}\right)} \cdot \exp\left(-\left(\frac{x}{T_{2B}}\right)^2\right) + A \cdot \exp\left(-\left(\frac{x}{T_{2A}}\right)^2\right) + C \cdot \exp\left(-\frac{x}{T_{2C}}\right) + D \cdot \exp\left(-\frac{x}{T_{2D}}\right) + q \quad (2)$$

where *B*, *A*, *C*, and *D* were regression coefficients for the sinc, gaussian, and two exponential functions, respectively, and T_{2B}, T_{2A}, T_{2C}, and T_{2D} were the spin-spin relaxation times for the sinc, gaussian, and 2 exponential components, respectively. The sinc and gaussian functions represent the wood and the exponential functions represent the water in the wood-water system. Further, the sinc function has been demonstrated to represent the 'rigid' area of the cell wall material and the gaussian function is related to the amorphous regions.

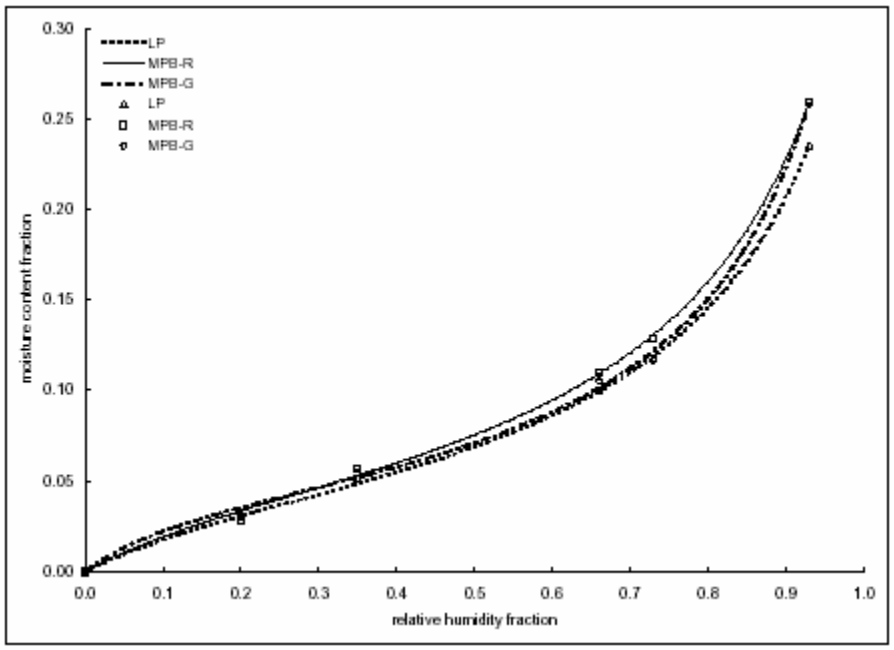
I-3 Results and Discussion

I-3.1 Sorption Experiment

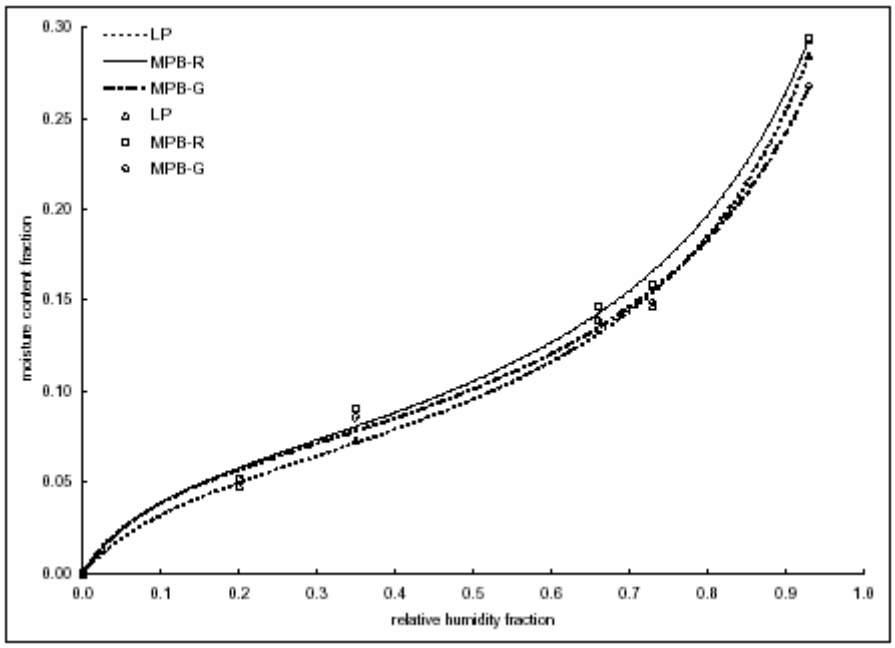
I-3.1.1 Adsorption and Desorption Isotherms

Figure I-1(a) and (b) show the sorption isotherms for wood. The equilibrium moisture contents (m_e) of the sorption isotherm were higher for both MPB-R and -G compared to LP for both adsorption and desorption. For the adsorption case (Figure I-1(a)), the MPB-R and -G wood also followed the same trend as the LP wood, but the MPB-R and -G wood has a slightly higher adsorption than LP at the same relative humidity.

The m_e values for the adsorption case were compared to literature values of lodgepole pine at 30°C (Avramidis and Iliadis 2005). In this study, values of m_e at low h were similar to that of Avramidis and Iliadis (2005), but at h=0.93, our values were much higher, especially for MPB-R and -G wood. However, compared to the work done by Fan et al. (1999), the values of m_e in this study for lower relative humidities were similar to the literature values, while our values for m_e at h=0.93 were significantly higher than the published values, with the MPB-R and -G wood having a m_e about 7% higher compared to LP.



(a)



(b)

Figure I-1: Isotherms for mountain pine beetle-attacked (MPB-R and –G) and non-attacked (LP) lodgepole pine: (a) adsorption and (b) desorption.

For the desorption case, at the lower h, the values from this study were comparable to Fan et al. (1999) and at h=0.93, the values from this study were significantly higher, with the MPB-R wood having a value for m_e about 6% higher than the literature values. For initial desorption, the MPB-R wood has a higher m_e compared to the LP and MPB-G wood. Below h=0.75, the m_e for MPB-G wood was higher than the LP wood (Figure I-1(b)). The trend remained for both adsorption and desorption in that the m_e for MPB-R wood was higher than both LP and MPB-G wood. For the range h=0.20 to 0.80, both the adsorption and desorption cases followed the same trends, where the MPB-R and -G wood had a higher m for a given h than the LP control.

I-3.1.2 Fibre Saturation Point

The fibre saturation point (m_{fsp}) of the MPB-R and -G wood and LP wood was estimated by using the GAB model with adsorption regression coefficients (Todoruk and Hartley 2006). It was found that the values for m_{fsp} were 0.331 for LP, 0.365 for MPB-R, and 0.394 for MPB-G. The importance of this finding was that the m_{fsp} is considerably higher than the generally accepted 0.30 for temperate wood (Skaar 1988) and that the beetle-killed wood has a very high fibre saturation point.

I-3.1.3 Hysteresis

Based on the regression equation from the GAB model (Todoruk and Hartley 2006), the hysteresis for each type of wood was examined (Figure I-2). At low humidities (h<0.20), the MPB-R wood had a lower hysteresis whereas the MPB-G wood had a higher hysteresis. At h>0.80, the MPB-G wood had the highest hysteresis and the LP control had the lowest hysteresis. However, the response to humidity between h=0.20 and 0.80 is similar.

Stamm (1964) reported the average hysteresis value for klinki pine as 0.78; Skaar (1988) and Hartley and Avramidis (2002) reported the average hysteresis value of lodgepole pine at 30°C to be 0.788. In this study, the calculated average hysteresis value for LP was found to be 0.69 (s.e. = 0.10), MPB-R was found to be 0.68 (s.e. = 0.13) and MPB-G was found to be 0.70 (s.e. = 0.11). Therefore, despite the hysteresis differences at low and high relative humidities as shown in Figure I-2, the respective averages were statistically the same over the entire hygroscopic range.

A possible explanation for the higher m_e and lower hysteresis in the study compared to literature values could be attributed to the physical size of the samples. The wood chips in this study were smaller compared to the wood samples in the other studies, allowing for more water to be adsorbed (adsorption) or held (desorption), giving higher m_e (Skaar 1988) during the sorption process. It has been suggested that large pieces of wood (i.e., a 2 X 4 board) do not exhibit hysteresis, i.e., the ratio of moisture content during adsorption and desorption at constant humidity (A/D) =1 (Stamm 1964); therefore it is inferred that small samples would have a smaller A/D ratio as in this study.

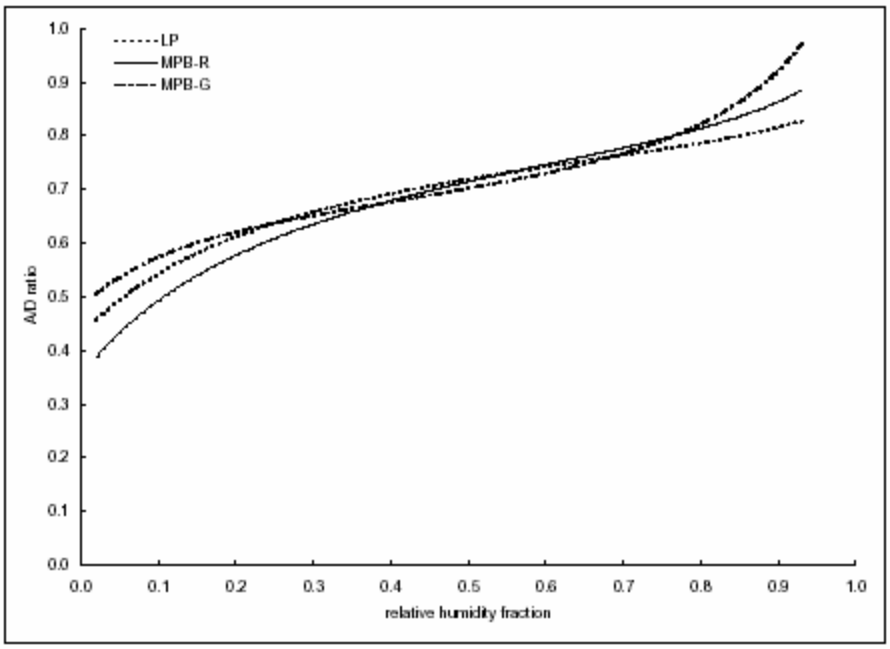


Figure I-2: Hysteresis values for mountain pine beetle-attacked (MPB-R and -G) and non-attacked (LP) lodgepole pine (from Todoruk and Hartley 2006).

I-3.2 NMR T_2

Figure I-3, through Figure I-6 present the T_2 for the wood and water components, as well as the signal fraction component, as a function of moisture content. The T_2 are used to explain the interaction of the water within the wood material. (For a simple illustration, pure water has a higher T_2 than ice where the molecular motion is becoming restricted and is indicated by a lower T_2. In this study, and based on Eq. 2, there are two components found for the wood and two components found for water.) For discussion, it is important to include the fraction components as well as the T_2's where the fraction components represent the strength of the signal as a contribution to the overall FID curve.

I-3.2.1 Wood Component

Figure I-3 (a, b) and Figure I-4 (a, b) show the T_2 and fraction components, respectively, for adsorption and desorption for the wood components. The upper set of data in the figures describe the sinc function of Eq. 2 and the lower set of data describe the gaussian function of Eq. 2. The wood T_2's are about the same for both adsorption and desorption. For the adsorption and desorption T_2's, there is not a lot of variation as a function of moisture content. That is, the T_2's and signal fractions are similar for each sorption case.

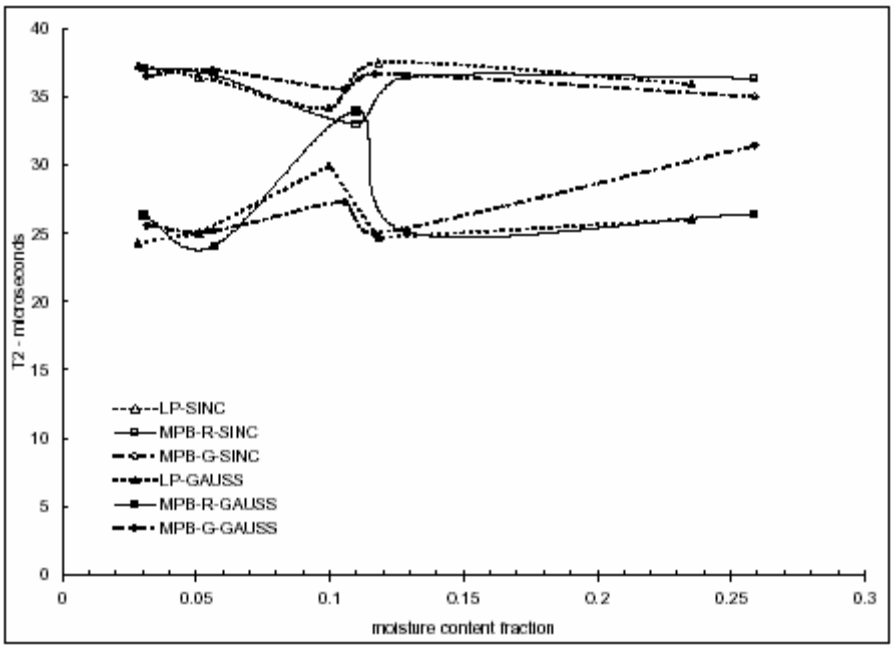
It should be noted that the differences between the three different types of wood (MBP-R, MBP-G and LP) are minor. A notable observation is the inflection of the data between m=0.10 and 0.15 which is more noticeable in the adsorption case; no explanation is provided for this occurrence.

I-3.2.2 Water Component

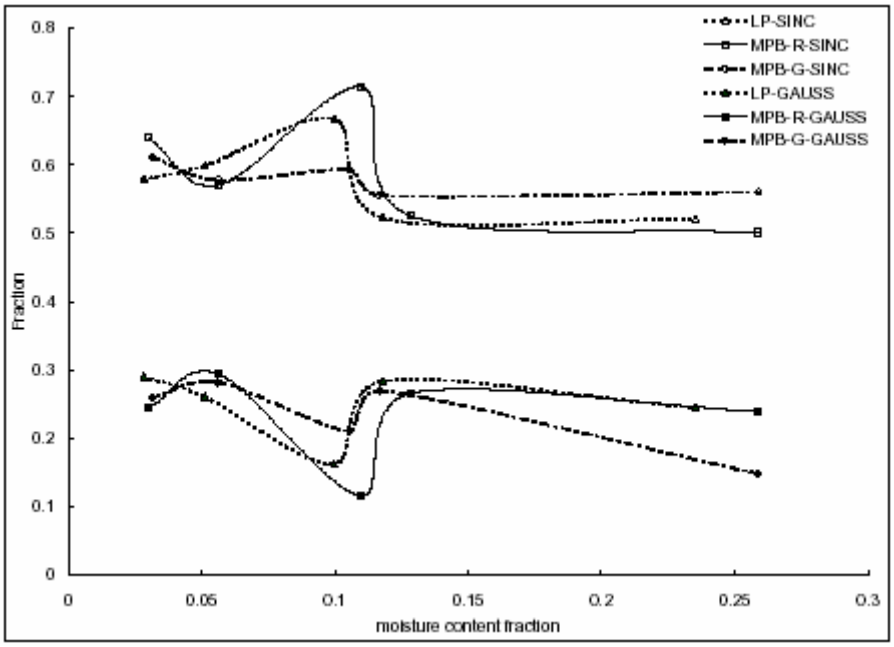
Figure I-5 (a, b) and Figure I-6 (a, b) show the T_2 and fraction components, respectively, for adsorption and desorption for the water components. There are two water components found, as described by Eq. 2. In the figures, the upper set of data is denoted as Component 1 and the other set of data is denoted as Component 2. The fraction Component 2 is about 5% of the signal strength for both adsorption and desorption. This is important to note because the finding of two components is only recent. It is apparent from Figure I-5(a) and Figure I-6(a) that the T_2 for Component 1 is influenced by the process of conditioning the samples, i.e., from desorption (drying) versus adsorption (explained below); Component 2 remained the same.

The T_2's for Component 1 for adsorption show an increase as the moisture content increases (Figure I-5(a)). As noted for the wood T_2's above, there is an inflection point between m=0.10 and 0.15 in Figure I-5(a) and Figure I-6(a) as well. Based on the *tsd*-stage, it appears that the LP has lower T_2's as a function of moisture content compared to the MPB-R and -G wood. This is evident in the desorption case (Figure I-6(a)) where the T_2's for the MPB-R and -G are considerably higher than for the LP wood.

It should be noted that the processes for water being adsorbed in wood is different than that of water leaving the wood (Hartley et al. 1992). Therefore, the interpretation of the adsorption and desorption T_2's are different. Except for the near m_{fsp}, the variation of the T_2's is the same for all of the samples. In the desorption case, however, there is a difference between the LP and the MPB-R and -G wood, which suggests that the water in the MPB-R and -G wood is different than in the LP in that the water is more liquid-like in comparison. It is not to say that there is more water, however, it is to say that the environment (i.e., wood-water interaction) is different. Since this difference is only in the attacked wood, it can be speculated that the water may be in a looser state or in parts of the wood that allow for higher T_2's, i.e., voids (Araujo et al. 1993). The fungi found in the blue-stained sapwood may create holes in the cell-wall of the tracheid, creating more voids (similar size of rays, or intercellular spaces) (Highley et al. 1994; Kirk and Cowling 1984) that allow for more molecular motion of the water corresponding to higher T_2's in the desorption case. The fact that the m_{fsp} is higher for the MPB-R and -G wood suggests that more water is present as a result of more voids in the wood.

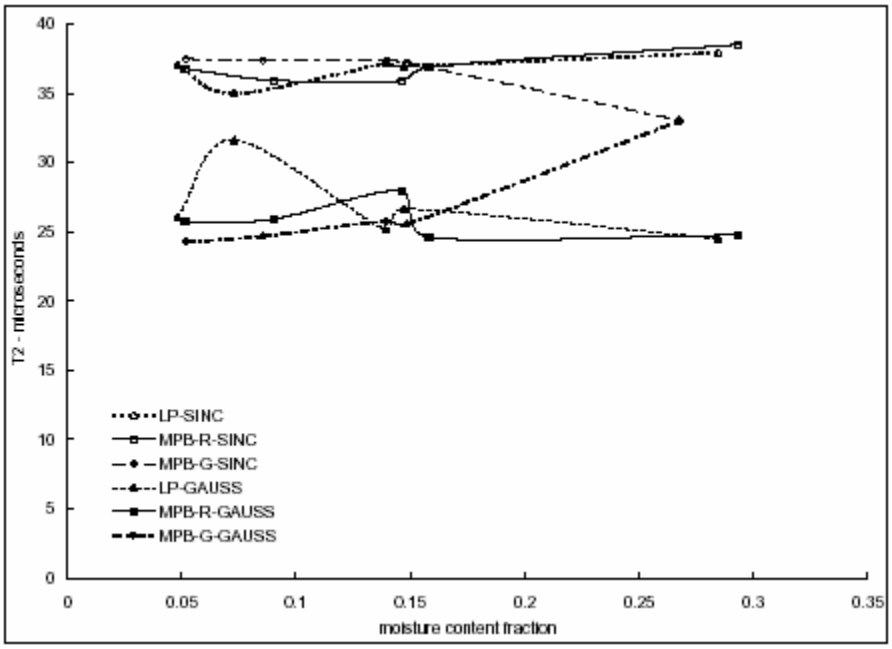


(a)

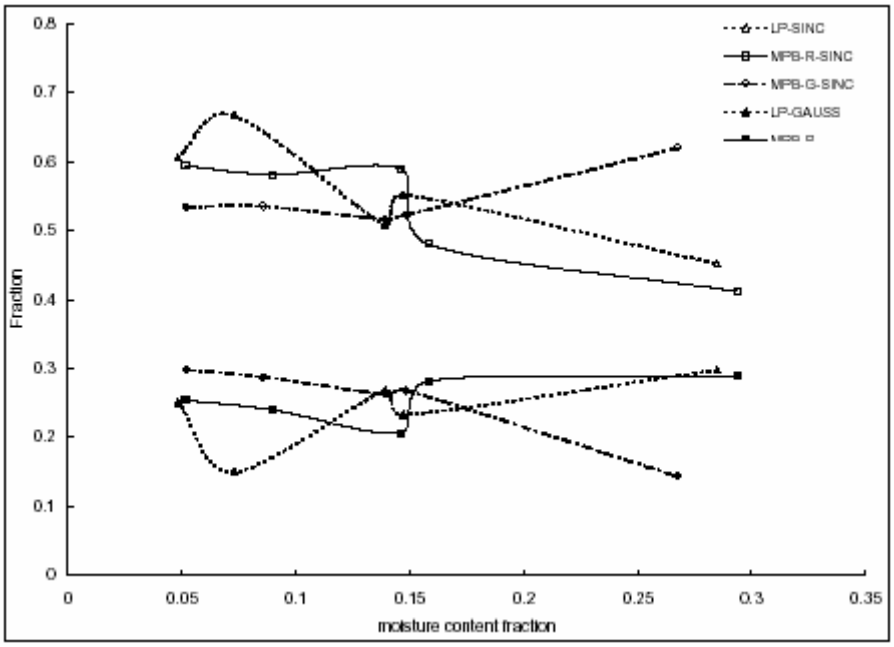


(b)

Figure I-3: Adsorption NMR values for wood component: MPB-R and –G and non-attacked (LP) lodgepole pine: (a) T_2 and (b) signal fraction.

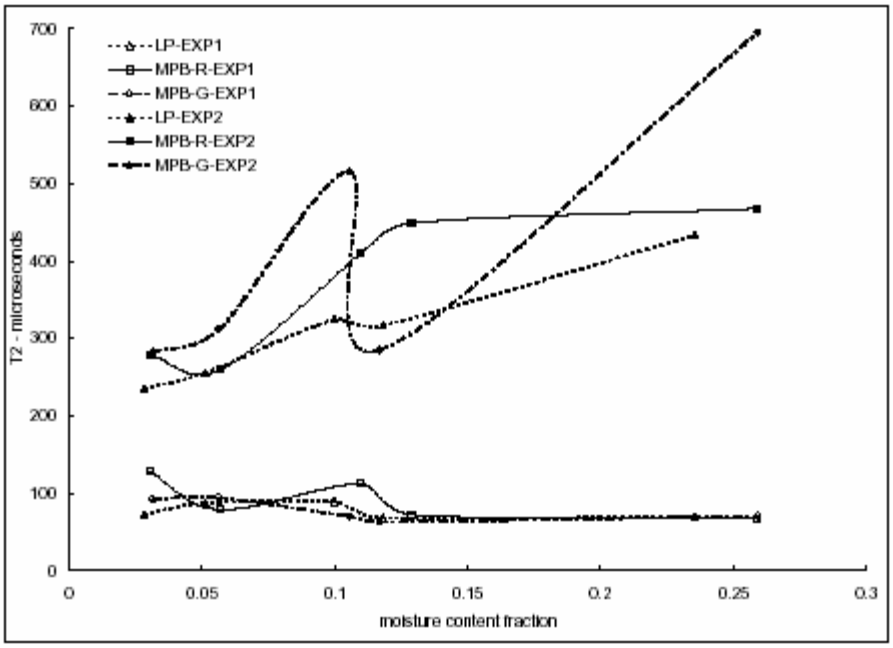


(a)

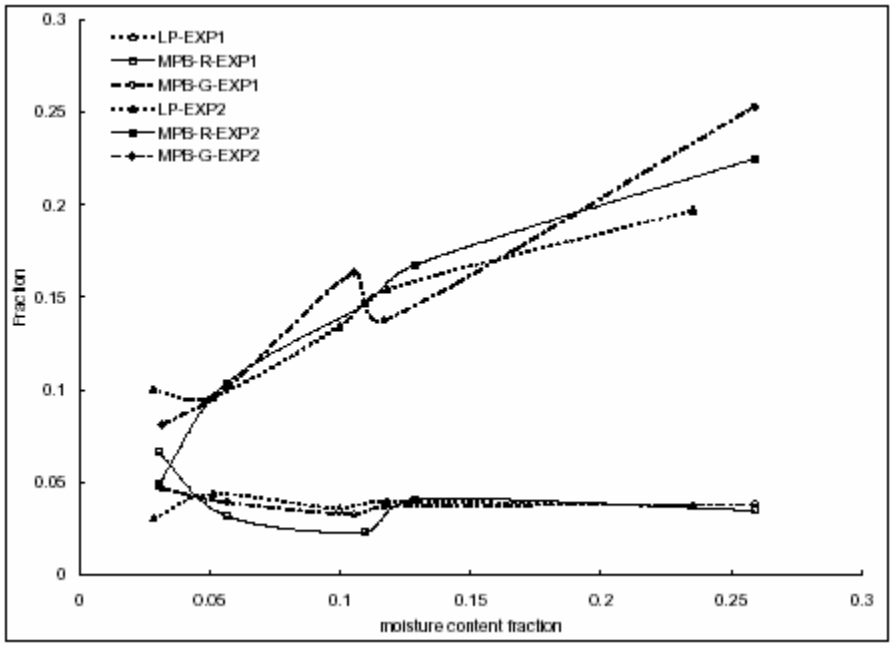


(b)

Figure I-4: Desorption NMR values for wood component: MPB-R and –G and non-attacked (LP) lodgepole pine: (a) T_2 and (b) signal fraction.

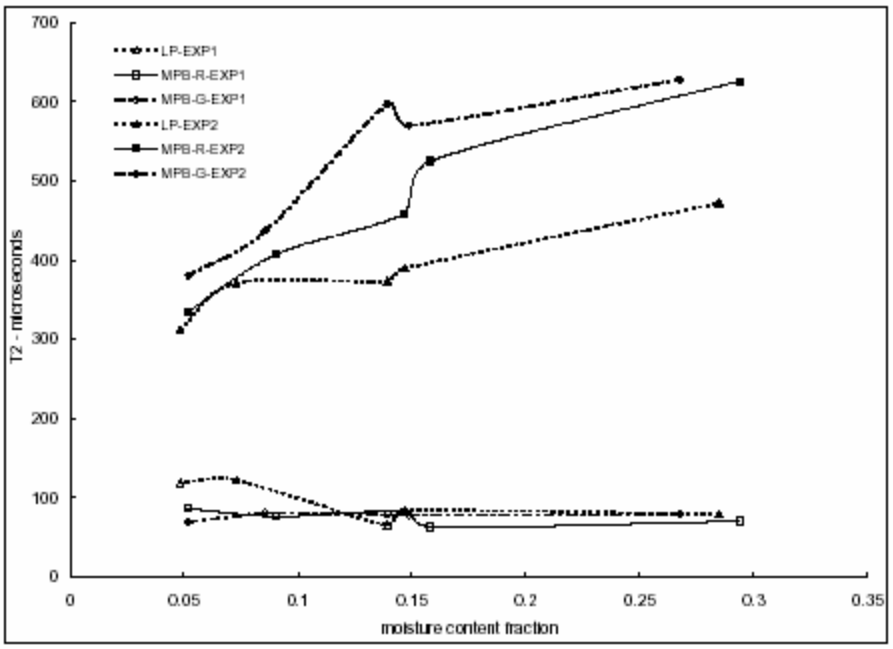


(a)

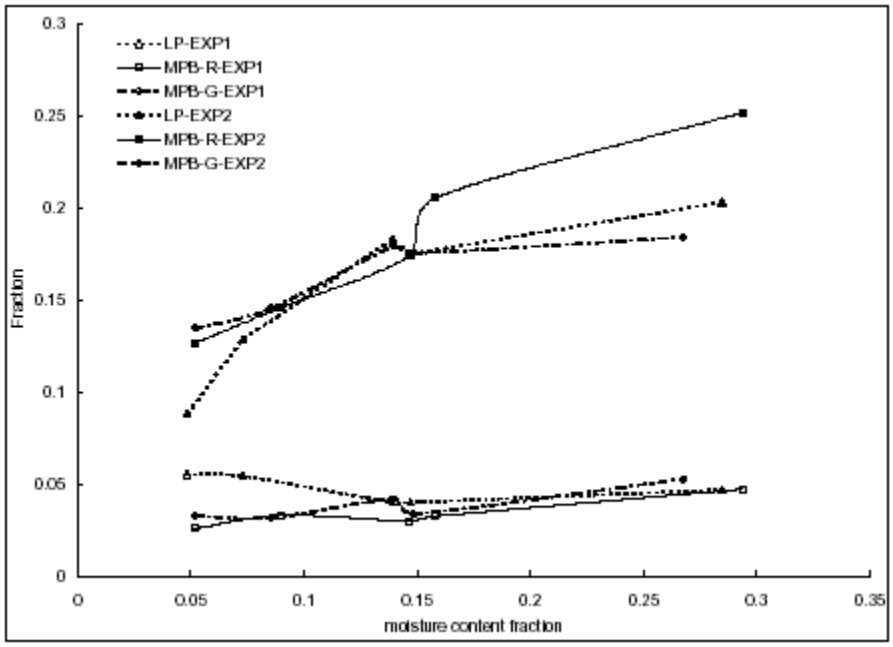


(b)

Figure I-5: Adsorption NMR values for water component: MPB-R and -G and non-attacked (LP) lodgepole pine: (a) T_2 and (b) signal fraction.



(a)



(b)

Figure I-6: Desorption NMR values for water component: MPB-R and -G and non-attacked (LP) lodgepole pine: (a) T_2 and (b) signal fraction.

I-4 Conclusion

The study showed that the basic wood-water interaction of wood that has been killed by the fungi associated with the mountain pine beetle is different from a sorption and NMR perspective. The sorption of the MBP-R and -G wood is slightly higher than the non-attacked logdepole pine. The fibre saturation point is considerably higher for the MBP-R and -G wood. The hysteresis was found to be similar over a humidity range between 20 and 80%. Based on the nuclear magnetic resonance studies, the MBP wood had a higher T_2 indicating a looser environment for the molecular motion of the water. This may be a result of the fungi changing the cell-wall structure, demonstrated by a higher fibre saturation point as well as a higher T_2, compared to non-attacked wood.

I-5 Acknowledgements

This project was funded by the Government of Canada through the Mountain Pine Beetle Initiative, a Program administered by Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resource Canada – Canadian Forest Service.

Support for this study was provided by EvalutreeTM Wood and Fibre Laboratory (a partnership among the Pulp and Paper Research Institute of Canada, the University of Northern British Columbia, and the University of Victoria) and Natural Science and Engineering Research Council (Discovery Grant). The authors would like to thank Dr. H. Peemoeller, R. Teymoori, and J. Liang for their assistance at the University of Waterloo.

I-6 Literature Cited

Araujo, C.D., MacKay, A.L., Whittall, K.P. and Hailey, J.R.T. 1993. A diffusion model for spin-spin relaxation of compartmentalized water in wood. Journal of Magnetic Resonance B 101(3):248-261

Avramidis, S. and Iliadis, L. 2005. Wood-water sorption isotherm prediction with arti_cial neural networks: A preliminary study. Holzforschung 59(3):336-341

Fan, K., Hatzikiriakos, S.G. and Avramidis, S. 1999. Determination of the surface fractal dimension from sorption isotherms of five softwoods. Wood Science Technology 33(2):139-149

Hartley, I.D. 2000. Application of the Guggenheim-Anderson-deBoer Sorption Isotherm Model to Klinki Pine. Holzforschung 54(6):661-663

Hartley, I.D. Avramidis, S. 2002. Sorption hysteresis of western Canadian softwood species. Journal of the Institute of. Wood Science 16(1):63-64

Hartley, I.D., Kamke, F.A. and Peemoeller, H. 1992. Cluster theory for water sorption in wood. Wood Science Technology 26:83-99

Highley, T.L., Clausen, C.A., Croan, S.C., Green, F., Illman, B.L. and Micales, J.A. 1994. Research on biodeterioration of wood, 1987-1992. Part I. Decay mechanisms and biocontrol. United States Department of Agriculture: Forest Service FPL-RP-529 10

Kirk, T.K. and Cowling, E.B. 1984. Biological decomposition of solid wood. The Chemistry of Solid Wood (Advances in Chemistry series 207: Rowell RM, ed.) Washington, D.C. American Chemical Society, Chapter 12

Koumoutsakos, A. and Avramidis, S. 1999. Enthalpy-entropy compensation in water sorption by various wood species. Holz Roh Werkst. 57(5):379-382

Lewis, K.J. and Hartley, I.D. 2006. Rate of deterioration, degrade, and fall of trees killed by mountain pine beetle. J. Ecosystems Management 7(2):11-19

Skaar, C. 1988. Wood-water relations (Springer series in wood sciences). Springer-Verlag, Berlin

Stamm, A.J. 1964. Wood and Cellulose Science. The Ronald Press, New York.

Thrower, J., Willis, R., de Jong, R., Gilbert, D. and Robertson, H. 2004. Sample plan to measure tree characteristics related to the shelf life of mountain pine beetle-killed lodgepole pine trees in British Columbia. Mountain pine beetle working paper 2005-01, Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre.

Todoruk, T.M. and Hartley, I.D. 2006. Sorption studies of lodgepole pine (Pinus contorta) wood chips affected by the mountain pine beetle (Dendroctonus ponderosae). Submitted to Holz Roh. Werkst.

PART II Utilization of over-dry (grey-stage and kiln-dried) lodgepole pine (*Pinus contorta*) wood in kraft pulping

By Theodore Radiotis and Richard Berry

II-1 Introduction

The initial moisture content of a fresh wood sample can theoretically be as high as 65% (on a wet-wood weight basis). Unfortunately, the total stem moisture content of grey-stage mountain pine beetle (*Dendroctonus ponderosa* Hopkins)-infested wood may drop below the fibre saturation point, making it of questionable utility for solid lumber applications and raising questions about the effect this type of wood may have on kraft pulping operations (Watson 2006, Watson 2005, Woo et al. 2006, Gee et al. 2004).

The kraft pulping process is widely considered to be extremely forgiving of incoming wood quality. However, the industry needs to produce a uniform product and to do this needs to ensure a uniform performance from the incoming furnish. Dry wood responds differently in both the chipping and pulping processes. Chipping dry wood increases the levels of small (pin) chips and fines which can cause plugging of liquor extraction screens and consume excessive amounts of cooking chemicals (Hartler and Stade). Dryer chips also cook differently in the pulping digester because of changes in chip impregnation rates and liquor concentrations. Within BC's kraft industry there is significant concern regarding the longer term viability of grey-stage lodgepole pine (*Pinus contorta*) given poor experiences when using kiln-dried wood, which is currently a low volume but routine source of pulp chips. Grey-stage beetle-killed wood might be considered to perform in the same way as kiln-dried wood. In addition, owing to the nature of the interior BC wood supply at the time of construction, none of the Kamyr continuous digesters in BC's interior region are fitted with impregnation vessels which could alleviate some of the issues associated with a low moisture content chip supply.

In this report, we address the issues associated with the utilization of over-dry (grey-stage and kiln-dried) wood in kraft pulping. This work had two objectives:

1. Assess the opportunities of chip pre-treatments to enhance the pulpability and pulp quality of over-dry lodgepole pine.
2. Pilot-plant pulping and testing of green-stage, grey-stage, and kiln-dried lodgepole pine chips to quantify the effect on conventional and LoSolids® cooking and kraft pulp quality, and to determine the maximum permissible levels of over-dry chips that can be utilized.

II-2 Material and Methods

II-2.1 Sampling and chip preparation

Samples of green-stage, grey-stage, and kiln-dried wood were obtained as follows:
Green – three stems of lodgepole pine which had been beetle-infested during 2005 were harvested in December 2005 from a site north of Vanderhoof in the Sub-Boreal Spruce dry warm biogeoclimatic zone (SBSdw3).

Grey – three stems of lodgepole pine which had been beetle-infested in 1999 were harvested in December 2005 from a site near Ootsa Lake in the Nadina Forest District in the Sub-Boreal Spruce moist cold biogeoclimatic zone (SBSmc2). This location had previously been sampled for MPBI Project 8.15 and was labelled 07-03.

Kiln-dried, bluestained utility lumber was obtained from the Tolko sawmill at Quesnel.

Figure I-1 shows an expanded map of British Columbia with the three sites marked. The site index values for the green and grey-stage sites were 18 and 15, respectively (BCMoF 1997). The site index value is a measure of potential site productivity and is expressed in units of tree height (m) at 50 years breast height age.

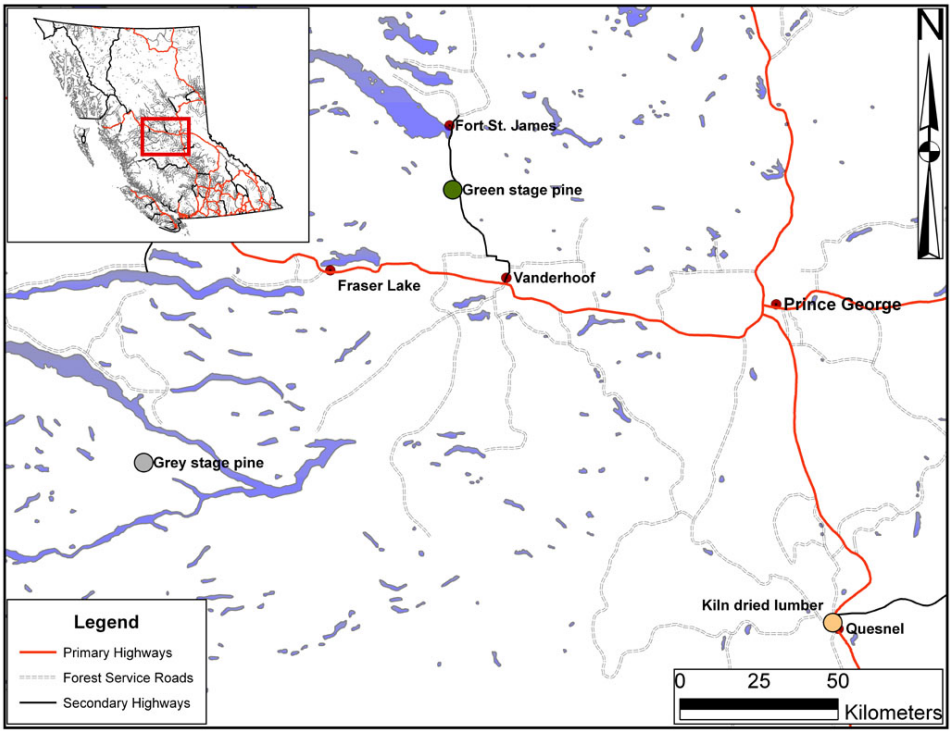


Figure II-1: Expanded map of British Columbia showing the harvesting sites of the green-stage and grey-stage logs and the location of the sawmill where the kiln-dried lumber was obtained.

All samples were shipped to Paprican's facilities in Vancouver for further processing. In order to remove any variability associated with different chipping configurations, the

roundwood was segregated into juvenile and mature wood by means of a portable Wood Mizer sawmill, and the mature wood was chipped in Paprican's 36" CM&E disc chipper. The kiln-dried utility wood was also chipped as received in the same disc chipper.

II-2.2 Chip quality

II-2.2.1 Chip moisture content and size distribution

For each wood furnish, the chips were well mixed by shovelling them from pile to pile (six times) and taking representative subsamples to measure the chip moisture and size distribution according to the methods described by Hatton (1979). The chip thickness distributions of the green, grey-stage, and kiln-dried chips were measured using both Domtar and Gradex chip classifiers.

The moisture content in this section of the report is expressed as a percentage of wet-wood mass, that is, moisture content = $(w - w_{od})/w$, where w is the wet or moist wood mass and w_{od} is the oven-dry wood mass. The moisture contents of the grey-stage (16.3%) and kiln-dried (15.9%) chips were lower than that of the green-stage (44.5%) chips. Both the grey-stage and kiln-dried chips had stem moisture contents that were below the fibre saturation point. Because of their lower moisture content, the grey-stage and kiln-dried chips produced, during chipping, a higher proportion of fines (defined as less than 2 mm thick in a Domtar classifier) and lower fraction of accepts (2 to 8 mm thick) than the green chips (Figure II-2) (Bicho et al. 2006). Similar results were obtained with the Gradex classifier (Figure II-3) which uses a combination of holes and bar screens.

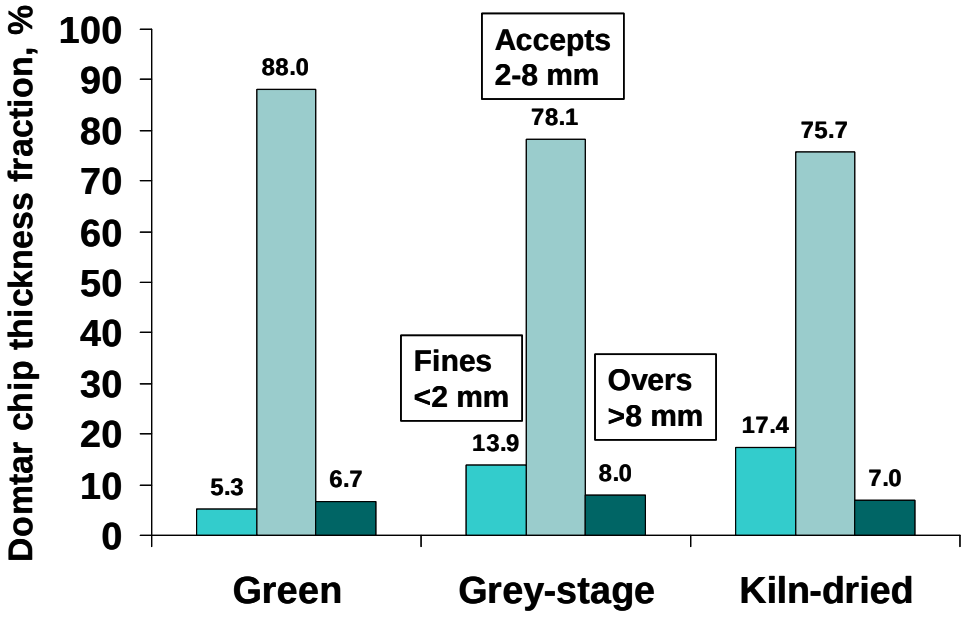


Figure II-2: Domtar chip thickness classification, showing that the grey-stage and kiln-dried chips have more fines and less accepts than the green chips.

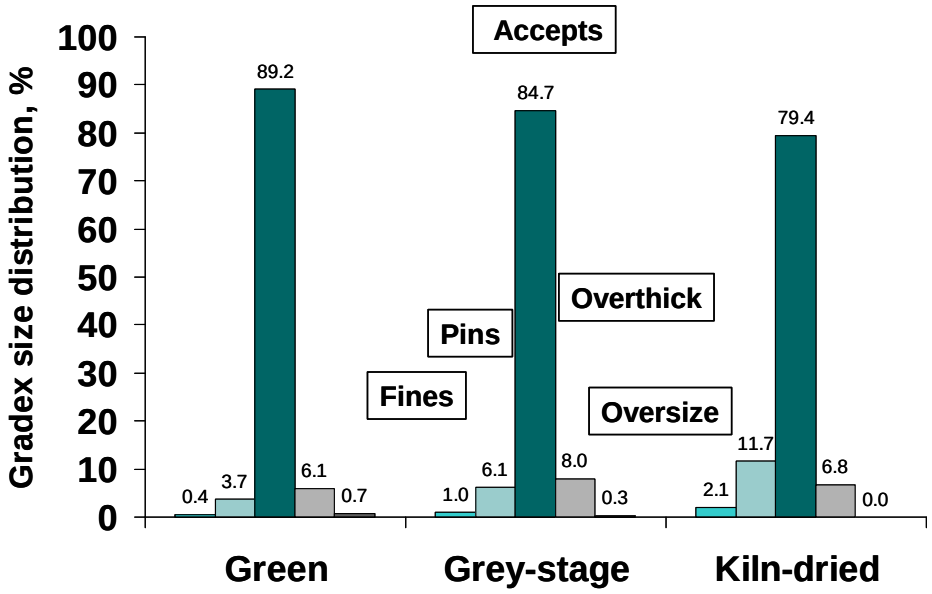


Figure II-3: Gradex chip size distribution, showing that the grey-stage and kiln-dried chips have more pins and fines and less accepts than the green chips. Here, the fines are defined as material passing a 3 mm RH (round hole); Pins as passing a 7 mm RH and retained on 3mm RH; Accepts as passing 8 mm wide slots and retained on 7 mm RH; overthick as passing a 45 mm RH and retained on a 10 mm wide slot; and oversize as material retained on a 45 mm RH.

II-2.2.2 Chemical composition of chips

For each chip furnish, a sample (approximately 100 g each) were Wiley milled through a 40-mesh screen (TAPPI Standard Method T-257). The ash was determined as the residue remaining after heating the sample at 575^{o}C for several hours and expressed as a percentage of the original weight of wood on an oven-dried basis (TAPPI Standard Method T-211). The ground wood (20 g) was then soxhlet-extracted with 100 mL's of acetone for 8 hours to remove the extractable components. The total weight of the acetone-extractables was determined gravimetrically by rotatory-evaporation, and expressed as percentage of the original weight of wood (TAPPI Standard Method T-264). The extractive–free lignocellulosic samples were then air-dried to remove the remaining acetone and analyzed for lignin using a modified Klason lignin method (TAPPI Standard Method T-222). The acid-soluble lignin was measured with TAPPI Useful Method 250. Monosaccharides for each extractive-free sample were determined by gas-liquid chromatography of their alditol acetate derivatives, according to TAPPI Standard Method T-249.

The chemical composition analysis of the three beetle-infested chips showed that the grey-stage and kiln-dried chips had similar chemical composition (Table II-1). The green-stage chips, however, had higher cellulose content and lower acetone extractives, suggesting that a higher pulping yield should be obtained from these chips compared to the grey-stage or kiln-dried chips. These differences are very likely the result of variations in wood from different locations rather than differences caused by infestation or wood moisture content. The interpretation of the results have to take into account these natural wood furnish variations.

Table II-1: The grey-stage and kiln-dried chips had similar chemical composition, but the green-stage chips had a higher cellulose content and lower acetone extractives. The results are expressed in percentage based on oven-dry solid weight.

	Green	Grey	Kiln-dried
Acetone Extracts, %	1.06	4.05	3.71
Ash at 575ºC, %	0.25	0.20	0.25
Carbohydrates by GC			
Arabinan, %	1.8	1.9	2.0
Xylan, %	6.0	5.2	5.8
Mannan, %	10.4	10.2	9.6
Galactan, %	2.4	3.4	3.7
Glucan, %	47.0	41.9	39.4
Acid-insoluble (Klason) Lignin, %	27.4	27.5	27.3
Acid-soluble Lignin, %	0.43	0.42	0.37
Total Lignin, %	27.8	27.9	27.7
Cellulose*, %	42.3	37.5	35.1
Hemicelluloses, %	25.3	25.1	25.4

*The glucose contribution to the hemicelluloses was estimated from a ratio 3:1 for mannose:glucose and 5:1 for xylose:glucose. The cellulose fraction was then calculated by difference between total glucose and the glucose associated with hemicelluloses, i.e., cellulose = glucan – mannan/3 – xylan/5.

II-3 Results and Discussion

II-3.1 Conventional kraft pulping of grey, green, and kiln-dried chips

II-3.1.1 Chip moisture and water impregnation tests

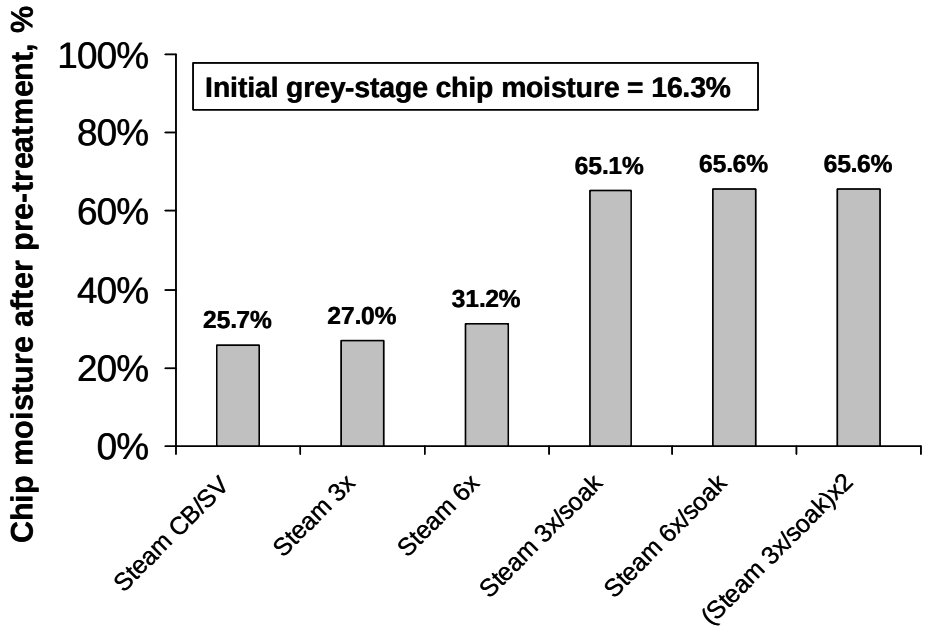
Chip steaming is recognised as a way to improve the uniformity of kraft cooking by ensuring that air is removed from the chips and that they have a constant initial moisture content. The effectiveness of chip steaming can be assessed by measuring average chip

moisture content, but, more valuable, is determining what proportion of chips have a density greater than water after a steaming procedure. The following pre-treatments were assessed:

1. **Steam CB/SV**: Simulation of 5-minute atmospheric steaming in a chip bin (CB) followed by 2-minute steaming at 131 kPa in a steaming vessel (SV).
2. **Steam 3x**: Three cycles of steaming, each cycle lasting 3 minutes at 138 kPa.
3. **Steam 6x**: Six cycles of steaming, each lasting 3 minutes at 138 kPa.
4. **Steam 3x/Soak**: Three cycles of steaming followed by 15 minutes of water soaking. In this procedure the digester was allowed to cool for 5 minutes after steaming, then the digester was filled with water and the chips were allowed to soak for 15 minutes.
5. **Steam 6x/Soak**: Six cycles of steaming followed by 15 minutes of water soaking.
6. **(Steam 3x/Soak) x 2**: Two cycles of Process 4.

Pre-treatments using only steam (Processes 1 to 3) were unable to raise the chip moisture (on a wet-wood weight basis) adequately and to saturate the chips with water (Figure II-4a, Figure II-5a, and Figure II-6a); a very low percentage of chips sunk with these processes (Figure II-4b, Figure II-5b and Figure II-6b). Particularly telling is that the simulation of pre-steaming in a conventional industrial chip bin and steaming vessel (Steam CB/SV) for the grey-stage chips increased the chip moisture by only 9.4 points from its initial moisture of 16.3% (on a wet-wood weight basis), and only 3% of the chips sunk when placed in water. However, steam/soak pre-treatments (Processes 4 to 6) increased the chip moisture to the maximum saturation level, resulting in a higher percentage of chips that sunk. Only the kiln-dried chips (Figure II-5b) required the most aggressive pre-treatment, where the chips were steam soaked twice, to achieve complete saturation.

a)



b)

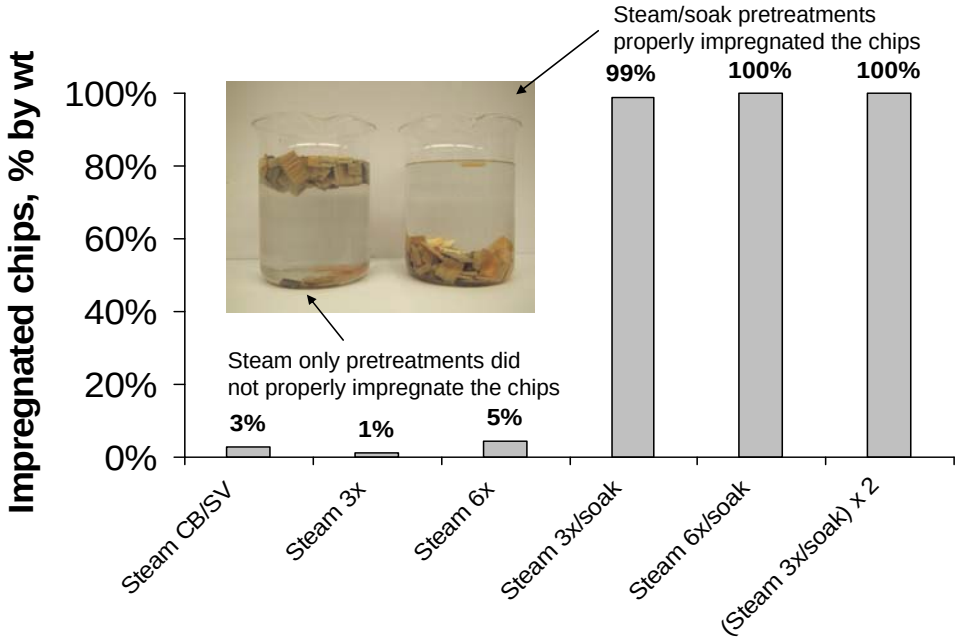
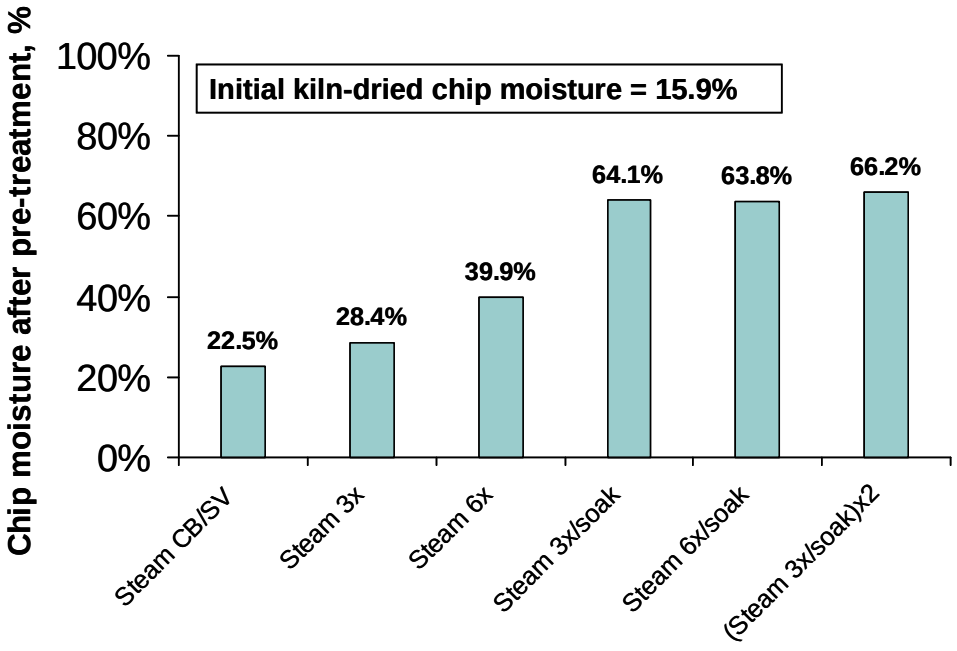


Figure II-4: a) Pre-treatments of grey-stage chips using only steam were insufficient in raising the chip moisture (on a wet-wood weight basis); however, steam/soak pre-treatments increased the chip moisture to the maximum saturation level, resulting b) in a higher percentage of chips that sunk (99 to 100% versus 1 to 5%).

a)



b)

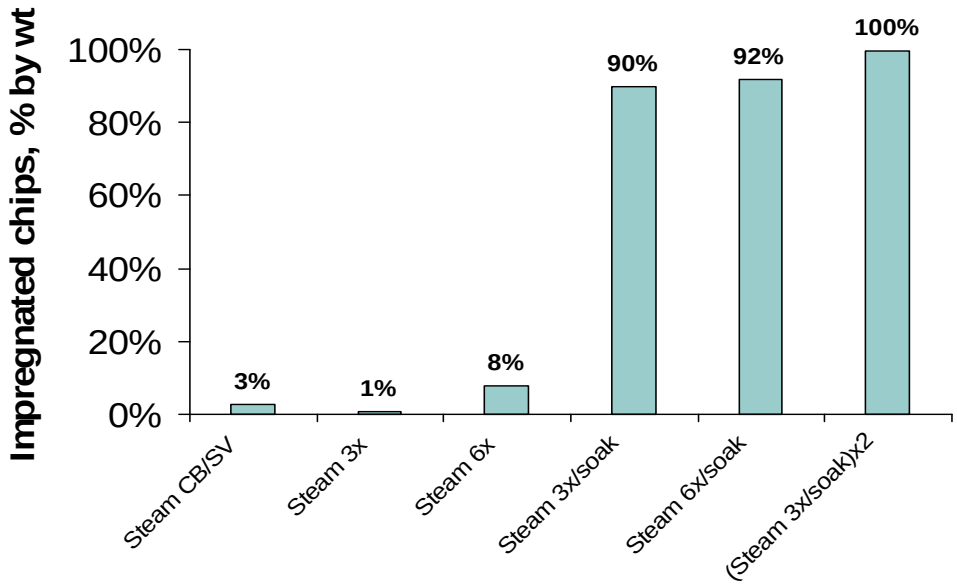
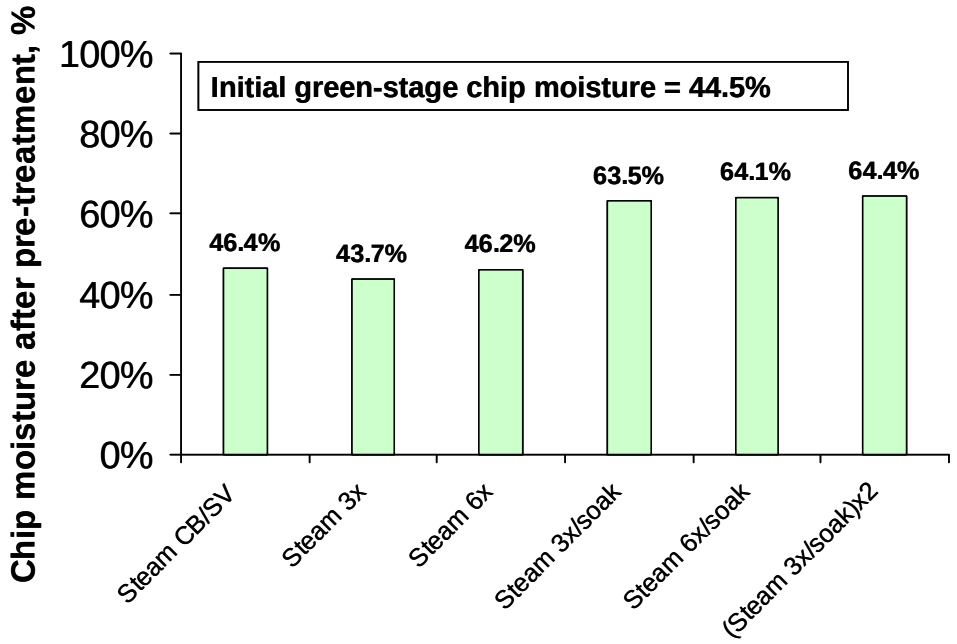


Figure II-5: Pre-treatments of kiln-dried chips using only steam were insufficient in raising the chip moisture (on a wet-wood weight basis); however, steam/soak pre-treatments increased the chip moisture to a high saturation level. The steam/soak twice pre-treatment resulted b) in the highest percentage of chips that sunk.

a)



b)

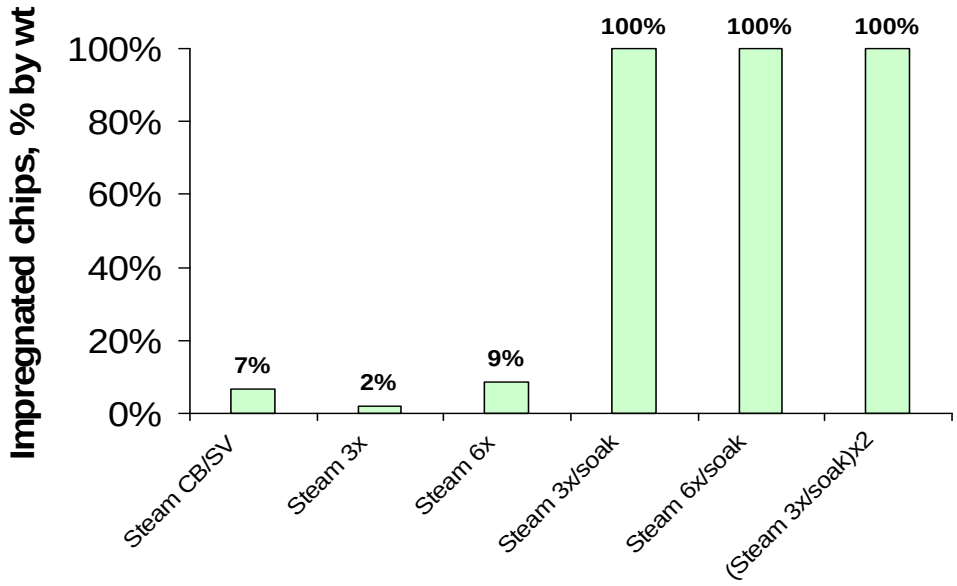


Figure II-6: a) Pre-treatments of green-stage chips using only steam were insufficient in raising the chip moisture (on a wet-wood weight basis); however, steam/soak pre-treatments increased the chip moisture to the maximum saturation level, resulting b) in a higher percentage of chips that sunk (100% versus 2 to 9%).

II-3.1.2 Conventional kraft pulping conditions

Since the chip thickness distribution of the green-stage chips was close to the average digester feed chip thickness from a survey of 20 North American mills (MacLeod and Dort 2005), the green-stage, grey-stage, and kiln-dried chips were used as received. Each chip furnish was pulped with the conventional kraft process using four pre-treatments under the following conditions: 19% active alkali, 34% sulphidity, and a 5:1 liquor:wood ratio (including chip moisture after pre-treatment). The four pre-pulping treatments were no pre-treatment, steam 3x, steam CB/SV, and (steam 3x/soak) x2. For simplicity, the steam 3x and (steam 3x/soak) x2 will be denoted as steam-only and steam/soak, respectively. The cooking temperature profiles after the no pre-treatment, steam-only, and steam/soak treatments were chosen to simulate typical temperature profiles of conventional kraft batch digester systems, i.e., 90 minutes to a cooking temperature of 170ºC. Note that a 5:1 liquor-to-wood ratio that includes the chip moisture after pre-treatment will remove any difference in liquor concentration resulting from the degree of dryness of the chips, and a long 90-minute rise to temperature will allow sufficient time for liquor impregnation. For the fourth pre-treatment, steam CB/SV, we chose a temperature profile that simulates cooking in conventional kraft continuous digester systems, i.e., 10 minutes to 120°C, 30 minutes at 120°C (impregnation zone), and 10 minutes to 170°C (cooking zone). This profile shortens the time for liquor impregnation. All these cooks were done in six-bomb runs where H-factors of 1000, 1300, 1500, 1800, and 2100 were used to produce pulps with a wide range of kappa numbers. Two bombs were cooked to 1500 H-factor to determine cook reproducibility.

II-3.1.3 Pulpability of as-received chips after pre-pulping treatments

As seen in Figure II-7, the no pre-treatment, steam-only and steam/soak pre-pulping treatments did not affect the delignification rate but the steam CB/SV pretreatment and the modified temperature profile caused a decrease in delignification rate of between 200 and 300 H-factor units, irrespective of the wood chips. As the steam CB/SV treatment is no worse than the no pre-treatment or steam-only pre-treatment, the observed rate difference is most likely due to the time given for the rise to temperature; a 90-minute rise to temperature allows a sufficiently long time for proper liquor impregnation while the faster rise to impregnation and cooking temperatures in the continuous digester simulation does not.

The main difference caused by dry chips is the quantity of screened rejects. As seen in Figure II-8, the rejects were highest with chips without any pre-treatment and generally the quantity of rejects increased with kappa number. The reject level was greatly improved for the chips with the steam/soak pre-treatment and this eliminated the variability with kappa number. The rejects represent a loss of productivity and wood utilization and are preferably minimized. The main advantage of good chip steaming is, therefore, to minimize the rejects even at high kappa number; a mill could try to deal with increasing rejects by pulping to a lower kappa number, but at the expense of fibre yield.
This effect of changing kappa number on total yield is seen in Figure II-9. There was no discernible difference in total yield, however, of the pulps cooked after the different pre-pulping treatments.

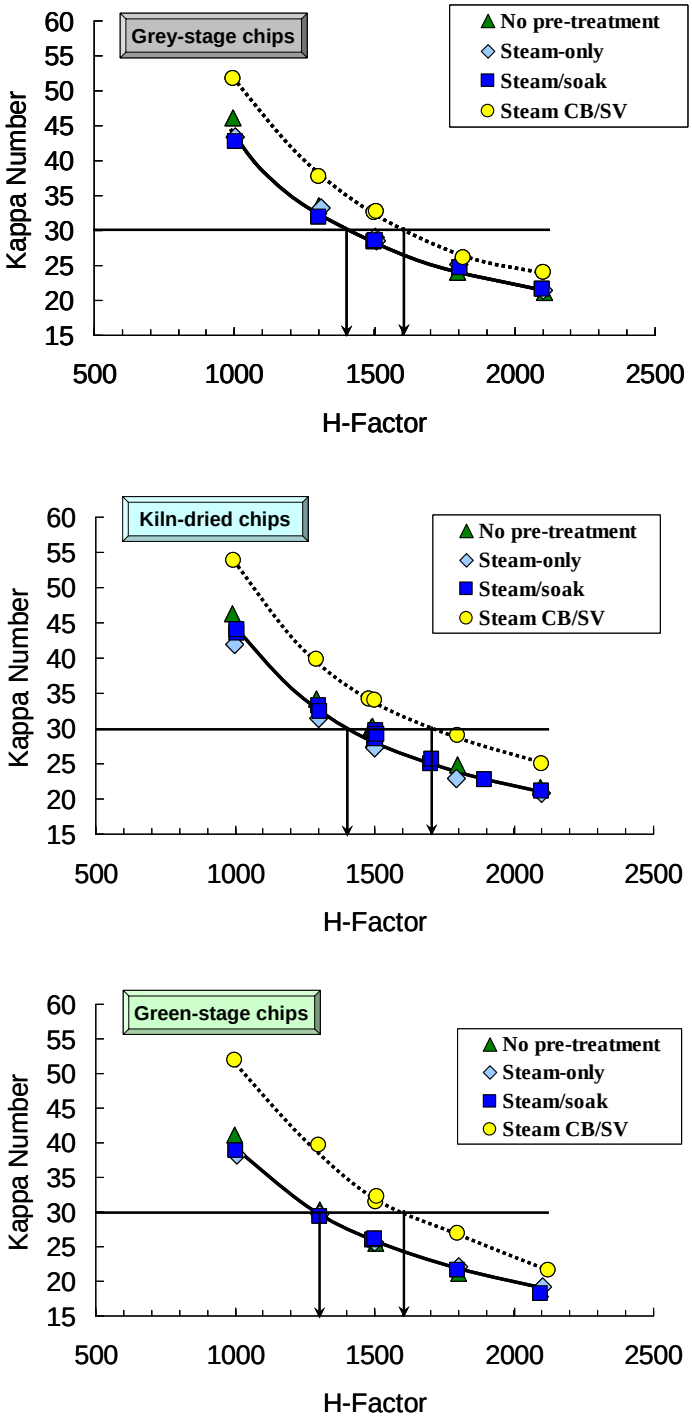


Figure II-7: Irrespective of the wood chips, the no pre-treatment, steam-only, and steam/soak pre-pulping treatments delignified at the same rate, but the steam CB/SV delignified more slowly by an H-Factor between 200 and 300.

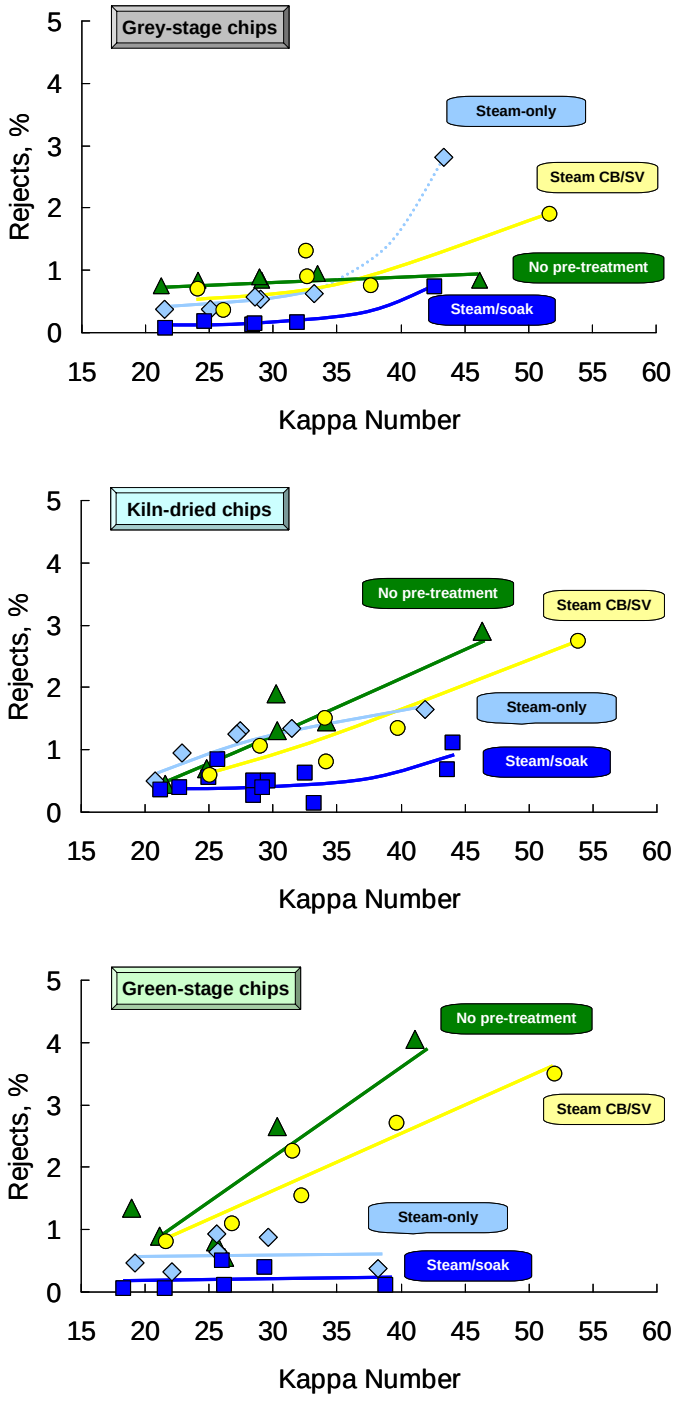


Figure II-8: Irrespective of the wood chips, the pulp screening rejects were highest for chips without any pre-treatment, improved with steaming and were best for chips with the steam/soak pre-treatment.

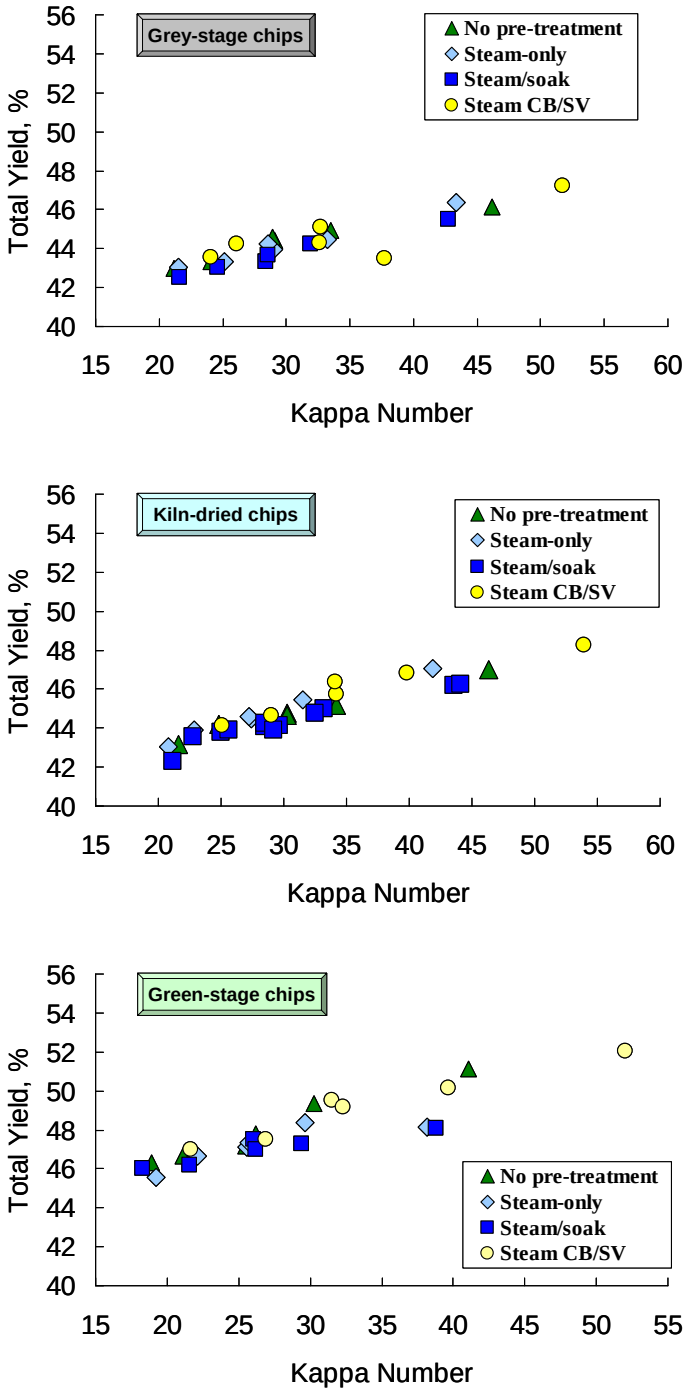


Figure II-9: The pre-pulping treatments had no effect on the pulping yield.

3.1.4. Pulpability of as-received green, grey, and kiln-dried chips for a given pre-treatment

Figure II-10 shows that the green chips required 160-H factor units less than the grey and kiln-dried chips after a steam/soak pre-pulping treatment to give a kappa number of 30. Alternatively, at a constant H-factor the green chips cooked to a lower kappa number; at an H-factor of 1440 the kappa numbers of the grey and kiln-dried pulps were 30 while the kappa number of the pulp from the green chips was 27. Another difference was that the green chips consumed about 2% less EA (Figure II-11) than the grey and kiln-dried chips to reach a given kappa number.

Revisiting Table II-1, it is important to remember that the sample of green-stage furnish used in this work had an acetone extractive level of 1.1% while both the grey-stage and kiln-dried samples had levels between 3.7 and 4.1%. These values are significantly different, but fall within the range of 1 to 6% as reported by Dalpke et al. 2006b for beetle-infested lodgpole pine from different biogeoclimatic subzones, or the 2 to 7% range found in sound lodgepole pine (Dalpke and Bicho 2007). As the extractives can impede liquor penetration by obstructing fibre-wall pits (Hillis and Suminoto 1989, Louden 1981) and consume sodium hydroxide during cooking (Cohen and Mackney 1951), and as sodium hydroxide is a factor in determining the rate of cooking, this difference in extractive content can explain the faster rate of delignification and the lower sodium hydroxide consumption of the green-stage sample.

Large variations in extractives are common in wood and are the result of a range of factors such as individual tree genetics, wounding, and local soil, climate, and lighting conditions (Weigel et al. 2002). Recently Dalpke et al. (2006b) found that there were no statistical differences in extractives content caused by time since death or site index. The explanation given was that the between–tree variability was too high. Therefore, the result found in this work is more likely a difference caused by between-tree variability rather than mountain pine beetle infestation. On the larger scale, mills have identified that early stages of mountain beetle-infested chips have higher extractives content than control furnishes. This difference is an expected outcome of the tree's natural defense mechanism (Woo et al. 2003a, 2003b, 2006). This work indicates that wood chips with higher extractives content would cause higher alkali consumption and a slower cooking rate if the alkali charge is not adjusted.

Another difference between the furnishes is that the screened yield of the green-stage chips was ~ 3.6% higher while the kiln-dried chips were 0.2% higher than that of the grey-stage chips (Figure II-12), although the rejects for all three furnishes were about the same (Figure II-13).

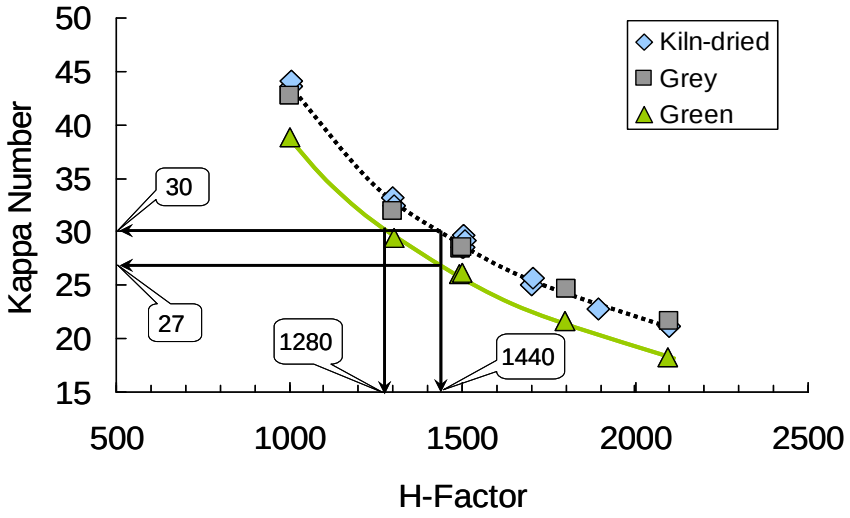


Figure II-10: The green chips delignified faster than the grey and kiln-dried chips after a steam/soak pre-treatment.

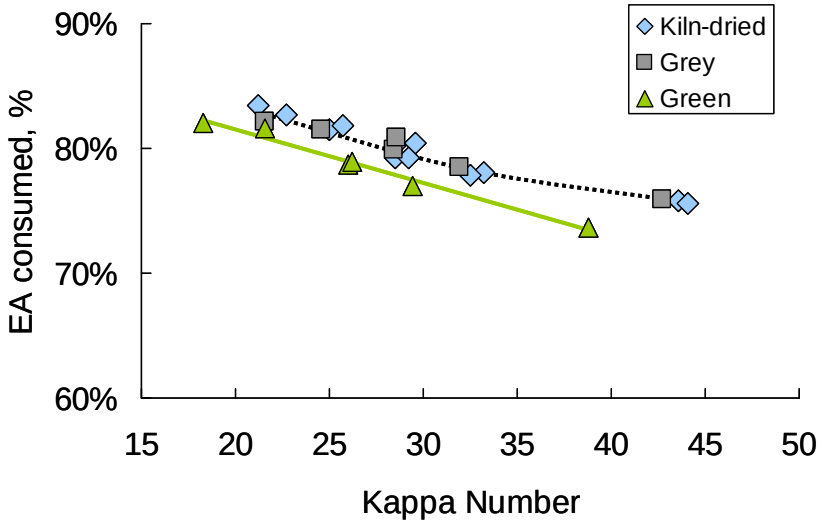


Figure II-11: The green chips consumed about 2% less EA to reach the same kappa number as the grey and kiln-dried chips after a steam/soak pre-treatment.

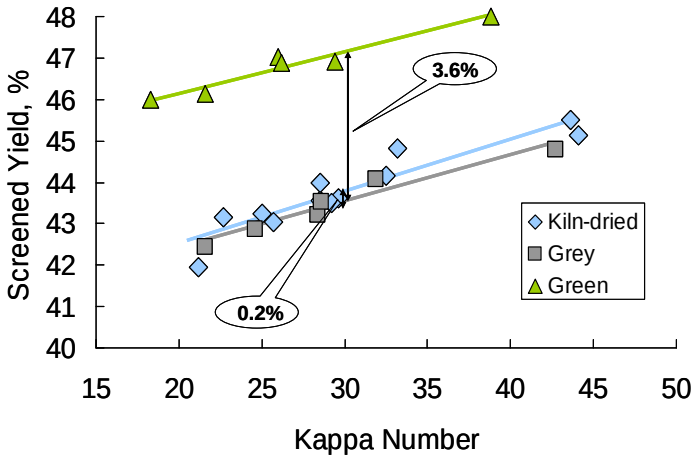


Figure II-12: After a steam/soak pre-pulping treatment, the screened yield from the green chips, at kappa number 30, was 3.6% higher than the grey-stage chips. The kiln-dried chips had a slightly higher (0.2%) yield relative to the grey-stage chips.

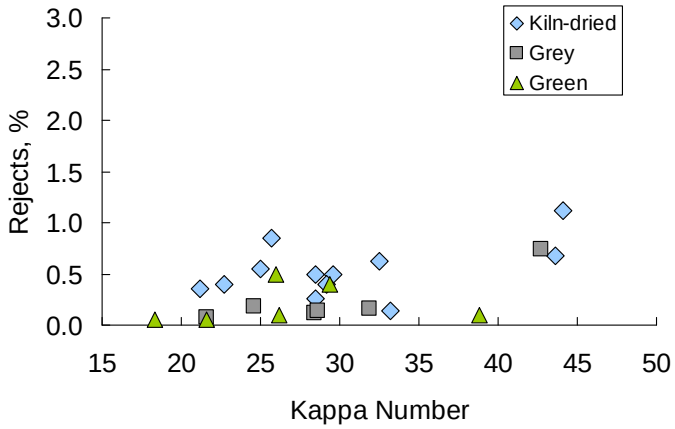


Figure II-13: After a steam/soak pre-pulping treatment, the rejects from the three wood furnishes were lower than 0.5% at a kappa number of 30.

Again, the data in Table II-1 is instructive. The green-stage furnish sample has a higher cellulose content than do the grey-stage and kiln-dried furnish samples. When the cellulose contents are adjusted for the different mass balances, which are 96.7% for the green-stage, 94.8% for the grey-stage and 92.2% for the kiln-dried samples, the corrected cellulose contents are 43.7%, 39.6% and 38.1% respectively. It is clear that the difference between the yield delivered by green-stage and grey-stage furnishes are caused by the initial cellulose content of the samples and the lower extractives.

There is limited data on the effect of mountain pine beetle infestation on wood chemistry. Woo et al. 2003a, 2003b have shown a decrease in total carbohydrates between a sound lodgepole pine tree and an 8-month infested tree, with most of the difference being

caused by an apparent loss of the easier to degrade hemicellulose fraction. If this is a statistically valid difference, it is the reverse of what is observed in the samples used in this study. Data from the literature, on the other hand, shows that the effect of site on pulping yield from sound lodgepole pine can be as high as 4% (Dalpke et al. 2006a, Hatton et al. 1992). Therefore, the present result is more likely a difference caused by the variability in wood composition caused by harvesting location or tree-to-tree variability than mountain pine beetle infestation.

All the pulping data are in Appendix A (Table II-8 to Table II-19). Other plots of the data which are not included in this report show that, with all of the pre-pulping treatments, the green chips required on average 150 H-factor units less than the grey and kiln-dried chips; consumed 2% less EA; and had a 3-4% higher yield. Table II-2 gives a summary of the key measurements at kappa number 30. It can be seen that, irrespective of the pre-pulping treatment, the green-stage chips had 3 to 4% higher yield, and the kiln-dried chips had a 0.5% higher yield than the grey-stage chips. The different pre-treatments had no effect on the total yield, but the rejects were the lowest for the steam/soak pre-treatment and highest for the no pre-treatment. The steam-only and steam CB/SV pre-treatments were in between the two.

Table II-2: At a kappa number of 30, the green-stage chips had, on average, a 3.3% higher yield than grey-stage chips; kiln-dried chips had 0.5% higher yield than grey-stage chips. For all three chip furnishes, the rejects were reduced when the steam/soak treatment was applied before pulping.

		No Pre-treatment	Steam CB/SV	Steam only	Steam/ soak
Total yield, %	**Green**	**48.7%**	**48.6%**	**48.4%**	**47.4%**
	Kiln-dried	**44.7%**	**45.1%**	**45.0%**	**44.3%**
	Grey-stage	**44.3%**	**44.4%**	**44.2%**	**43.8%**
Screened yield,%	**Green**	**46.6%**	**47.0%**	**47.0%**	**47.2%**
	Kiln-dried	**43.3%**	**44.2%**	**43.8%**	**43.8%**
	Grey-stage	**43.5%**	**43.4%**	**43.4%**	**43.5%**
Rejects, %	**Green**	**2.1%**	**1.6%**	**0.5%**	**0.2%**
	Kiln-dried	**1.3%**	**0.8%**	**1.0%**	**0.4%**
	Grey-stage	**0.9%**	**0.6%**	**0.5%**	**0.1%**

II-3.1.4 Pulpability of 2-8 mm thick green, grey, and kiln-dried chips

It is possible that the differences in rate and yield between the green and grey chips can be partly explained by the differences in fines content (Figure II-2 and Figure II-3). We did additional work to assess the effect of the fines content, which is higher in the grey and kiln-dried furnishes than in the green furnishes, on rate and yield.

In general, fines tend to cook faster with a lower yield than the 2-8 mm thick fraction (accept chips); the >8 mm thick chips tend to cook slower and produce more screening rejects (Akhtaruzzaman 1980, Hatton 1975, Tikka et al. 1993). To eliminate this factor, we removed the <2 mm and >8 mm thick fractions from the three chip furnishes. The 2-

8 mm thick fractions were cooked using conventional kraft pulping conditions with a steam/soak pre-treatment and a 5:1 L:W ratio that included the chip moisture after the pre-treatment. Figure II-14 shows that the green-stage chips still delignified faster than the grey or kiln-dried chips (60 to 140 H). The remaining pulping results showed similar trends for accept chips and whole chips: the green chips consumed about 2% less EA (Figure II-15) than the grey and kiln-dried chips; the screened yield was ~ 3.9% higher for the green chips relative to the grey-stage chips and 0.3% higher for the kiln-dried chips (Figure II-16); the rejects were minimal for all three samples (Figure II-17). These results show that the differences found between the green- and grey-stage furnishes are not due to chip size distribution.

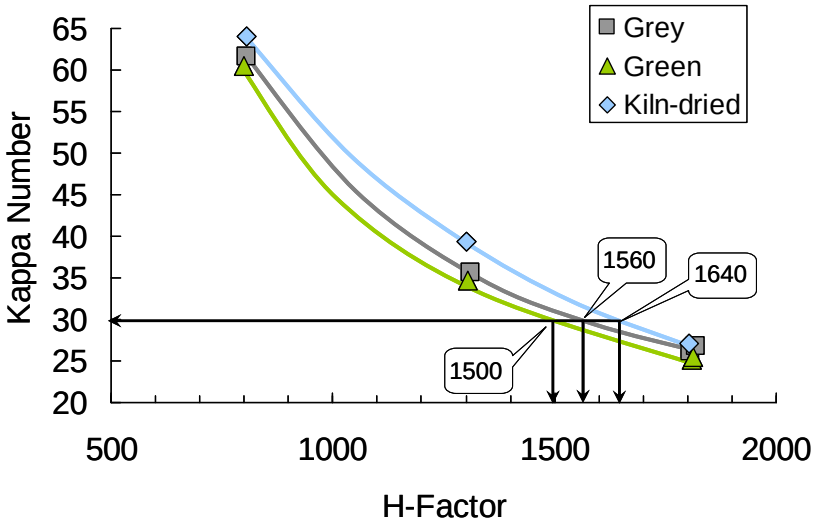


Figure II-14: Conventional kraft pulping of the 2-8 mm thick fraction chips showed that the green chips delignified slightly faster than the grey and kiln-dried chips after a steam/soak pre-treatment.

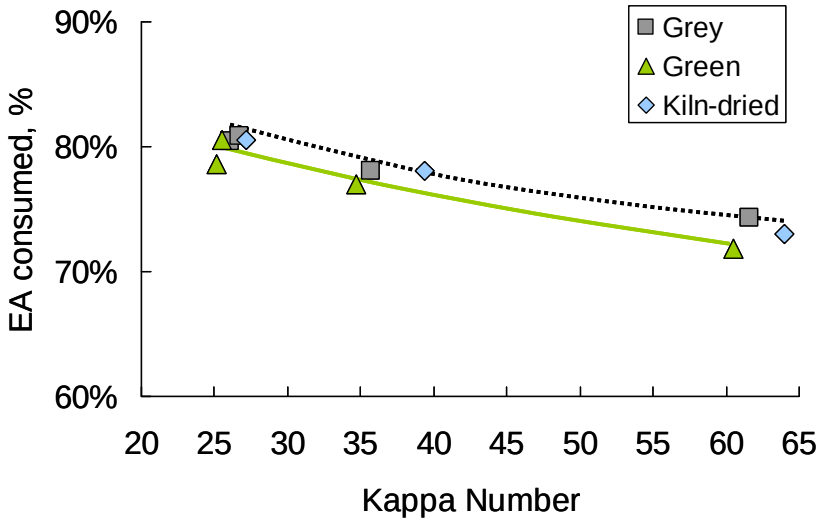


Figure II-15: The green chips (2-8 mm thick fraction) consumed about 2% less EA to reach the same kappa number as the grey and kiln-dried chips for a steam/soak pre-treatment followed by conventional kraft pulping conditions.

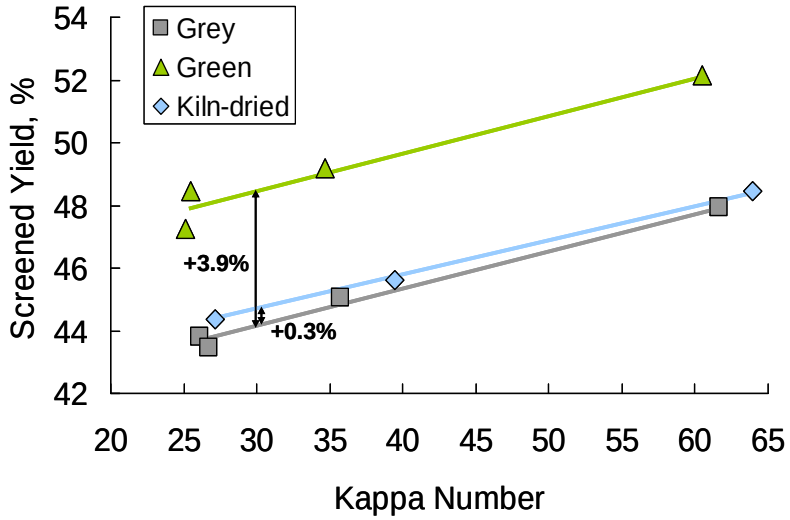


Figure II-16: After a steam/soak pre-pulping treatment, the screened yield from the green chips (2-8 mm thick fraction), at kappa number 30, was 3.9% higher than the grey-stage chips. The kiln-dried chips had a slightly higher (0.3%) yield relative to the grey-stage chips.

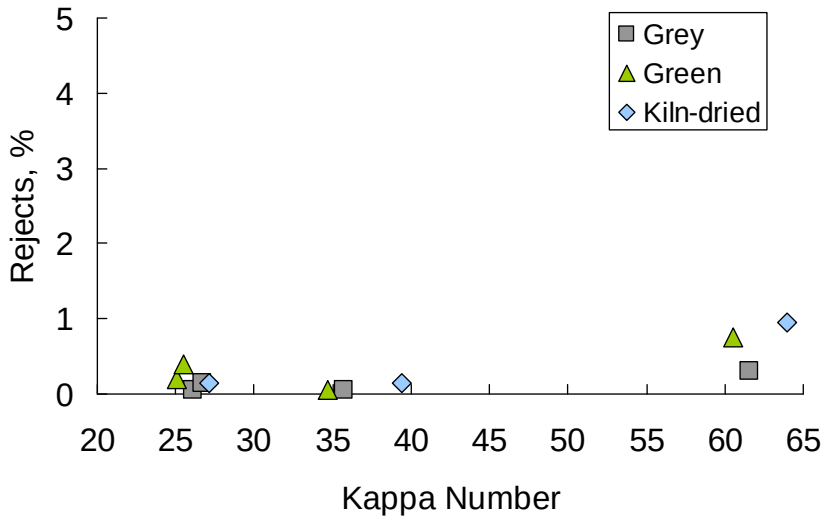


Figure II-17: After a steam/soak pre-pulping treatment, the rejects from the three wood furnishes (2-8 mm thick fraction) were minimal, especially at a kappa number of 30.

The results obtained with the accept chips and those with whole chips can also be compared. Comparison of Figure II-10 and Figure II-14 shows that, for all three furnishes, the 2-8 mm thick chips cooked more slowly than the whole chips. For example, the 2-8 mm green chips required 1500 H to reach a 30 kappa number pulp whereas the whole chips required 1280 H. Comparisons with the kiln-dried and grey-stage wood showed a similar trend (Figure II-18). These results show that the fines have a more pronounced effect than the overs.

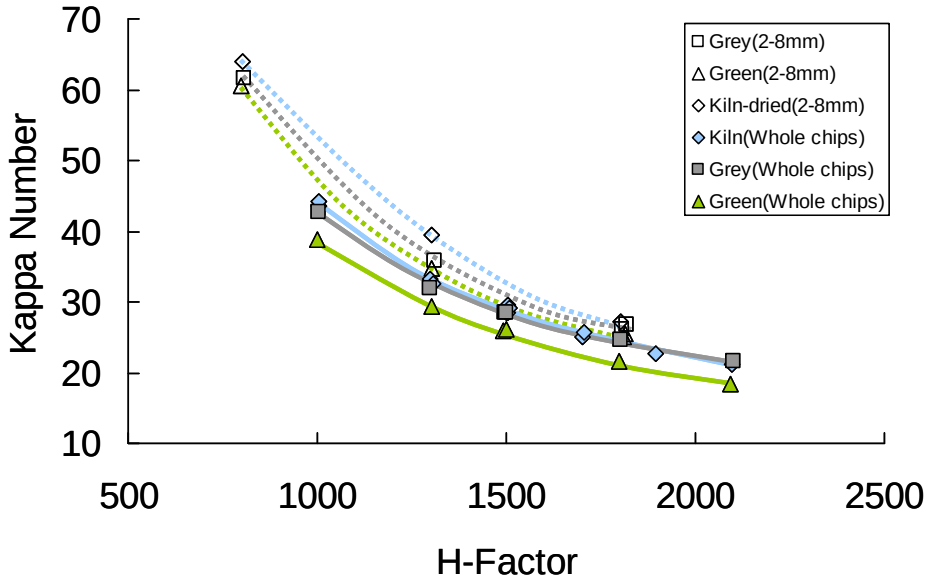


Figure II-18: The 2-8 mm thick fraction chips cooked slower than the whole chips (conventional kraft pulping after a steam/soak pre-treatment).

Table II-3 shows that, at kappa number 30, the accept chips had a 0.5 to 1.0% higher yield than those from whole chips. This yield gain is due to the removal of fines that tend to give a lower yield. The rejects generated were about the same, showing that a steam/soak pre-treatment was sufficient to reduce the rejects in the whole chips to the level found in the 2-8 mm thick chips.

Table II-3: At a kappa number of 30, the accept chips (2-8 mm thick) had a 0.5 to 1.0% higher yield than those from whole chips; the rejects were the same. A steam/soak pretreatment was used.

		Whole chips	2-8 mm thick	Difference
Total yield, %	**Green**	**47.4%**	**48.3%**	**+0.9%**
	Kiln-dried	**44.3%**	**44.8%**	**+0.5%**
	Grey-stage	**43.8%**	**44.4%**	**+0.6%**
Screened yield,%	**Green**	**47.2%**	**48.2%**	**+1.0%**
	Kiln-dried	**43.8%**	**44.6%**	**+0.8%**
	Grey-stage	**43.5%**	**44.3%**	**+0.8%**
Rejects, %	**Green**	**0.2%**	**0.2%**	**0%**
	Kiln-dried	**0.4%**	**0.2%**	**-0.2%**
	Grey-stage	**0.1%**	**0.1%**	**0%**

Further work was done with the 2-8 mm thick accept chips to test the difference in delignification rate and yield when using typical industrial cooking conditions designated here as a steam CB/SV pre-treatment and a 4:1 liquor-to-wood ratio that does not take into account the chip moisture after the pre-treatment. Figure II-19 shows that the rate is now the same for the three furnishes. The differences in rates between these cooks and the previous steam CB/SV pretreatment at 5:1 L:W ratio is caused by the variations of L:W ratio due to variable moisture content which in this new work can be calculated to be 4.35:1, 4.29:1, and 4.87:1 for the grey, kiln-dried, and green-stage chips, respectively. The liquid-to-wood ratio for the green chips is about the same as before (5:1), resulting in equivalent rates. However, the grey and kiln-dried chips with a lower L:W should cook faster. It appears that this difference in L:W ratio increases the delignification rate of the drier chips to that of the wetter green-stage chips. In terms of yield, Table II-4 shows that 2-8 mm thick had a 0.7 to 0.9% higher screened yield than those from whole chips that can be explained from the lower rejects. The yield data from the 2-8 mm thick chips once again shows that the yield was ~ 3.0% higher for the green chips relative to the grey-stage chips and 0.7% higher for the kiln-dried chips relative to the grey-stage chips. These results provide further evidence that the higher yield found in the green-stage chips is not related to the effect of mountain pine beetle infestation, but to the inherent properties of the chips.

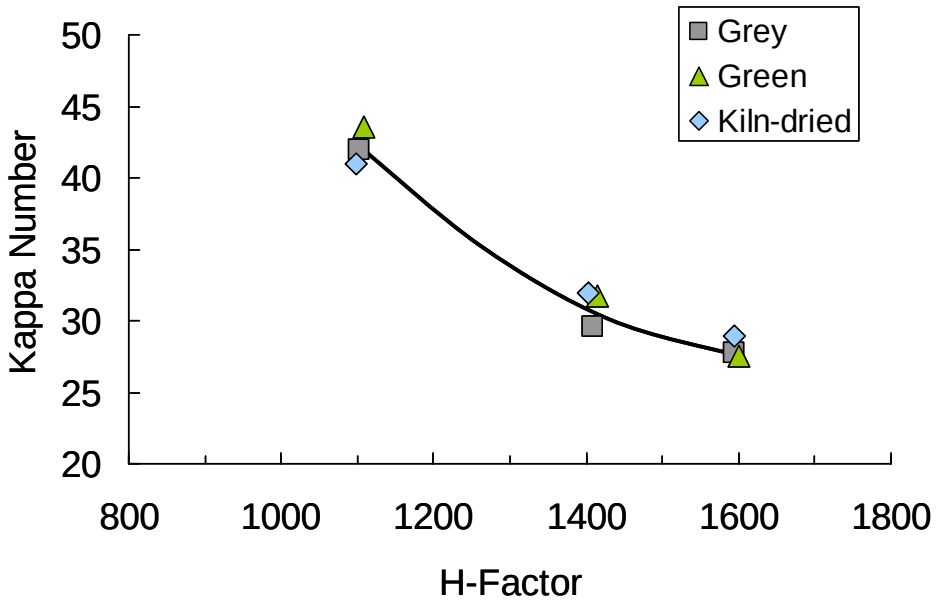


Figure II-19: Conventional kraft pulping of the 2-8 mm thick fraction chips using a steam CB/SV pre-treatment and a 4:1 L:W ratio that excludes the chip moisture showed that the green, grey, and kiln-dried chips delignified at the same rate.

Table II-4: At a kappa number of 30, the accept chips (2-8 mm thick) had the same total yield, a 0.7 to 0.9% higher screened yield, and lower rejects than those from whole chips (conventional kraft with a 4:1 L:W, excluding chip moisture after a steam CB/SV pre-treatment).

		Whole chips	2-8 mm thick	Difference
Total yield, %	**Green**	**48.6%**	**48.2%**	**-0.4%**
	Kiln-dried	**45.1%**	**45.1%**	**+0%**
	Grey-stage	**44.4%**	**44.4%**	**+0%**
Screened yield,%	**Green**	**47.0%**	**47.9%**	**+0.9%**
	Kiln-dried	**44.2%**	**44.9%**	**+0.7%**
	Grey-stage	**43.4%**	**44.2%**	**+0.8%**
Rejects, %	**Green**	**1.6%**	**0.2%**	**-1.4%**
	Kiln-dried	**0.8%**	**0.2%**	**-0.6%**
	Grey-stage	**0.6%**	**0.1%**	**-0.5%**

II-3.2 LoSolids® kraft pulping of green, grey, and kiln-dried chips

3.2.1. Experimental

In this part of the work, pilot-plant LoSolids® pulping was done on the green-stage, kiln-dried, and grey-stage lodgepole pine chips and testing was done on the resulting pulps to quantify the effect of the furnishes on kraft cooking, pulp quality, and the maximum

permissible levels of over-dry chips that can be utilized. Pulping experiments were done with a wide range of mixtures of dry (grey-stage and kiln-dried) and green chips (Table II-5) to determine the effect that the increased amount of pins and fines has on liquor flow pattern, pulpability, and pulp quality.

Table II-5: The range of mixtures of dry (grey-stage and kiln-dried) and green chips.

Green/Grey chips (wt%/wt%)	Green/kiln-dried chips (wt%/wt%)
100/0	100/0
95/5	95/5
90/10	90/10
85/15	85/15
80/20	80/20
75/25	75/25
50/50	50/50
0/100	0/100
75/25*	75/25*
50/50*	50/50*

* Layered cooks, dry chips on top

The conditions were chosen to simulate the industrial operating practices in a Kamyr single-vessel hydraulic digester modified for LoSolids® pulping (Figure II-20). The white liquor split used was 55/45, where 55% of the white liquor charge is added to the impregnation zone and 45% to the lower cooking zone. Black liquor was extracted at two locations — one at the upper cooking screens and the other at the main extraction screens. Cooking was done in a 20-L forced liquor circulation digester (Figure II-21) that has been modified for multi-stage pulping (Radiotis et al. 2001). This digester is equipped with a magnetic flow meter that measures the liquor flow during cooking. The cooking conditions were 19%AA, 34% sulphidity, and 5:1 L:W (including moisture after pre-treatment). After a steam/soak pretreatment and the addition of white liquor, the following time-temperature profile was used: 10 minutes to reach a temperature of 120^{o}C, 30 minutes at 120^{o}C, 10 minutes to reach 165^{o}C, and the temperature kept at 165^{o}C for the remainder of the cook (Figure II-22) until an H-factor of 1960 was accumulated, producing pulps in the 25-30 kappa number range.

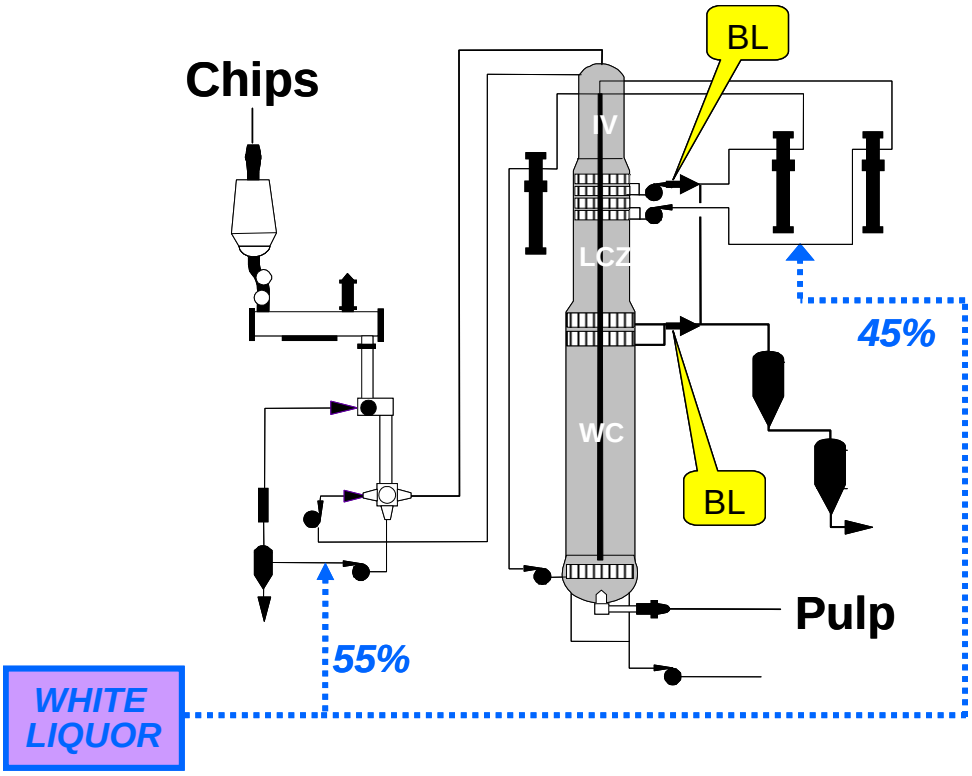


Figure II-20: Schematic of an industrial Kamyr single-vessel hydraulic digester modified for LoSolids® pulping with a 55-45 white liquor split, that is 55% of the white liquor charge goes to the impregnation zone (IV) and 45% in the lower cooking zone (LCZ). There are also two black liquor (BL) extractions. One at upper cooking screens (between the IV and LCZ) and the other at the main extraction screens (between the LCZ and WC, wash zone).

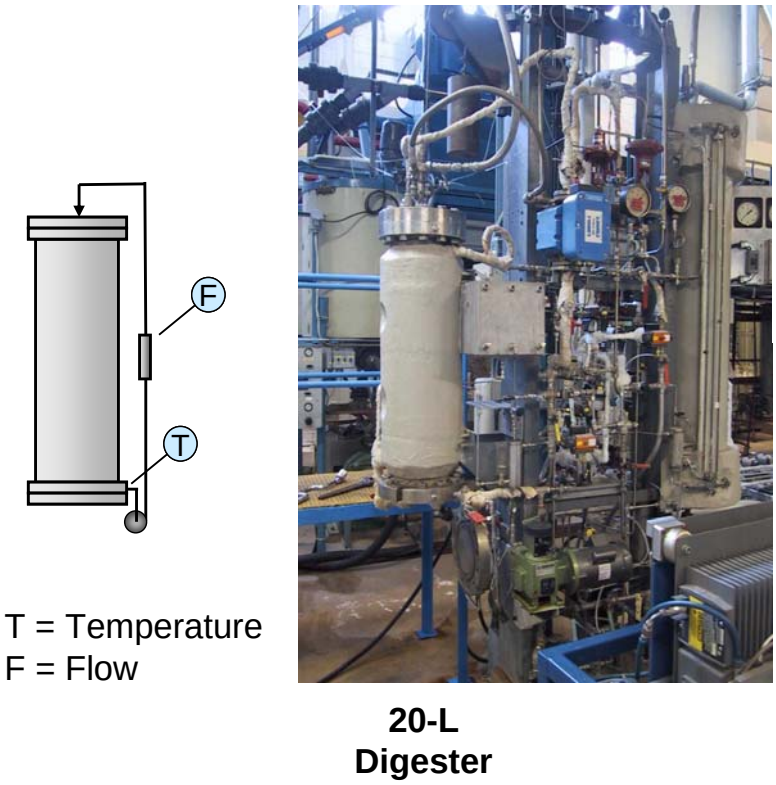


Figure II-21: Photo of pilot-scale 20-L forced liquor digester used in simulating LoSolids® cooking and a schematic diagram showing the location of the temperature sensor and flow meter.

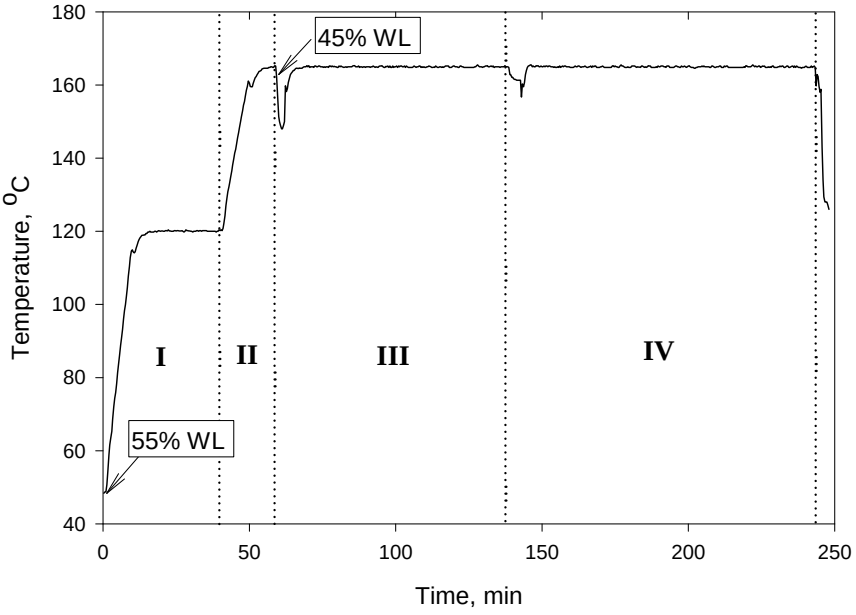


Figure II-22: Typical temperature-time profile and white liquor (WL) splits for pilot-plant LoSolids® pulping. Stage I = impregnation; II = heating (upper cooking zone); III = cooking (lower cooking zone); IV = wash circulation.

II-3.2.1 Liquor flow patterns

Figure II-23 shows that the liquor flow was highest for the green chips and the lowest for the kiln-dried chips; the flow for grey-stage chips was in between the two. This result is caused by the different amount of pins and fines (Figure II-2 and Figure II-3) in the three chip furnishes; the higher the pins/fines fraction the more the liquor flow is restricted. To simplify the data presentation, the average flows were calculated from the central part of the two cooking zones; the average was taken between 75 and 100 minutes in the lower cooking zone and between 180 and 230 minutes in the wash circulation. Figure II-24 shows that there is an obvious decrease in flow as the proportion of grey-stage chips increase in the green/grey mixture cooks. The decrease in flow was more pronounced in the wash circulation (WC) than the lower cooking zone (LCZ); a decrease in liquor flow of 10 mL/min compared to 2 mL/min of liquor per percent of grey chips in the mixture. This difference is caused by the collapse of the chip column as the cook proceeds. Table II-22 lists the average flows for all the green/grey mixture cooks. Similar results were obtained for the kiln-dried mixture cooks (Table II-23), but the kiln-dried flows were lower with a higher variability. The decrease in liquor flow per % of kiln-dried chips was also higher in both the lower cooking (11 mL/min per % of kiln-dried chips in the mixture) and in the wash circulation (26 mL/min per %kiln-dried chips) zones, a consequence of the higher amount of pins and fines found in the kiln-dried chips compared to the grey-stage chips. These changes in liquor flow have the potential to affect pulping uniformity and digester screen operation. In the pilot-plant, pins and fines passed the 3 mm extraction holes and blocked the pumping system.

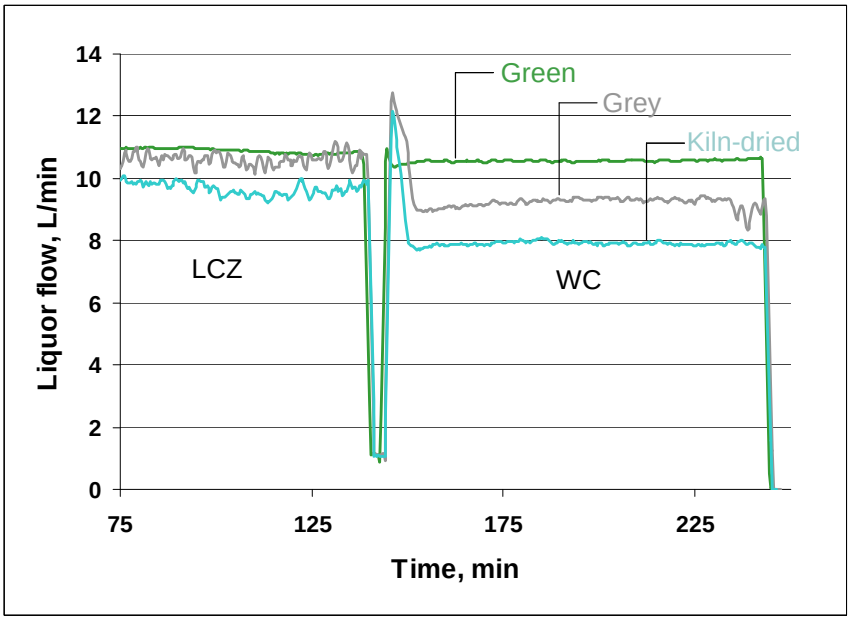


Figure II-23: The liquor flow for the grey-stage chips was between the green and kiln-dried chips in both the lower cooking (LCZ) and wash circulation (WC) zones.

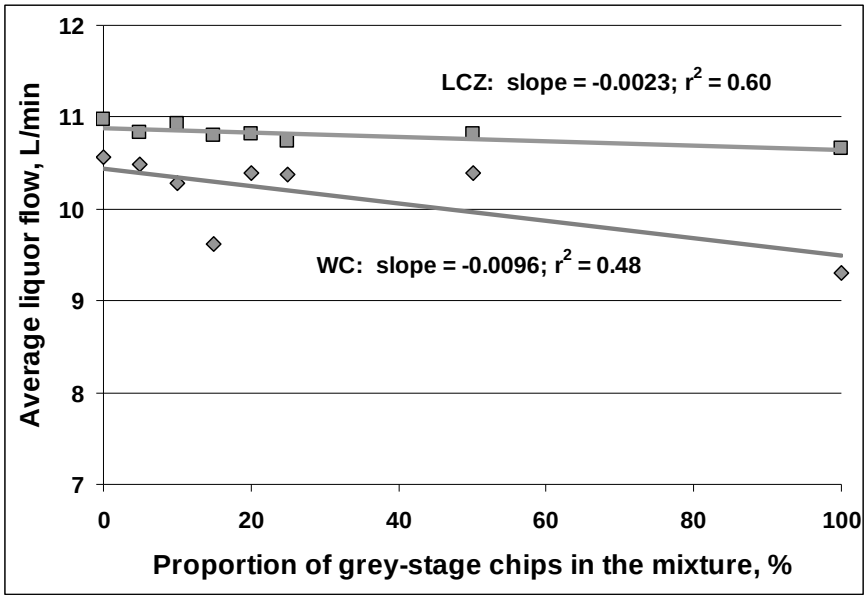


Figure II-24: The average liquor flow decreased as the proportion of grey-stage chips increased in the green/grey mixture cooks. The decrease in flow was more pronounced in the wash circulation (WC) than the lower cooking zone (LCZ) — a restricted liquor flow of 9.6 compared to 2.3 mL/min of liquor per percentage of grey chips in the mixture.

II-3.2.2 Pulping results

The LoSolids® pulping results showed several trends that were in good agreement with the conventional kraft pulping results. First, the green chips cooked faster than the grey chips. Figure II-25 shows the kappa numbers of the pulps from different mixtures that were cooked at a constant H-factor of 1960. The difference in kappa number between the green and grey-stage chips was 4.5 units. The linear regression line shows a poor fit (r^2 =0.49), however, it is important to note that this is a consequence of the small range of kappa numbers and the standard deviation in kappa number for this digester is 0.5 to 1.0 (Radiotis et al. 2001). Second, a steam/soak pretreatment of the chips minimized the amount of rejects, which were less than 0.3%, as shown in Table II-22. The reject value was obtained by subtracting screened yield from total yield. Third, the green chips had ~4% higher yield than the grey chips. Figure II-26, in addition, shows that the total yield (corrected to kappa number 30 by assuming a 0.16% yield loss per kappa number) decreased linearly (r^2 = 0.99) as the amount of grey-stage chips increased in the green/grey mixture. The slope of the line indicates that the yield will decrease by 0.04% for every percentage point of grey chips that is added to chip green/grey mixture. Fourth, the green chips consumed about 4% less EA than the grey chips; Figure II-27 shows that the EA consumption increased as the proportion of grey chips in the mixture increased. Similar trends and results were found for the green/kiln-dried mixture cooks (pulping results are given in Table II-23).

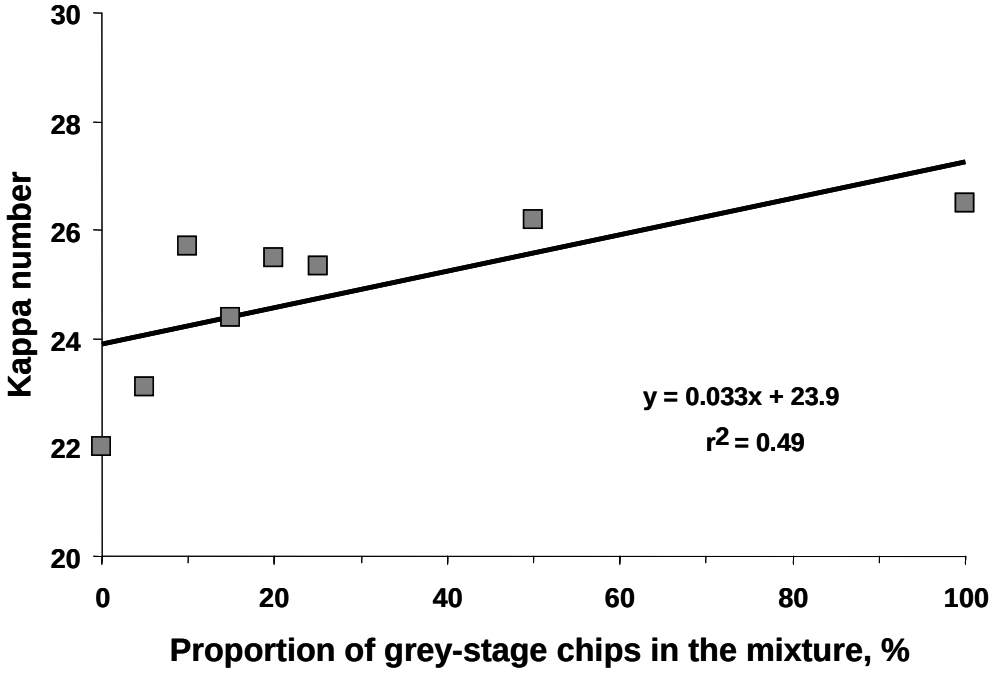


Figure II-25: Kappa number of LoSolids® green/grey mixture cooks (at a constant H-factor of 1960), showing that the green chips cooked faster than the grey chips.

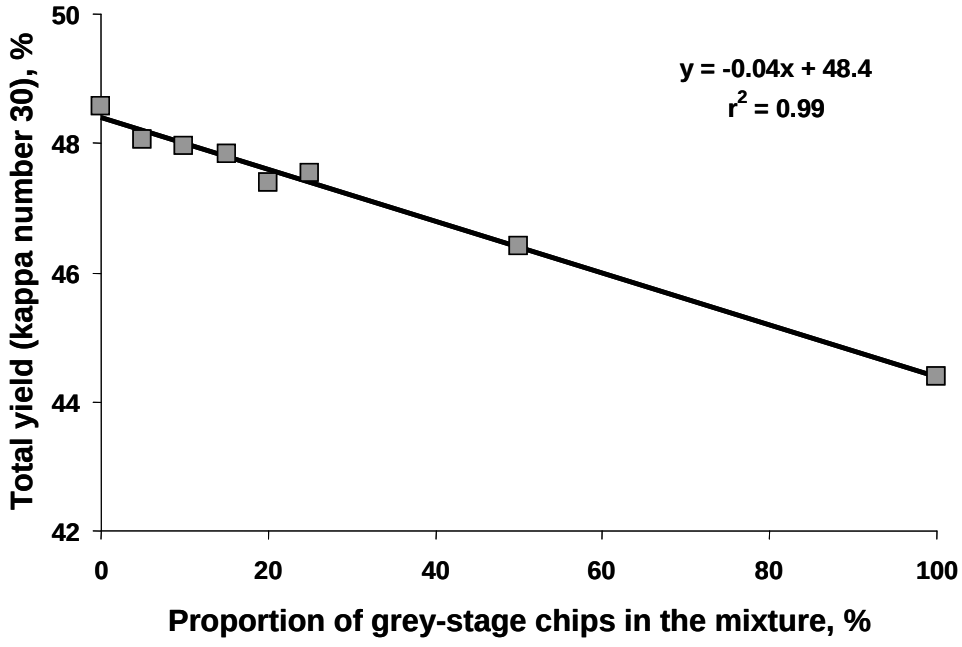


Figure II-26: The LoSolids® total yields (corrected to a kappa number 30) decreased as the amount of grey-stage chips increased in the green/grey mixture — the yield decrease was 0.04% per percentage of grey chips in the mixture.

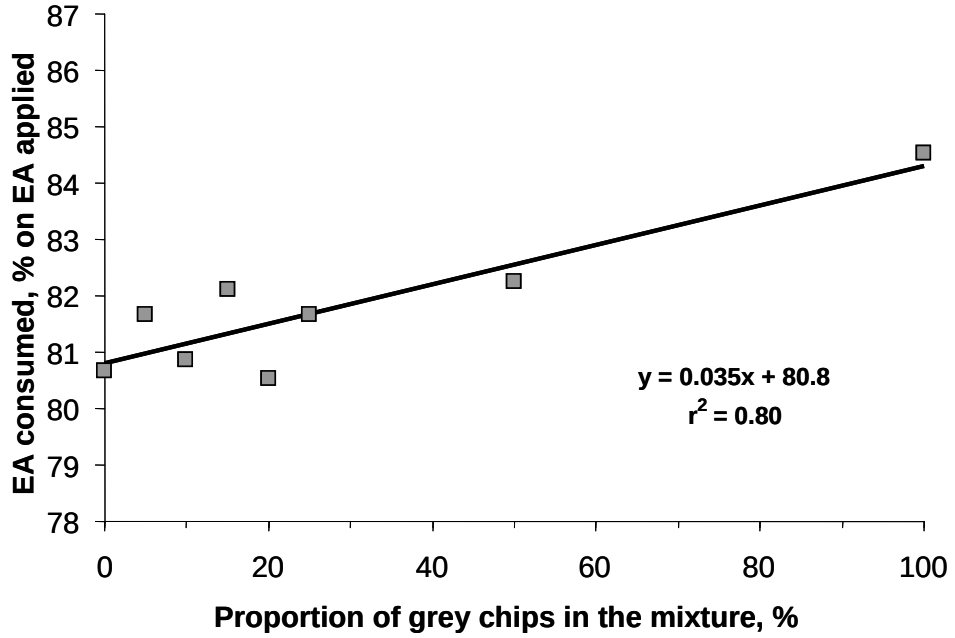


Figure II-27: More effective alkali was consumed as the amount of grey-stage chips increased in the green/grey mixture.

For the 75/25 and 50/50 green/dry chips mixtures, we also did layered cooks where the digester volume was split into two, with stacked baskets. The basket with the dry wood was placed on top and the one with the green chips on the bottom. The cooked material from each basket was disintegrated, washed, and screened separately, and pulp yield and kappa numbers were determined.

The uniformity of cooking of this technique has been tested in the past by placing 2-8 mm black spruce reference chips in both the top and bottom baskets and cooking with the same conditions. At the end of the cook, when the kappa numbers of the pulps from the top and bottom baskets were determined, the pulp from the bottom basket had a kappa number two units lower than the pulp from the top basket.

The results of the layered cooks (Table II-6) show that the green chips cooked faster than the dry chips, causing on average, a 6 kappa number difference. When the non-uniformity of cooking is taken into account, the difference is reduced to 4 kappa number units. The yield difference was again 3-4% higher for the green chips. These results show that the pulpability of the chips were the same whether they were pulped alone or as a mixture.

Table II-6: Layered cooks of green/dry chips showing that the pulpability of the chips were the same whether they were pulped alone or as a mixture; the green chips still cooked faster and the yield was 3-4% higher than that from the dry chips.

		Kappa number	Total yield at 30 kappa number
Green/grey	Green	24.6	48.0
75/25	Grey	31.1	44.5
Green/grey	Green	27.4	47.8
50/50	Grey	32.7	44.1
Green/kiln-dried	Green	25.4	48.3
75/25	kiln-dried	32.6	44.6
Green/kiln-dried	Green	27.6	48.2
50/50	kiln-dried	33.3	44.4

II-3.2.3 Pulp Properties

Experimental: The average fibre lengths and coarseness of the screened LoSolids® pulp fibres were measured using a Fibre Quality Analyzer (FQA, Optest). The pulps were then beaten in a PFI mill (0, 1500, 3000, 6000, and 12000 revolutions), made into standard handsheets, and tested for physical and optical properties according to PAPTAC Standard Methods.

Fibre length and coarseness: Relative to the green and grey-stage pulps, the kiln-dried pulp had a lower R14 fraction (fibres retained on a 14 mesh screen; the long fibre-length fraction) as seen in the Bauer McNett classification (Figure II-28). This resulted in a ~0.4 mm lower length weighted fibre length (Table II-7). The coarseness of the grey-stage pulp was slightly lower.

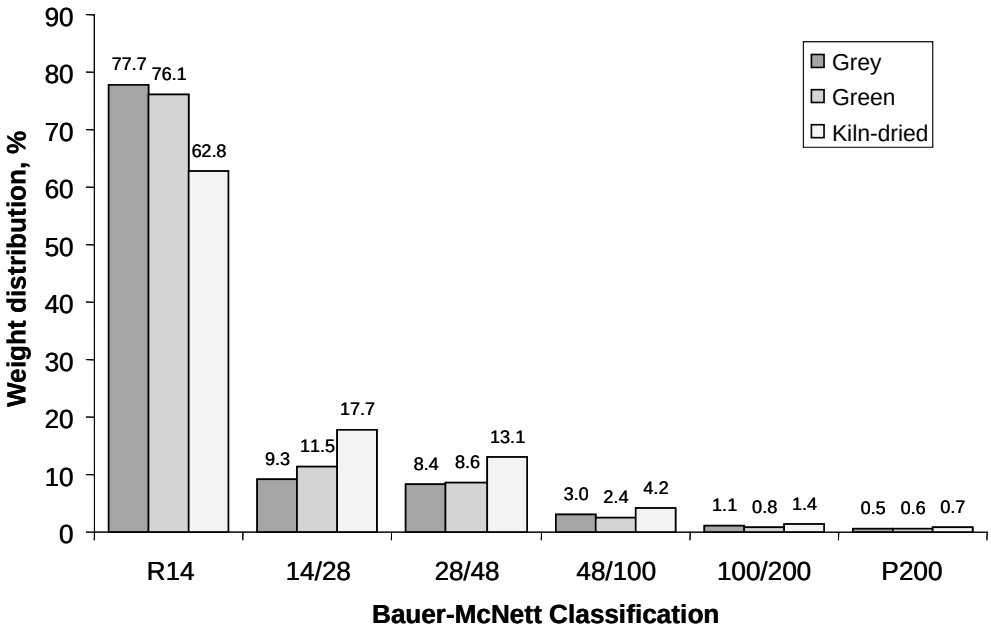


Figure II-28: Bauer-McNett classification showing that the long fibre fraction R14 (fibres that are retained on a 14-mesh screen) is lower for the kiln-dried pulp compared to the grey- and green-stage pulps.

Table II-7: Kiln-dried pulp has a lower fibre length than the grey and green-stage pulps; the grey-stage pulp had a slightly lower coarseness.

	Grey	Green	Kiln-dried
Length weighted fibre length, mm	2.87	2.80	2.48
Coarseness, mg/mm	0.113	0.127	0.128

Beating performance: Figure II-29 shows that the LoSolids® kraft pulps from the three furnishes responded similarly to beating in a PFI mill. The green-stage pulp had a slightly higher freeness at any given beating energy, but the largest difference was only 45 mL. The values are also in good agreement with previous work on conventional kraft lodgepole pine pulp (MacLeod 1983).

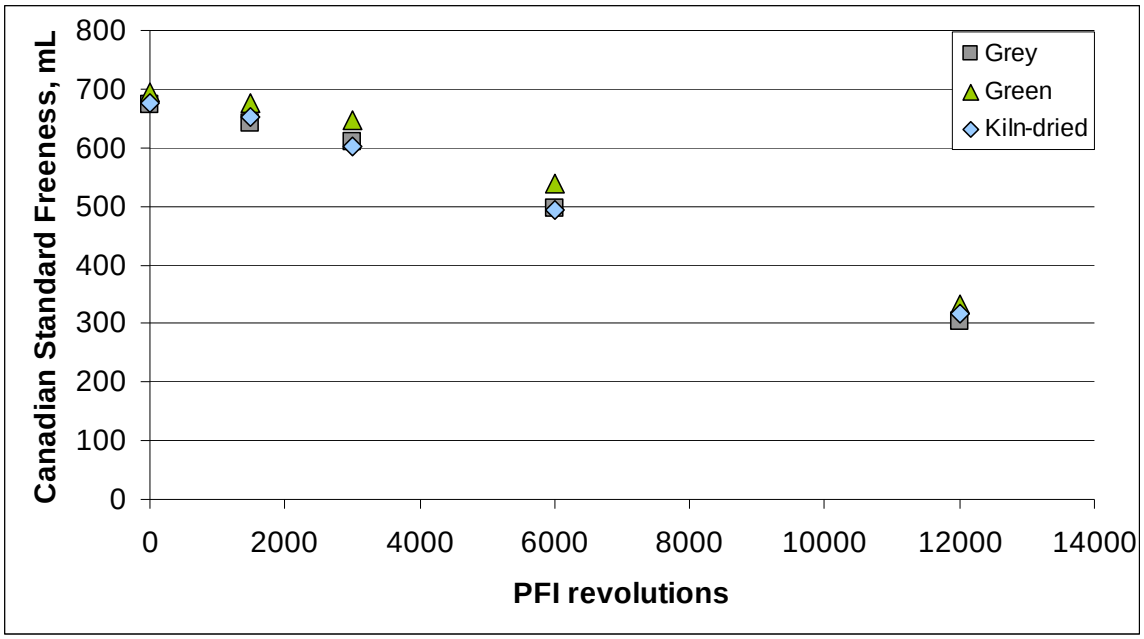


Figure II-29: The LoSolids® pulps from the three types of woods had a similar response to beating in a PFI mill.

Another way to assess beating performance is to follow the development of tensile strength (Figure II-30) or the decline of tear strength (Figure II-31) upon PFI beating. Figure II-30 shows that the grey-stage pulps had a 1 to 1.5 km higher breaking length value in the unbeaten state than the kiln-dried and green lodgepole pine pulps and this was retained during beating. Figure II-31 shows that the grey-stage and kiln-dried pulps had a 5 to 6 mNm^2/g lower tear index than the green pulps in the unbeaten state. This difference in tear strength was reduced to between 1.5 and 2.0 mNm^2/g after heavy PFI beating.

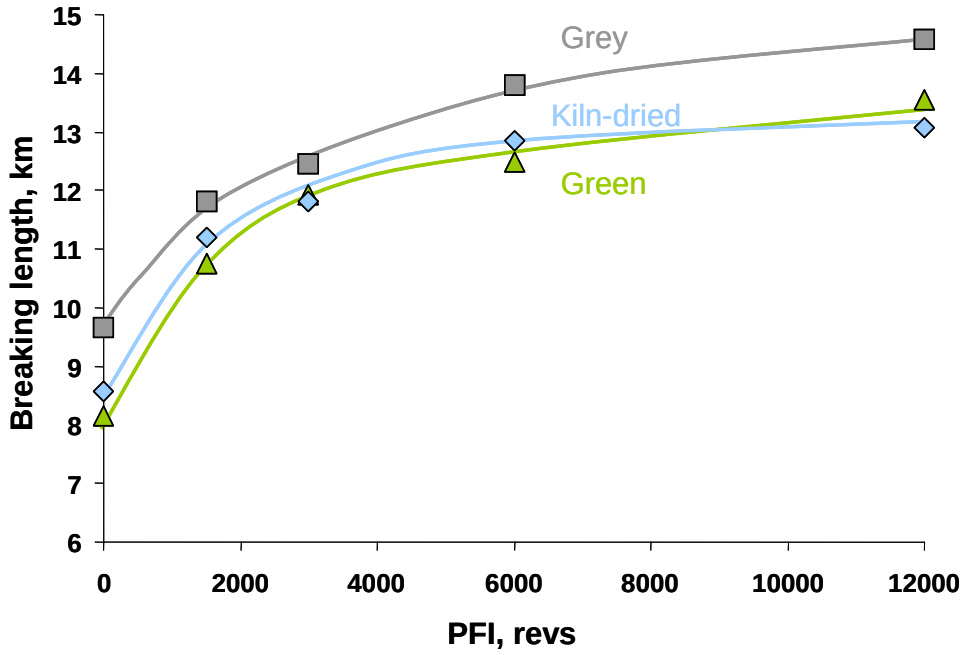


Figure II-30: In the unbeaten state, the grey-stage pulp had a 1 to 1.5 km higher breaking length than the green or kiln-dried pulps. This higher tensile strength was retained after heavy PFI beating.

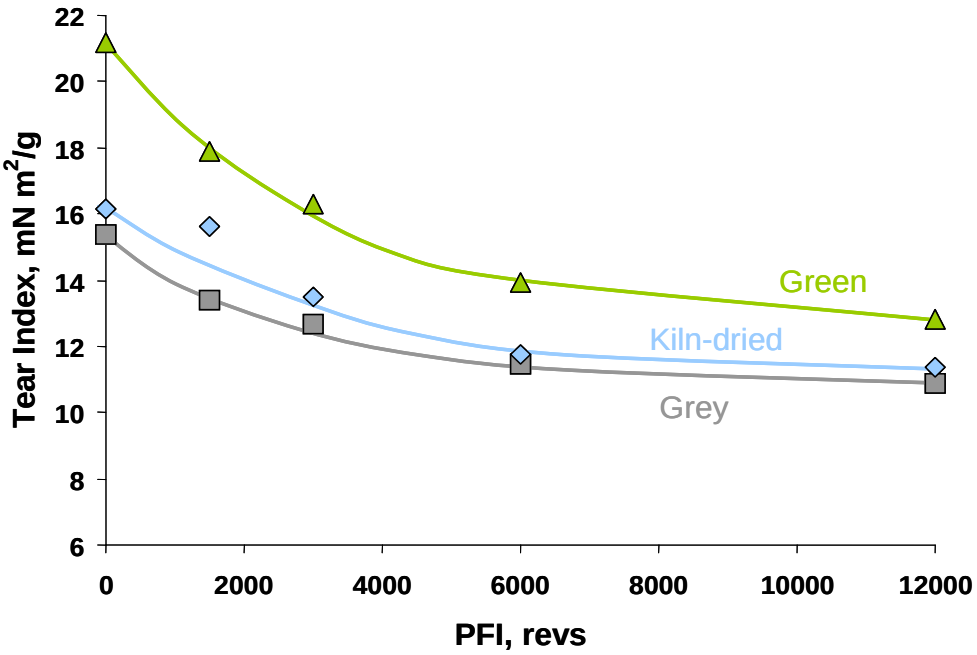


Figure II-31: In the unbeaten state, the grey-stage and kiln-dried pulps had a 5-6 mNm^2/g lower tear index than the green pulps. This difference in tear strength was reduced to 1.5-2.0 mNm^2/g after heavy PFI beating.

Tear-tensile performance: Plotting the tear strength against tensile strength allows a strength comparison to be made between different pulps. Pulps with tear-tensile lines that are further from the axes intercept are considered stronger (Rydholm 1965, Freriksson and Hoglund 1978, MacLeod 1980). Figure II-32 shows that the green-stage pulp exhibited the highest overall strength. Pulp strength is very dependent on the ratio of cellulose to hemicellulose with higher ratios of cellulose to hemicellulose giving a pulp with higher tear and requiring a little more beating energy to provide a given freeness (Kleppe and Kringstad 1963, Kleppe 1970, Hu et al. 1998, Jameel et al. 1995, Radiotis et al. 2003, Jiang 1995, Hakanen and Teder 1997, Kleppe and Minja 1998, Ahlgren et al. 1975, Annergren et al. 1963, Pekkala and Palenius 1973, Sayner and Laundrie 1964, Vinje and Worster 1969, Molin and Teder 2002). Table II-1 shows that the ratio of cellulose to hemicellulose is higher for the green-stage sample than for the others and this difference can explain the difference in response to beating and in physical properties. Again, this result is difficult to consider as a difference caused by the mountain pine beetle, but more likely caused by the variability in wood composition caused by harvesting location.

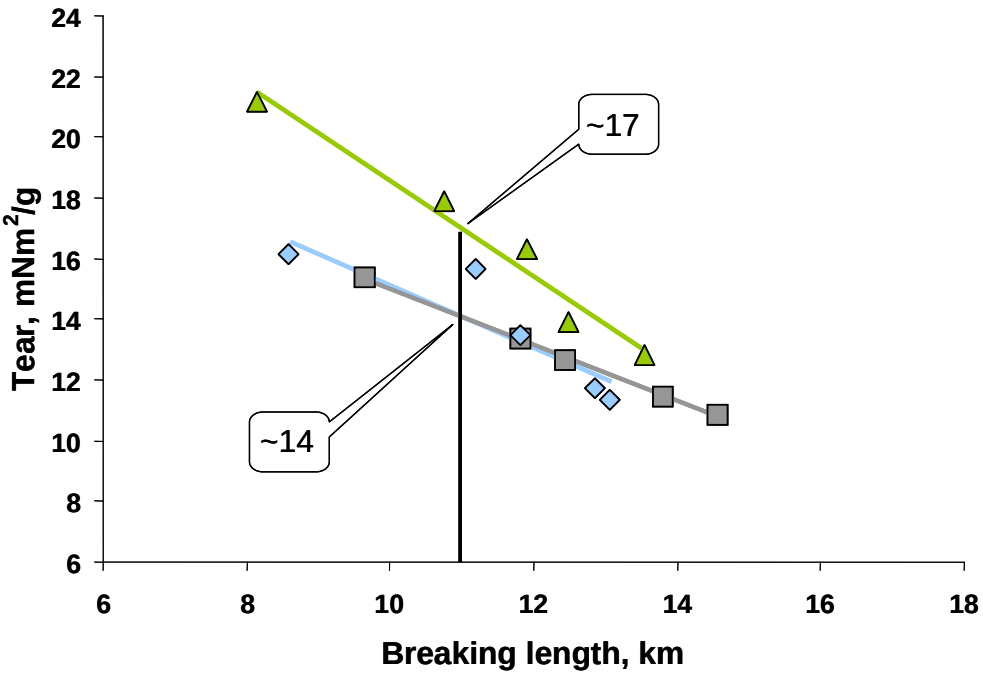


Figure II-32: At a mid-point tensile of 11 km, the green-stage pulp had 3 mNm^2/g higher tear than grey-stage or kiln-dried pulps.

Tear-bulk curves: The results in Figure II-33 resemble those in Figure II-32 with green-stage chips producing a more bulky, high-tear pulp, while grey-stage chips produced a more dense, lower-tear pulp. At a bulk of ~1.5 cm^3/g the three pulps had an equivalent tearing resistance. Again, this can be explained as the consequence of the differing cellulose to hemicellulose ratios.

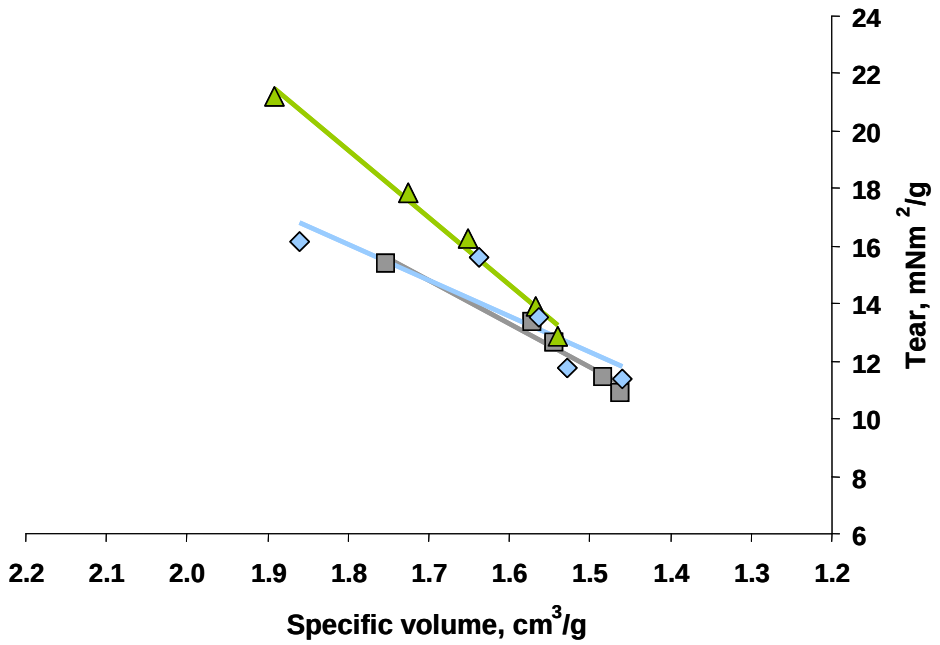
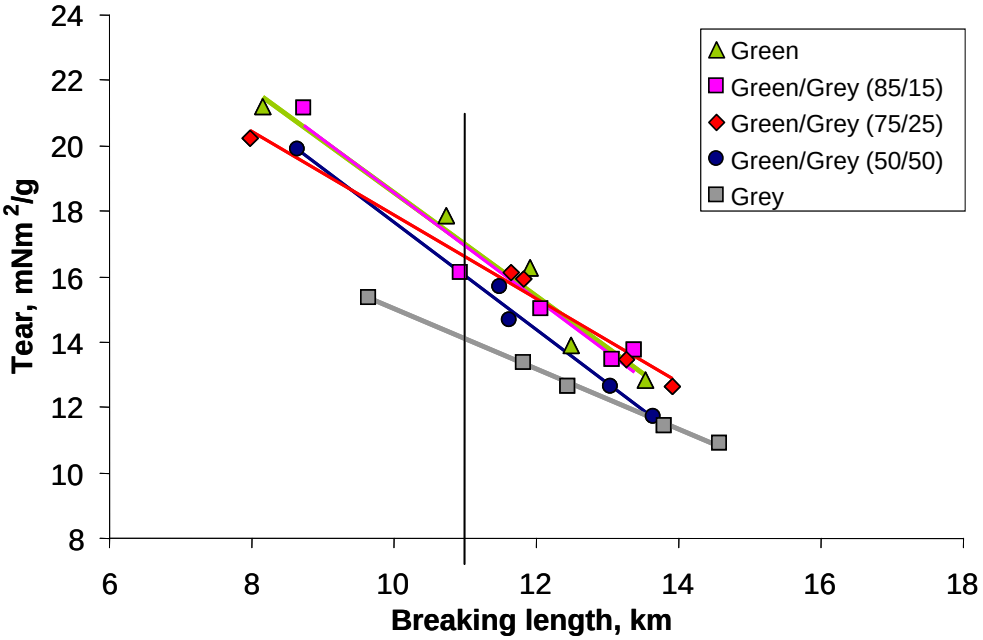


Figure II-33: Green-stage chips produced fibers that are stiffer and formed bulky handsheets which have a high tearing resistance. The grey or kiln-dried chips produced fibres that collapsed easily into denser handsheets with a lower tearing resistance (or higher tensile when compared to Figure 32).

Pulp properties from 2-8 mm thick chips: The trends and differences in pulp and fibre properties found between the three types of pulps produced from the whole chip distribution, as described above, were the same in every respect to the pulps from the 2 to 8 mm thick fractions (Appendix B, Table II-24 to Table II-29 show the detailed fibre and pulp properties from the whole and 2-8 mm thick chips). For example, at a breaking length of 11 km, the tear strengths were 17.6 and 14.4 mNm^2/g for the grey and kiln-dried which are slightly higher tears than those seen with the whole chips (17 and 14 mNm^2/g, Figure II-32); the difference between the green and grey-stage pulps was about the same (3.2 mNm^2/g). The similarity of the results rules out fines as the cause of the lower strength of the kiln-dried and grey-stage pulps. These results support that the observed difference is most likely caused by the higher cellulose content in the green chips.

Tear-tensile performance of green/over-dry mixture pulps: As seen from Figure II-32, the biggest difference between the three types of woods was that the green pulp had a 3 mNm^2/g higher tearing resistance than the grey or kiln-dried pulps. Similar analysis was done for the green/over-dry (Figure II-34) mixture pulps. The tearing resistance, at a mid-point tensile of 11 km, was then plotted as a function of the proportion of grey in the green/grey mixture (Figure II-35a) or the proportion of kiln-dried in the green/kiln-dried mixture (Figure II-35b). In both analyses the tear index decreased linearly by 0.03 mN m^2/g for every 1% of grey or 1% kiln-dried chips added to the mixture. The measured properties of the mixture pulps can be found in the Table II-31, Table II-32, Table II-33, Table II-34 and Table II-35.

a)



b)

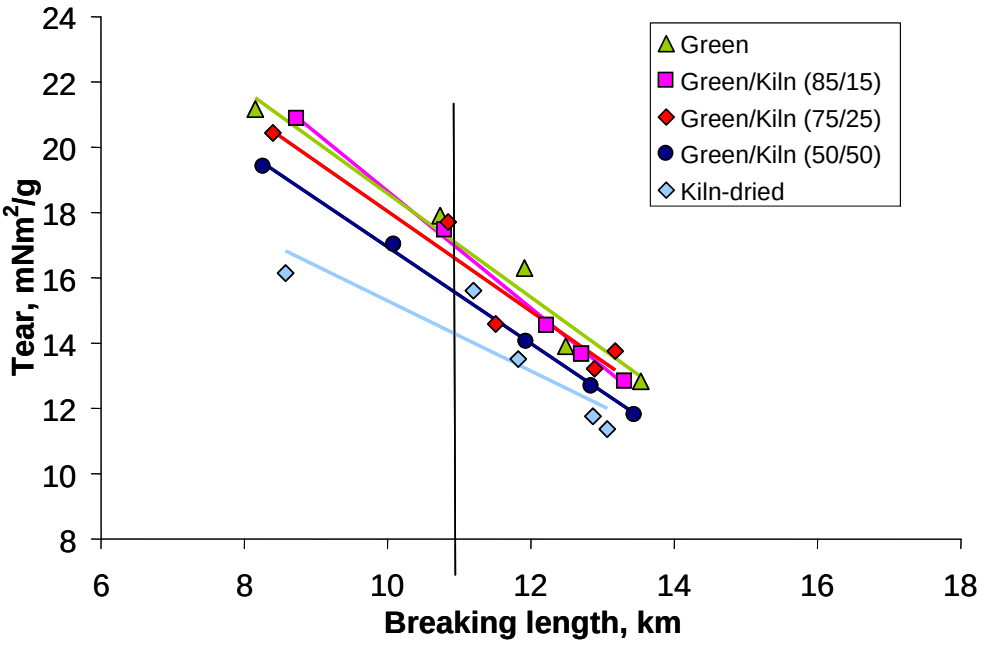
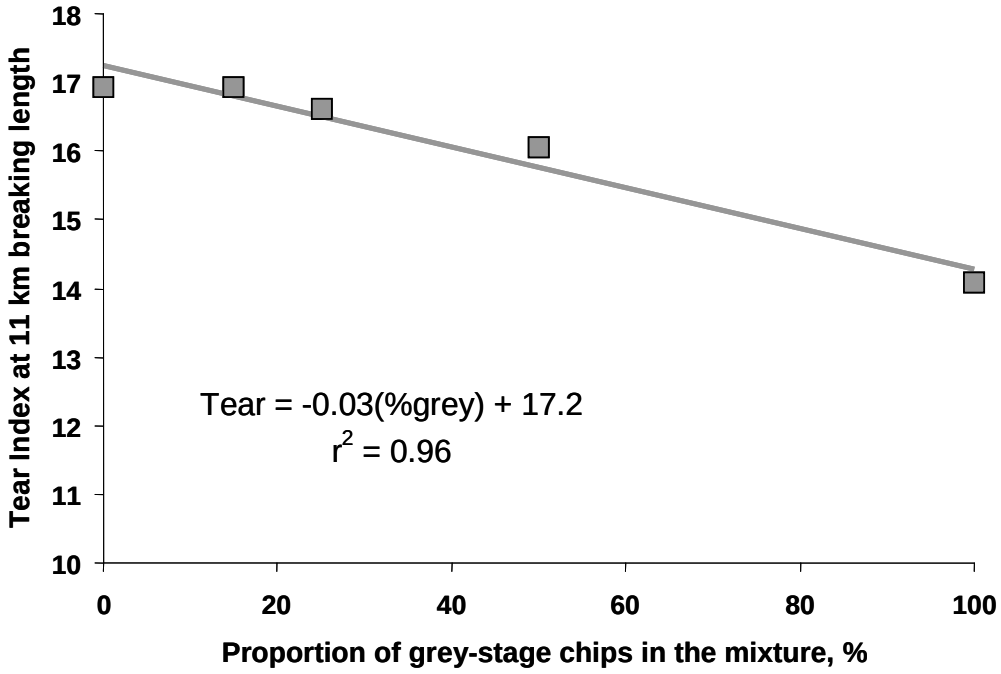


Figure II-34: The tearing resistance of the (a) green/grey mixture pulps was in between the green and grey pulps; similar results were obtained for the (b) green/kiln-dried mixture pulps.

a)



b)

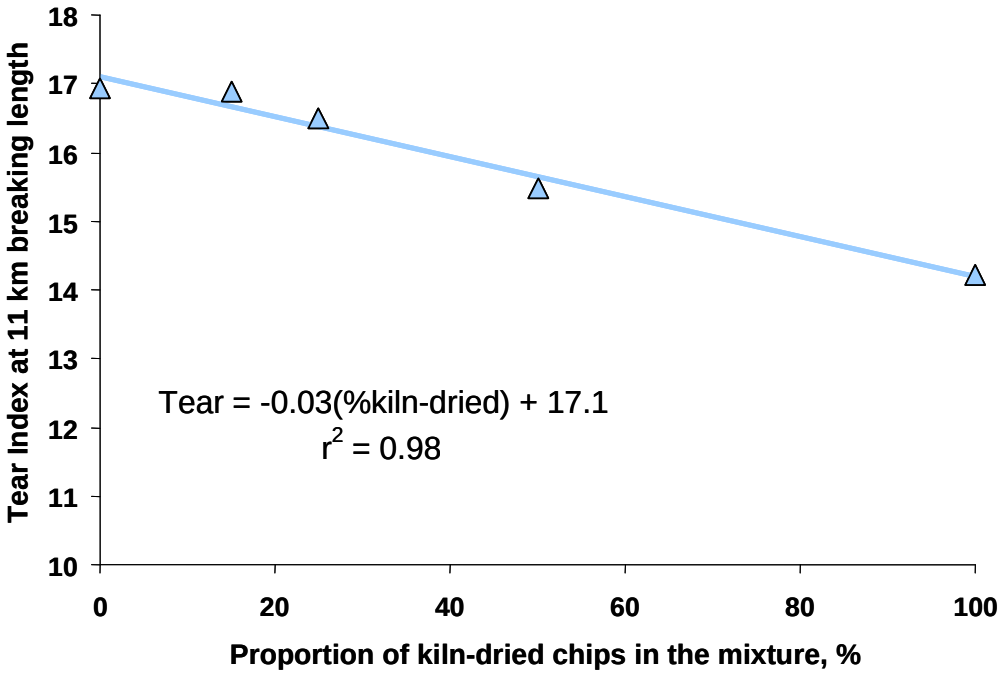


Figure II-35: The tearing resistance of the green/grey mixture pulps (a) was in between the green and grey pulps; similar results were obtained for the green/kiln-dried mixture pulps (b).

II-4 Conclusions

- Because of their lower moisture content, the grey-stage and kiln-dried wood produced more fines and less accepts in chipping than the green-stage wood.
- When the chips were pre-treated with an effective steaming procedure (steam-soak process), the screening rejects were reduced to less than 0.5% (on oven-dried wood basis) compared to 1-2% when no pre-treatment was applied.
- Green-stage whole chips cooked faster and had a 3-4% higher yield than grey or kiln-dried whole chips. These differences can be explained by the chemical composition of the chips that showed that the green chips had a higher cellulose content and lower extractives than the other furnishes. This variability in wood composition is most likely caused by tree-to-tree variability caused by harvesting location rather than the mountain pine beetle infestation.
- The liquor flows in the pilot plant digester, operating with a LoSolids® configuration, were highest for the green chips and lowest for the kiln-dried chips. The higher fines in the drier furnishes explain the differences in the flows.
- Pulping of 2-8 mm thick fractions of the grey, green, and kiln-dried chips gave pulps with the same yield differences as the pulps made from the whole chip furnish. This result eliminates the possibility that the difference in yield is caused by the difference in fines and oversized fractions in the whole chips.
- When green/grey or green/kiln-dried mixtures were cooked, the yield (corrected to a kappa number 30) decreased as the amount of dry chips (grey-stage or kiln-dried) increased in the green/dry mixture. The decrease is caused by the higher cellulose content of the green chips.
- At mid-point tensile of 11 km, the grey-stage or kiln-dried pulps had a 3-point lower tear index than the green-stage pulp. The difference in pulp strength can be explained by the differences in the ratio of cellulose to hemicellulose in the chips. The green-stage chips had a higher ratio that resulted in a higher tear and an increase in the beating energy needed to provide a given freeness.
- In mixed furnishes, the decrease in tearing resistance was proportional to the amount of dry chips added to the green/dry.
- The differences found between the green-stage and grey-stage furnishes (higher yield, faster delignification rate, and higher tear index) are caused by differences in wood chemistry (lower extractives and higher cellulose content). This variability in wood composition is most likely caused by tree-to-tree variability caused by harvesting location rather than the mountain pine beetle infestation.

II-5 Acknowledgements

The authors would like to thank Arnold Dort and Romana Kowalska for doing the pulping experiments. Tennessee Trent for providing the wood chips, chip classification data, and harvesting site information. The physical and chemical analysis groups at Paprican for the testing of wood chips and pulp properties.

This project was funded by the Government of Canada through the Mountain Pine Beetle Initiative, a six-year, $40 million Program administered by Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resource Canada – Canadian Forest Service.

II-6 Literature Cited

Ahlgren, P., Olsson, L.A. and Vikström, B. 1975. Comparison between the properties of high yield conventional kraft pulp and those of polysulfide and hydogen sulfide high yield pulps, Svensk Papperstidn., 78(3):95.

Akhtaruzzaman, A.F.M. and Virkola, N.-E. 1980. Paperi Puu 62 (1,2,4):15, 70, 297.

Annergren, G., Rydholm, S. and Vardheim, S. 1963. Influence of raw material and pulping process on the chemical composition and physical properties of paper pulps, Svensk Papperstidn. 66(6):196.

BCMoF, 1997. Site Index Estimates by Site Series for Coniferous Tree Species in British Columbia, Site Productivity Working Group, Forest Renewal B.C. and British Columbia Ministry of Forests.

Bicho, P., Hussein, A., Yuen, B., Gee, W., and Johal, S., 2006. Evaluation of In-Woods Chipping Options for Beetle-Killed Lodgepole Pine Wood, Paprican Report PRR 1811, Paprican, Vancouver, B.C.

Cohen, W.E. and Mackney, A.W. 1951. The Influence of Wood Extractives in Digester Control, Pulp Pap. Mag. Can., 54(12), p. 125-130.

Dalpke, B. and Bicho, P. 2007. Influence of Mountain Pine Beetle Attack on Lodgepole Pine Extractives, Paprican Report PSR 571, Paprican, Vancouver, B.C.

Dalpke, B., Hussein, A., Gee, W. and Watson, P. 2006a. Assessment of the Pulping and Pulp Quality Effects of Increased Lodgepole Pine in SPF Chip Mixtures. Part II: Kraft Pulping, Paprican Report PRR 1809, Paprican, Vancouver, B.C.

Dalpke, B., Trent, T., Lawrence, V., Woo, K., Drummond, J. and Watson, P. 2006b. The Influence of Time Since Death on Wood and Fibre Quality of Mountain Pine Beetle-Killed Wood Differentiated by Biogeoclimatic Subzone, Paprican Report PRR 1814, Paprican, Vancouver, B.C.

Fredriksson, B. and Hoglund, H. 1978. Chemithermomechanical Pulps in Different Grades, Appita, 31(5):365.

Gee, W., Johal, S., Hussein, A., Yuen, B., and Watson, P. 2004. The Pulping Properties of Mountain Pine Beetle-Killed Lodgepole Pine, Paprican Report PRR 1695, Paprican, Vancouver, B.C.

Hakanen, A. and Teder, A. 1997. Modified kraft cooking with polysulphide: yield, viscosity, and physical properties, Tappi J., 80(7):189.

Hartler, N. and Stade, Y. 1979. Chip Specifications for Various Pulping Processes, Chapter 13 in Chip Quality Monograph, Edited by Hatton, J.V., Joint Textbook Committee of the Paper Industry.

Hatton, J.V. 1979. Chip Quality Analytical Procedures, Chapter 14 in Chip Quality Monograph, Edited by Hatton, J.V., Joint Textbook Committee of the Paper Industry.

Hatton, J.V. 1975. Quality and kraft pulping characteristics of residual chips, Tappi 58(2), 110-114.

Hatton, J.V., Gee, W.Y., and Cisneros, H.A. 1992. Managed Lodgepole Pine Forests: II. Yield and Quality of Unbleached Kraft Pulps from Juvenile, Mature, and Top Wood, and their Relationships with Wood and Fibre Properties, Paprican Report PPR 966, Paprican, Vancouver, B.C.

Hillis, W.E. and Suminoto, M. 1989. Effect of Extractives on Pulping. In: Natural Products of Woody Plants, Rowe, J.W. (Ed.), Springer-Verlag, p. 880-913.

Hu, T.Q., Chow, W., van Heek, R., Uloth, V., and Wearing, J.T. 1998. Polysulphide pulping of softwood with oxidized mill white liquor generated from Paprican's PS process, TAPPI Pulping Conference Proceedings, TAPPI Press, Atlanta, p. 561; PPR 1332.

Jameel, H., Gratzl, J., Prasad, D.Y., and Chivukula, S. 1995. Extending delignification with AQ/polysulphide, Tappi J. 78(9):151.

Jiang, J.E. and Lowe, R.W. 1995. Extended modified cooking of Southern pine with polysulphide — Effect on elemental-chlorine-free bleaching, J. Pulp Pap. Sci., 21(3):76.

Kleppe, P.J. 1970. Kraft pulping, Tappi J., 53(1):35.

Kleppe, P.J. and Kringstad, K., 1963. Sulphate pulping by the polysulphide process. I. Investigations on spruce and pine, Norsk Skogind., 17(11):428.

Kleppe, P.J. and Minja, R.J.A. 1998. The possibilities to apply polysulphide-AQ pulping in kraft mills, Breaking the Pulp Yield Barrier Symposium Proceedings, TAPPI Press, Atlanta, p.113.

Louden, L. 1981. Pitch: Problems and Control. Institute of Paper Chemistry.

MacLeod, J.M., March 1980. Comparing Pulp Strengths, Pulp Paper Can., 81(12):128, 1980; Paprican Report PPR 272, Paprican, Pointe Claire, P.Q.

MacLeod, J.M. 1983. Kraft pulps from Canadian wood species, Paprican Report PPR 434, Paprican, Pointe Claire, P.Q.

MacLeod, J.M, and Dort, A. 2005. The Decline and Fall of Tensile Strength in Kraft Pulp Mills, Paprican Report PRR 1784, Paprican, Pointe Claire, P.Q.

Molin, U. and Teder, A. 2002. Importance of cellulose/hemicellulose - ratio for pulp strength, Nord. Pulp Pap. Res. J., 17(1):14.

Pekkala, O. and Palenius, I. 1973. Hydrogen sulphide pretreatment in alkaline pulping, Pap. Puu, 55(9):659.

Radiotis, T., O'Hagan, T. and MacLeod, J.M. 2001. Paprican's Automated Pilot-Plant Pulping System and its use in Assessing EMCC® Cooking, Paprican Report MR 440, Paprican, Pointe Claire, P.Q.

Radiotis, T., MacLeod, J.M., O'Hagan, T. 2003. Softwood Yield Gain and Effects on Pulp Properties During a Paprilox Polysulphide-AQ Mill Trial, Paprican Report PRR 1639, Paprican, Pointe Claire, P.Q.

Rydholm, S.A. 1965. Pulping Processes, Interscience, New York, Chapters 9 and 21.

Sanyer, N. and Laundrie, J.F., 1964. Factors affecting yield increase and fiber quality in polysulphide pulping of Loblolly pine, other softwoods, and Red oak, Tappi J., 47(10):640.

Tikka, P., Tahkanen, H., and Kovasin, K., 1993. Chip thickness vs. kraft pulping performance: Experiments by multiple hanging baskets in batch digesters, Tappi J., 76(3), 131-136.

Vinje, M.G. and Worster, H.E. 1969. Hydrogen sulphide alkaline pulping. Part II. A quantitative comparison with polysulphide pulping, Pulp Pap. Can., 70(11):T431.

Watson, P., 2006. The Mountain Pine Beetle Epidemic: Changing the face of the BC industry, Pulp Pap. Can., 107(5), 12.

Watson, P., 2005. The Impact of Mountain Pine Beetle on Pulping and Papermaking, Paprican Report PSR 544, Paprican, Vancouver, B.C.

Weigel, G., Bicho, P., and Watson, P. 2002. Seasonal Variations in the Extractives Contents of Four British Columbia Softwoods, Paprican Report PRR 1590, Paprican, Vancouver, B.C.

Woo, K., Mansfield, S., and Watson, P. 2003a. Mountain Pine Beetle Infestation in Lodgepole Pine Forests: A Literature Review, Paprican Report PSR 501, Paprican, Vancouver, B.C.

Woo, K., Omholt, I. and Watson, P. 2006. Moisture Loss in Wood: Implications for use of grey-stage mountain pine beetle-killed wood, Paprican Report PSR 561, Paprican, Pointe Claire, P.Q.

Woo, K., Watson, P., and Mansfield, S. 2003b. The Effects of Mountain Pine Beetle and Associated Blue Staining Fungi on Wood Morphology and Chemistry, Paprican Report PUR 831, Paprican, Vancouver, B.C.

II-7 Contacts

Theodore Radiotis
Pulp & Paper Res. Inst. of Canada
570 St. John's Blvd
Pointe-Claire, QC, Canada
tradiotis@paprican.ca
(514) 630-4101 #2205

Gail Sherson
Pulp & Paper Res. Inst. of Canada
3800 Wesbrook Mall
Vancouver, BC, Canada
gsherson@paprican.ca
(604) 222-3208

II-8 Appendices

II-8.1 Appendix A. Pulping data

Table II-8: Pulping data for kiln-dried LPP as received chips with no pre-treatment

"H" Factor	990	1291	1488	1492	1799	2095
Rejects, %	2.90	1.45	1.90	1.30	0.70	0.45
Total Yield, %	46.99	45.18	44.76	44.62	44.18	43.18
Screened Yield, %	44.09	43.73	42.86	43.32	43.48	42.73
Kappa number	46.3	34.2	30.2	30.3	24.8	21.6
Residual EA, g/L	7.64	6.69	6.35	6.25	5.50	5.12
EA consumed,%	75.8%	78.8%	79.9%	80.2%	82.6%	83.8%

Table II-9: Pulping data for kiln-dried LPP as received chips with a steam-only pre-treatment

"H" Factor	996	1301	1499	1499	1795	2100
Rejects, %	1.65	1.35	1.30	1.25	0.95	0.50
Total Yield, %	47.05	45.44	44.47	44.56	43.92	43.03
Screened yield, %	45.40	44.09	43.17	43.31	42.97	42.53
Kappa number	41.9	31.5	27.4	27.2	22.9	20.8
Residual EA, g/L	7.70	6.50	6.41	5.97	5.83	5.18
EA consumed, %	75.6%	79.4%	79.7%	81.1%	81.5%	83.6%

Table II-10: Pulping data for kiln-dried LPP as received chips with a steam/soak pre-treatment

"H" Factor	1005	1005	1300	1305	1503	1508
Rejects, %	0.68	1.12	0.14	0.62	0.26	0.40
Screened Yield, %	45.50	45.14	44.83	44.16	43.98	43.50
Total Yield, %	46.18	46.26	44.97	44.78	44.24	43.90
Kappa number	43.6	44.1	33.2	32.5	28.5	29.2
Residual EA, g/L	7.63	7.72	6.91	7.02	6.53	6.55
EA consumed, %	75.8%	75.6%	78.1%	77.8%	79.3%	79.3%
"H" Factor	1501	1506	1700	1706	1895	2097
Rejects, %	0.50	0.50	0.55	0.85	0.40	0.35
Screened Yield, %	43.56	43.61	43.23	43.04	43.16	41.94
Total Yield, %	44.06	44.11	43.78	43.89	43.56	42.29
Kappa number	28.5	29.6	25.0	25.6	22.7	21.2
Residual EA, g/L	6.23	6.16	5.82	5.74	5.45	5.24
EA consumed, %	80.2%	80.4%	81.5%	81.8%	82.7%	83.4%

Table II-11: Pulping data for kiln-dried LPP as received chips with a CB/SV pre-treatment

"H" Factor	995	1291	1479	1502	1799	2099
Rejects, %	2.75	1.35	0.80	1.50	1.05	0.60
Screen Yield, %	45.51	45.46	44.93	44.85	43.59	43.54
Total Yield, %	48.26	46.81	45.73	46.35	44.64	44.14
Kappa	53.9	39.8	34.2	34.1	29.0	25.1
Residual EA, g/L	7.73	6.95	6.57	6.44	5.75	5.45
EA consumed, %	75.5%	77.9%	79.2%	79.6%	81.8%	82.7%

Table II-12: Pulping data for grey-stage LPP as received chips with no pre-treatment

"H" Factor	993	1299	1498	1502	1797	2104
Rejects, %	0.85	0.95	0.85	0.90	0.85	0.75
Screened Yield, %	45.27	44.01	43.56	43.71	42.48	42.23
Total Yield, %	46.12	44.96	44.41	44.61	43.33	42.98
Kappa number	46.2	33.5	29.1	28.9	24.1	21.2
Residual EA, g/L	7.49	6.66	6.47	6.18	5.63	5.31
EA consumed, %	76.3%	78.9%	79.5%	80.4%	82.2%	83.2%

Table II-13: Pulping data for grey-stage LPP as received chips with steam-only pre-treatment

"H" Factor	1002	1309	1500	1505	1801	2102
Rejects, %	2.82	0.62	0.54	0.58	0.37	0.38
Screen Yield, %	43.53	43.86	43.41	43.66	42.98	42.66
Total Yield, %	46.35	44.48	43.95	44.24	43.35	43.04
Kappa number	43.4	33.2	29.0	28.6	25.1	21.5
Residual EA, g/L	7.48	6.56	6.18	6.29	5.72	5.39
EA consumed, %	76.3%	79.2%	80.4%	80.1%	81.9%	82.9%

Table II-14: Pulping data for grey-stage LPP as received chips with steam/soak pre-treatment

"H" Factor	1004	1299	1497	1502	1802	2099
Rejects, %	0.74	0.16	0.12	0.14	0.18	0.08
Screen Yield, %	44.78	44.08	43.21	43.52	42.86	42.44
Total Yield, %	45.52	44.24	43.33	43.66	43.04	42.52
Kappa number	42.7	31.9	28.4	28.6	24.6	21.6
Residual EA, g/L	7.63	6.80	6.34	6.03	5.85	5.63
EA consumed, %	75.9%	78.5%	79.9%	80.9%	81.5%	82.2%

Table II-15: Pulping data for grey-stage LPP as received chips with CB/SV pre-treatment

"H" Factor	995	1302	1499	1505	1815	2101
Rejects, %	1.90	0.75	1.30	0.90	0.35	0.70
Screen Yield, %	45.30	42.75	42.98	44.19	43.89	42.83
Total Yield, %	47.20	43.50[†]	44.28	45.09	44.24	43.53
Kappa number	51.7	37.7	32.6	32.7	26.1	24.1
Residual EA, g/L	7.46	7.12	6.70	6.48	5.78	5.49
EA consumed, %	76.4%	77.4%	78.8%	79.5%	81.7%	82.6%

[†] Some pulp was lost during processing

Table II-16: Pulping data for green-stage LPP as received chips with no pre-treatment

"H" Factor	998	1303	1500	1505	1801	2096
Rejects, %	4.05	2.65	0.55	0.80	0.90	1.35
Screen Yield, %	47.07	46.67	47.26	46.36	45.76	44.93
Total Yield, %	51.12	49.32	47.81	47.16	46.66	46.28
Kappa	41.1	30.3	26.2	25.5	21.1	18.9
Residual EA, g/L	8.12	7.21	6.38	6.83	5.99	5.50
EA consumed, %	74.4%	77.2%	79.9%	78.4%	81.1%	82.6%

Table II-17: Pulping data for green-stage LPP as received chips with steam-only pre-treatment

"H" Factor	1007	1303	1495	1501	1802	2101
Rejects, %	0.38	0.87	0.94	0.64	0.33	0.46
Screen Yield, %	47.76	47.49	46.15	46.68	46.34	45.10[†]
Total Yield, %	48.14	48.36	47.09	47.32	46.67	45.56
Kappa	38.2	29.6	25.6	25.7	22.1	19.2
Residual EA, g/L	8.21	7.09	6.68	6.70	6.00	5.78
EA consumed, %	74.0%	77.5%	78.8%	78.8%	81.0%	81.7%

[†] Some pulp was lost during processing

Table II-18: Pulping data for green-stage LPP as received chips with steam/soak pre-treatment

"H" Factor	1001	1302	1493	1498	1799	2094
Rejects, %	0.10	0.40	0.50	0.10	0.05	0.05
Screen Yield, %	48.00	46.91	47.03	46.87	46.14	46.00
Total Yield, %	48.10	47.31	47.53	46.97	46.19	46.05
Kappa	38.8	29.4	26.0	26.2	21.6	18.3
Residual EA, g/L	8.28	7.23	6.7	6.62	5.79	5.65
EA consumed, %	73.7%	77.0%	78.7%	79.0%	81.6%	82.1%

Table II-19: Pulping data for green-stage LPP as received chips with CB/SV pre-treatment

"H" Factor	999	1300	1503	1508	1798	2124
Rejects, %	3.50	2.70	2.25	1.55	1.10	0.80
Screen Yield, %	48.55	47.45	47.29	47.62	46.43	46.22
Total Yield, %	52.05	50.15	49.54	49.17	47.53	47.02
Kappa	52.0	39.7	31.5	32.3	26.9	21.7
Residual EA, g/L	8.54	7.30	7.14	7.01	6.41	5.95
EA consumed, %	73.0%	76.9%	77.4%	77.8%	79.7%	81.2%

Table II-20: Pulping data for grey, kiln-dried, and green-stage LPP 2-8mm thick fraction chips with a steam/soak pre-treatment followed by conventional kraft pulping conditions.

	Grey					Kiln-dried			Green		
"H" Factor	805	1309	1806	1819	804	1301	1804	800	1303	1809	1814
Rejects, %	0.30	0.05	0.05	0.15	0.95	0.15	0.15	0.75	0.05	0.2	0.4
Screen Yield, %	47.92	45.06	43.80	43.45	48.45	45.62	44.37	52.15	49.19	47.25	48.47
Total Yield, %	48.22	45.11	43.85	43.6	49.4	45.77	44.52	52.90	49.24	47.45	48.87
Kappa number	61.6	35.7	26.1	26.74	63.97	39.41	27.13	60.5	34.7	25.1	25.5
Residual EA, g/L	8.11	6.92	6.18	6.06	8.51	6.92	6.16	8.89	7.25	6.76	6.14
EA consumed, %	74.3	78.1	80.4	80.8	73.1	78.1	80.5	71.8	77.0	78.6	80.6

Table II-21: Pulping data for grey, kiln-dried, and green-stage LPP 2-8mm thick fraction chips with a steam CB/SV pre-treatment followed by conventional kraft pulping conditions at a 4:1 L:W that excludes the chip moisture after the pre-treatment.

	Grey			Kiln-dried			Green		
"H" Factor	1102	1408	1595	1098	1402	1595	1109	1414	1601
Rejects, %	0.45	0.15	0.10	0.40	0.30	0.10	0.65	0.30	0.10
Screen Yield, %	45.36	44.44	43.71	46.27	45.19	44.69	49.69	48.18	47.60
Total Yield, %	45.81	44.59	43.81	46.67	45.49	44.79	50.34	48.48	47.70
Kappa	41.9	29.6	27.7	41.0	31.9	28.9	43.6	31.7	27.5
Residual EA, g/L	8.05	7.47	7.01	8.47	7.20	7.19	8.26	7.44	7.49
EA consumed, %	77.9%	79.4%	80.7%	76.8%	80.3%	80.3%	74.9%	77.4%	77.3%

Table II-22: Average liquor flows in the lower cooking (LCZ) and wash circulation (WC) zones, kappa numbers at 1960 H-factor, pulping yields, and effective alkali consumed in the green/grey mixture cooks.

Green/Grey chips (wt%/wt%)	Liquor flow in LCZ, L/min	Liquor flow in WC, L/min	Kappa number	Total yield, %	Screened yield, %	EA consumed, % on EA applied
100/0	10.97	10.56	22.0	47.30	47.16	80.66
95/5	10.83	10.48	23.1	46.96	46.89	81.67
90/10	10.93	10.28	25.7	47.28	46.99	80.85
85/15	10.79	9.61	24.4	46.93	46.70	82.12
80/20	10.81	10.38	25.5	46.66	46.57	80.53
75/25	10.74	10.38	25.3	46.79	46.65	81.67
50/50	10.81	10.39	26.2	45.8	45.64	82.24
0/100	10.66	9.31	26.5	43.83	43.58	84.53

Table II-23: Average liquor flows in the lower cooking (LCZ) and wash circulation (WC) zones, kappa numbers at 1960 H-factor, pulping yields, and effective alkali consumed in the green/kiln-dried mixture cooks

Green/kiln-dried chips (wt%/wt%)	Liquor flow in LCZ, L/min	Liquor flow in WC, L/min	Kappa number	Total yield, %	Screened yield, %	EA consumed, % on EA applied
100/0	10.97	10.56	22.0	47.30	47.16	80.66
95/5	10.83	10.48	24.7	47.06	47.00	79.82
90/10	11.47	11.10	28.0	47.74	47.48	82.14
85/15	10.98	10.29	23.8	46.56	46.44	81.10
80/20	10.85	10.45	26.4	46.98	46.77	80.90
75/25	10.94	10.99	23.8	46.30	46.20	81.80
50/50	11.12	10.60	27.5	46.05	45.94	83.58
0/100	9.83	7.92	26.1	44.08	43.91	84.78

II-8.2 Appendix B. Physical testing data

Table II-24: Fibre and kraft pulp physical and optical properties of grey-stage whole chips.

SAMPLE	7967-1	7967-2	7967-3	7967-4	7967-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	672	642	611	496	305
B-McNett R14 - %	77.7				
B-McNett 14/28 - %	9.3				
B-McNett 28/48 - %	8.4				
B-McNett 48/100 - %	3.0				
B-McNett 100/200 - %	1.1				
B-McNett P200 - %	0.5				
FQA Arith, mm	1.395				
FQA L. Wtd, mm	2.87				
FQA W. Wtd, mm	3.35				
FQA Coarseness, mg/m	0.1125				
FQA P<0.2mm, %	37.65				
Grammage (O.D.) - g/m^2	62.0	61.6	60.9	60.0	58.3
Caliper - SS - um	109	97	94	89	85
Specific Volume - SS - cm^3/g	1.75	1.57	1.54	1.48	1.46
Apparent Density - SS - g/cm^3	0.57	0.64	0.65	0.67	0.68
Burst Index - kPm^2/g	7.18	9.18	9.09	10.92	11.52
Tear Index - 4PL - HS - mNm^2/g	15.36	13.38	12.66	11.45	10.88
Breaking Length - DRY - HS - km	9.65	11.82	12.44	13.80	14.57
Stretch - DRY - HS - %	2.62	3.01	3.74	3.63	3.74
Tensile Index - DRY - HS - N.m/g	94.64	115.88	122.03	135.34	142.89
TEA Index - DRY - HS - mJ/g	1,566.38	2,140.06	2,854.28	2,996.67	3,251.07
Elastic Modulus - DRY - HS - km	792	782	720	792	816
Z-Span B. length - DRY - HS - km	20.75	20.67	20.64	21.68	22.30
Gurley Air Res. - s/100 mL	5.2	16.6	12.9	36.8	144.9
Bright. - STD - %	29.48				
Bright. - TOP - %	27.86	25.14	23.96	22.58	21.67
Luminos. - TOP - %	39.39	36.82	35.88	34.28	33.02
Opacity (ISO) - TOP - %	97.28	95.07	94.23	91.95	90.50
Opacity (TAPPI) - TOP - %	92.48	86.33	83.99	78.02	74.23
L* - TOP	69.03	67.14	66.43	65.18	64.18
a* - TOP	4.84	5.53	5.74	6.08	6.24
b* - TOP	16.47	17.64	18.41	18.66	18.56
Lt. Scat. Coeff - TOP - m^2/kg	25.92	19.88	18.47	15.58	14.31
Lt. Abs. Coeff. - TOP - m^2/kg	12.09	10.78	10.58	9.82	9.72

Table II-25: Fibre and kraft pulp physical and optical properties of green-stage whole chips.

SAMPLE	7969-1	7969-2	7969-3	7969-4	7969-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF – mL	694	676	647	539	332
B-McNett R14 - %	76.1				
B-McNett 14/28 - %	11.5				
B-McNett 28/48 - %	8.6				
B-McNett 48/100 - %	2.4				
B-McNett 100/200 - %	0.8				
B-McNett P200 - %	0.6				
FQA Arith, mm	1.640				
FQA L. Wtd, mm	2.800				
FQA W. Wtd, mm	3.150				
FQA Coarseness, mg/m	0.127				
FQA P<0.2mm, %	28.225				
Grammage (O.D.) - g/m^2	61.7	60.7	60.1	60.6	58.6
Caliper - SS - um	117	105	99	95	90
Specific Volume - SS - cm^3/g	1.89	1.73	1.65	1.57	1.54
Apparent Density - SS - g/cm^3	0.53	0.58	0.61	0.64	0.65
Burst Index - kPm^2/g	5.71	7.50	9.16	9.68	10.92
Tear Index - 4PL - HS - mNm^2/g	21.18	17.88	16.28	13.91	12.84
Breaking Length - DRY - HS - km	8.16	10.74	11.91	12.49	13.54
Stretch - DRY - HS - %	2.07	3.03	3.32	3.77	3.87
Tensile Index - DRY - HS - N.m/g	80.00	105.36	116.85	122.51	132.75
TEA Index - DRY - HS - mJ/g	1,089.46	2,001.84	2,391.22	2,822.13	3,143.79
Elastic Modulus - DRY - HS - km	843	770	769	731	772
Z-Span B. length - DRY - HS - km	22.74	21.60	22.21	21.78	22.43
Gurley Air Res. - s/100 mL	5	5	5	9.6	123.6
Bright. – STD - %	31.32				
Bright. – TOP - %	29.90	27.01	25.55	23.84	24.13
Luminos. - TOP - %	42.76	40.05	38.48	36.67	36.69
Opacity (ISO) - TOP - %	96.28	93.74	92.66	89.93	89.48
Opacity (TAPPI) - TOP - %	90.54	84.09	81.22	74.74	73.84
L* - TOP	71.39	69.51	68.37	67.03	67.04
a* - TOP	4.50	5.04	5.32	5.65	5.54
b* - TOP	17.43	18.68	19.11	19.66	19.15
Lt. Scat. Coeff - TOP - m^2/kg	26.29	20.50	18.56	15.15	15.37
Lt. Abs. Coeff. - TOP - m^2/kg	10.07	9.20	9.13	8.28	8.40

Table II-26: Fibre and kraft pulp physical and optical properties of kiln-dried whole chips.

SAMPLE	7972-1	7972-2	7972-3	7972-4	7972-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	677	651	602	495	318
B-McNett R14 - %	62.8				
B-McNett 14/28 - %	17.7				
B-McNett 28/48 - %	13.1				
B-McNett 48/100 - %	4.2				
B-McNett 100/200 - %	1.4				
B-McNett P200 - %	0.7				
FQA Arith, mm	1.34				
FQA L. Wtd, mm	2.485				
FQA W. Wtd, mm	2.96				
FQA Coarseness, mg/m	0.1275				
FQA P<0.2mm, %	29.525				
Grammage (O.D.) - g/m^2	60.4	60.5	59.8	57.3	60.2
Caliper - SS - um	112	99	94	88	88
Specific Volume - SS - cm^3/g	1.86	1.64	1.56	1.53	1.46
Apparent Density - SS - g/cm^3	0.54	0.61	0.64	0.65	0.69
Burst Index - kPm^2/g	5.78	7.80	8.61	9.70	10.10
Tear Index - 4PL - HS - mNm^2/g	16.13	15.63	13.50	11.75	11.36
Breaking Length - DRY - HS - km	8.58	11.19	11.82	12.86	13.06
Stretch - DRY - HS - %	2.38	3.15	3.65	3.71	3.80
Tensile Index - DRY - HS - N.m/g	84.15	109.78	115.92	126.11	128.10
TEA Index - DRY - HS - mJ/g	1,299.30	2,162.12	2,625.96	2,897.36	3,012.71
Elastic Modulus - DRY - HS - km	814	757	715	750	761
Z-Span B. length - DRY - HS - km	20.70	21.14	19.43	20.27	20.65
Gurley Air Res. - s/100 mL	5	5.8	14.9	29.5	170.2
Bright. – STD - %	29.31				
Bright. – TOP - %	28.16	24.83	23.43	22.17	21.58
Luminos. - TOP - %	39.90	36.73	35.20	33.71	33.05
Opacity (ISO) - TOP - %	97.36	95.09	93.91	91.66	91.84
Opacity (TAPPI) - TOP - %	92.76	86.34	82.96	77.13	77.25
L* - TOP	69.40	67.08	65.91	64.73	64.21
a* - TOP	4.70	5.42	5.76	6.02	5.94
b* - TOP	16.60	17.98	18.43	18.63	18.73
Lt. Scat. Coeff - TOP - m^2/kg	27.24	20.21	17.98	15.76	14.81
Lt. Abs. Coeff. - TOP - m^2/kg	12.33	11.01	10.72	10.27	10.04

Table II-27: Fibre and kraft pulp physical and optical properties of grey-stage 2-8 mm thick chips.

SAMPLE	8000-1	8000-2	8000-3	8000-4	8000-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	673	644	602	507	294
B-McNett R14 - %	75.1				
B-McNett 14/28 - %	11.6				
B-McNett 28/48 - %	9.0				
B-McNett 48/100 - %	1.4				
B-McNett 100/200 - %	2.9				
B-McNett P200 - %	0.1				
FQA Arith. - mm	1.42				
FQA L. Wtd	2.89				
FQA W. Wtd - mm	3.35				
FQA Coarse. - mg/m	0.110				
FQA P<0.2mm - %	37.45				
Grammage (O.D.) - g/m^2	62.0	58.4	61.3	59.6	58.9
Caliper - SS - um	105	92	91	87	84
Specific Volume - SS - cm^3/g	1.70	1.58	1.49	1.46	1.42
Apparent Density - SS - g/cm^3	0.59	0.63	0.67	0.68	0.70
Burst Index - kPm^2/g	7.52	9.20	9.93	10.45	11.41
Tear Index - 4PL - HS - mNm^2/g	15.83	13.38	11.94	11.04	10.71
Breaking Length - DRY - HS - km	9.69	12.18	12.73	13.88	14.19
Stretch - DRY - HS - %	2.73	3.25	3.59	3.89	3.93
Tensile Index - DRY - HS - N.m/g	95.04	119.46	124.82	136.12	139.14
TEA Index - DRY - HS - mJ/g	1,653.47	2,437.91	2,776.45	3,247.90	3,351.95
Elastic Modulus - DRY - HS - km	801	861	820	839	849
Z-Span B. length - DRY - HS - km	19.42	18.93	19.32	19.50	18.82
Gurley Air Res. - s/100 mL	5.2	7.6	17.0	39.4	241.6
Bright. – STD - %	28.87				
Bright. – TOP - %	27.44	23.69	22.56	21.70	20.97
Luminos. - TOP - %	38.40	34.97	33.77	32.83	31.78
Opacity (ISO) - TOP - %	97.67	94.37	94.34	92.18	91.01
Opacity (TAPPI) - TOP - %	93.38	84.02	83.56	77.93	74.75
L* - TOP	68.32	65.73	64.78	64.02	63.16
a* - TOP	5.36	6.17	6.42	6.62	6.57
b* - TOP	15.90	17.63	18.02	18.28	18.15
Lt. Scat. Coeff - TOP - m^2/kg	26.32	18.80	17.15	15.10	13.90
Lt. Abs. Coeff. - TOP - m^2/kg	13.01	11.37	11.14	10.38	10.18

Table II-28: Fibre and kraft pulp physical and optical properties of green-stage 2-8 mm thick chips.

SAMPLE	8002-1	8002-2	8002-3	8002-4	8002-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	691	683	643	542	316
B-McNett R14 - %	72.0				
B-McNett 14/28 - %	13.2				
B-McNett 28/48 - %	9.6				
B-McNett 48/100 - %	2.3				
B-McNett 100/200 - %	1.0				
B-McNett P200 - %	2.0				
FQA Arith. - mm	1.62				
FQA L. Wtd	2.85				
FQA W. Wtd - mm	3.23				
FQA Coarse. - mg/m	0.124				
FQA P<0.2mm - %	29.73				
Grammage (O.D.) - g/m^2	61.5	59.5	61.6	58.5	60.6
Caliper - SS - um	118	100	97	91	90
Specific Volume - SS - cm^3/g	1.91	1.67	1.57	1.56	1.49
Apparent Density - SS - g/cm^3	0.52	0.60	0.64	0.64	0.67
Burst Index - kPm^2/g	5.54	7.20	8.65	9.44	10.31
Tear Index - 4PL - HS - mNm^2/g	21.84	17.98	15.71	14.76	14.31
Breaking Length - DRY - HS - km	8.38	10.43	11.75	13.12	13.70
Stretch - DRY - HS - %	1.96	2.92	3.55	3.61	3.88
Tensile Index - DRY - HS - N.m/g	82.22	102.29	115.25	128.69	134.40
TEA Index - DRY - HS - mJ/g	1,007.83	1,877.89	2,555.26	2,867.99	3,194.68
Elastic Modulus - DRY - HS - km	854	812	770	827	816
Z-Span B. length - DRY - HS - km	19.73	20.30	20.66	20.81	19.74
Gurley Air Res. - s/100 mL	2	2	2	8.8	86.5
Bright. – STD - %	30.99				
Bright. – TOP - %	29.31	25.71	23.91	23.18	22.51
Luminos. - TOP - %	41.18	37.79	35.77	34.99	34.09
Opacity (ISO) - TOP - %	96.28	93.39	92.42	90.29	90.11
Opacity (TAPPI) - TOP - %	90.25	82.61	79.68	74.71	73.92
L* - TOP	70.30	67.87	66.35	65.74	65.03
a* - TOP	5.37	5.94	6.46	6.54	6.50
b* - TOP	16.40	17.92	18.31	18.53	18.52
Lt. Scat. Coeff - TOP - m^2/kg	25.08	19.08	16.34	15.11	14.03
Lt. Abs. Coeff. - TOP - m^2/kg	10.54	9.77	9.42	9.12	8.94

Table II-29: Fibre and kraft pulp physical and optical properties of kiln-dried 2-8 mm thick chips.

SAMPLE	8001-1	8001-2	8001-3	8001-4	8001-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	680	650	606	492	294
B-McNett R14 - %	61.6				
B-McNett 14/28 - %	18.8				
B-McNett 28/48 - %	13.4				
B-McNett 48/100 - %	4.1				
B-McNett 100/200 - %	1.6				
B-McNett P200 - %	0.5				
FQA Arith. - mm	1.36				
FQA L. Wtd	2.51				
FQA W. Wtd - mm	3.00				
FQA Coarse. - mg/m	0.130				
FQA P<0.2mm - %	27.35				
Grammage (O.D.) - g/m^2	61.8	60.4	60.9	59.7	58.6
Caliper - SS - um	110	95	93	88	86
Specific Volume - SS - cm^3/g	1.79	1.57	1.52	1.48	1.47
Apparent Density - SS - g/cm^3	0.56	0.64	0.66	0.68	0.68
Burst Index - kPm^2/g	6.13	7.91	9.00	10.15	10.15
Tear Index - 4PL - HS - mNm^2/g	16.15	14.18	12.62	11.72	10.61
Breaking Length - DRY - HS - km	9.51	10.96	12.20	12.56	13.67
Stretch - DRY - HS - %	2.43	3.15	3.57	3.69	3.67
Tensile Index - DRY - HS - N.m/g	93.27	107.45	119.60	123.16	134.08
TEA Index - DRY - HS - mJ/g	1,439.52	2,122.37	2,652.74	2,807.28	3,035.29
Elastic Modulus - DRY - HS - km	845	823	811	818	880
Z-Span B. length - DRY - HS - km	19.04	18.40	18.18	17.83	17.65
Gurley Air Res. - s/100 mL	2	7.0	13.1	38.9	146.0
Bright. – STD - %	28.35				
Bright. – TOP - %	26.74	23.02	21.97	20.89	20.12
Luminos. - TOP - %	37.30	33.74	32.65	31.28	30.38
Opacity (ISO) - TOP - %	97.61	95.24	94.57	93.13	91.81
Opacity (TAPPI) - TOP - %	93.05	85.86	83.75	79.54	75.86
L* - TOP	67.50	64.75	63.87	62.75	61.98
a* - TOP	5.82	6.73	6.93	7.07	7.08
b* - TOP	15.51	17.03	17.53	17.54	17.68
Lt. Scat. Coeff - TOP - m^2/kg	25.21	18.46	16.87	15.02	13.80
Lt. Abs. Coeff. - TOP - m^2/kg	13.29	12.01	11.72	11.34	11.00

Table II-30: Fibre and kraft pulp physical and optical properties of 85/15 green/grey mixture chips.

SAMPLE	7975-1	7975-2	7975-3	7975-4	7975-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	694	667	639	517	298
B-McNett R14 - %	77.4				
B-McNett 14/28 - %	9.9				
B-McNett 28/48 - %	8.7				
B-McNett 48/100 - %	2.6				
B-McNett 100/200 - %	1.0				
B-McNett P200 - %	0.4				
FQA Arith. - mm	1.58				
FQA L. Wtd	2.83				
FQA W. Wtd - mm	3.24				
FQA Coarse. - mg/m	0.118				
FQA P<0.2mm - %	30.18				
Grammage (O.D.) - g/m^2	61.0	60.2	60.6	62.9	59.5
Moisture Content - %					
Caliper - SS - um	119	100	98	97	90
Specific Volume - SS - cm^3/g	1.95	1.66	1.61	1.54	1.52
Apparent Density - SS - g/cm^3	0.51	0.60	0.62	0.65	0.66
Burst Index - kPm2/g	5.64	8.23	8.78	9.73	10.76
Tear Index - 4PL - HS - mNm^2/g	21.16	16.13	15.00	13.47	13.74
Breaking Length - DRY - HS - km	8.73	10.93	12.06	13.07	13.37
Stretch - DRY - HS - %	2.07	3.09	3.32	3.58	3.58
Tensile Index - DRY - HS - N.m/g	85.57	107.14	118.30	128.21	131.09
TEA Index - DRY - HS - mJ/g	1,141.07	2,089.28	2,443.30	2,850.33	2,929.22
Elastic Modulus - DRY - HS - km	910	838	850	853	893
Z-Span B.length - DRY - HS - km	19.14	19.51	19.80	19.19	20.86
Gurley Air Res. - s/100 mL	2.1	4.0	6.0	15.8	119.9
Bright. - STD - %	29.98				
Bright. - TOP - %	29.47	25.55	24.54	23.22	22.57
Luminos. - TOP - %	42.19	38.34	37.31	35.62	34.81
Opacity (ISO) - TOP - %	96.84	93.25	92.41	91.97	89.36
Opacity (TAPPI) - TOP - %	91.81	82.48	80.26	78.62	72.72
L* - TOP	71.00	68.27	67.51	66.23	65.60
a* - TOP	4.83	5.72	5.79	6.16	6.18
b* - TOP	17.32	18.76	19.16	19.20	19.38
Lt. Scat. Coeff - TOP - m^2/kg	27.71	19.04	17.50	15.56	14.17
Lt. Abs. Coeff. - TOP - m^2/kg	10.98	9.44	9.21	9.05	8.65

Table II-31: Fibre and kraft pulp physical and optical properties of 75/25 green/grey mixture chips.

SAMPLE	7976-1	7976-2	7976-3	7976-4	7976-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	696	666	636	523	311
B-McNett R14 - %	76.4				
B-McNett 14/28 - %	9.5				
B-McNett 28/48 - %	8.6				
B-McNett 48/100 - %	2.5				
B-McNett 100/200 - %	1.0				
B-McNett P200 - %	2.1				
FQA Arith. - mm	1.59				
FQA L. Wtd	2.84				
FQA W. Wtd - mm	3.24				
FQA Coarse. - mg/m	0.122				
FQA P<0.2mm - %	29.83				
Grammage (O.D.) - g/m^2	60.4	61.2	62.2	60.5	59.4
Moisture Content - %					
Caliper - SS - um	114	101	101	93	89
Specific Volume - SS - cm^3/g	1.89	1.65	1.62	1.54	1.50
Apparent Density - SS - g/cm^3	0.53	0.60	0.62	0.65	0.67
Burst Index - kPm2/g	5.41	8.33	9.15	10.71	10.63
Tear Index - 4PL - HS - mNm^2/g	20.24	16.13	15.94	13.47	12.66
Breaking Length - DRY - HS - km	7.97	11.64	11.82	13.26	13.92
Stretch - DRY - HS - %	2.09	2.98	3.16	3.47	3.91
Tensile Index - DRY - HS - N.m/g	78.14	114.16	115.93	130.06	136.48
TEA Index - DRY - HS - mJ/g	1,055.46	2,154.30	2,302.43	2,777.17	3,277.55
Elastic Modulus - DRY - HS - km	834	887	854	858	849
Z-Span B. length - DRY - HS - km	18.37	18.84	19.12	18.77	18.27
Gurley Air Res. - s/100 mL	2	4.1	5.7	15.2	95.6
Bright. – STD - %	29.93				
Bright. – TOP - %	28.66	25.30	23.97	23.19	21.45
Luminos. - TOP - %	41.23	38.00	36.58	35.68	33.53
Opacity (ISO) - TOP - %	96.34	94.73	93.78	91.60	90.40
Opacity (TAPPI) - TOP - %	90.40	85.80	83.13	77.83	74.25
L* - TOP	70.34	68.02	66.96	66.27	64.59
a* - TOP	4.58	5.27	5.55	5.65	6.05
b* - TOP	17.42	18.85	19.29	19.44	19.68
Lt. Scat. Coeff - TOP - m^2/kg	25.78	20.29	17.97	15.93	14.23
Lt. Abs. Coeff. - TOP - m^2/kg	10.79	10.26	9.88	9.24	9.37

Table II-32: Fibre and kraft pulp physical and optical properties of 50/50 green/grey mixture chips.

SAMPLE	7978-1	7978-2	7978-3	7978-4	7978-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	688	660	637	523	321
B-McNett R14 - %	76.5				
B-McNett 14/28 - %	9.2				
B-McNett 28/48 - %	8.5				
B-McNett 48/100 - %	2.8				
B-McNett 100/200 - %	1.2				
B-McNett P200 - %	1.9				
FQA Arith. - mm	1.39				
FQA L. Wtd	2.79				
FQA W. Wtd - mm	3.26				
FQA Coarse. - mg/m	0.138				
FQA P<0.2mm - %	36.75				
Grammage (O.D.) - g/m^2	60.9	61.3	58.0	61.0	59.8
Moisture Content - %					
Caliper - SS - um	117	100	92	92	89
Specific Volume - SS - cm^3/g	1.92	1.63	1.59	1.51	1.49
Apparent Density - SS - g/cm^3	0.52	0.61	0.63	0.66	0.67
Burst Index - kPm2/g	5.58	8.31	8.97	10.37	10.90
Tear Index - 4PL - HS - mNm^2/g	19.87	15.69	14.65	12.66	11.70
Breaking Length - DRY - HS - km	8.64	11.50	11.61	13.04	13.66
Stretch - DRY - HS - %	2.11	3.27	3.35	3.83	3.81
Tensile Index - DRY - HS - N.m/g	84.78	112.74	113.88	127.86	133.91
TEA Index - DRY - HS - mJ/g	1,126.48	2,344.05	2,395.20	3,036.49	3,146.03
Elastic Modulus - DRY - HS - km	863	831	826	813	858
Z-Span B. length - DRY - HS - km	18.77	18.63	19.51	19.33	20.93
Gurley Air Res. - s/100 mL	<2	5.2	4.9	19.8	168.3
Bright. – STD - %	29.78				
Bright. – TOP - %	28.86	24.85	23.33	22.19	21.87
Luminos. - TOP - %	41.17	37.25	35.75	34.36	33.81
Opacity (ISO) - TOP - %	97.14	95.29	92.05	92.27	90.44
Opacity (TAPPI) - TOP - %	92.38	86.99	78.85	78.78	74.51
L* - TOP	70.29	67.46	66.33	65.24	64.81
a* - TOP	4.34	5.14	5.34	5.74	5.76
b* - TOP	17.10	18.60	19.29	19.47	19.32
Lt. Scat. Coeff - TOP - m^2/kg	27.53	20.60	17.02	15.64	14.31
Lt. Abs. Coeff. - TOP - m^2/kg	11.57	10.89	9.83	9.81	9.28

Table II-33: Fibre and kraft pulp physical and optical properties of 85/15 green/kiln-dried mixture chips.

SAMPLE	7979-1	7979-2	7979-3	7979-4	7979-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	702	672	630	519	317
B-McNett R14 - %	73.8				
B-McNett 14/28 - %	10.0				
B-McNett 28/48 - %	9.3				
B-McNett 48/100 - %	2.6				
B-McNett 100/200 - %	1.0				
B-McNett P200 - %	3.2				
FQA Arith. - mm	1.58				
FQA L. Wtd	2.76				
FQA W. Wtd - mm	3.16				
FQA Coarse. - mg/m	0.116				
FQA P<0.2mm - %	28.38				
Grammage (O.D.) - g/m^2	58.5	59.8	61.7	58.9	59.4
Caliper - SS - um	115	100	99	91	90
Specific Volume - SS - cm^3/g	1.97	1.67	1.60	1.55	1.51
Apparent Density - SS - g/cm^3	0.51	0.60	0.63	0.65	0.66
Burst Index - kPm^2/g	5.64	7.65	9.26	10.54	10.76
Tear Index - 4PL - HS - mNm^2/g	20.86	17.48	14.52	13.67	12.82
Breaking Length - DRY - HS - km	8.74	10.81	12.23	12.72	13.32
Stretch - DRY - HS - %	2.21	3.15	3.60	3.63	3.68
Tensile Index - DRY - HS - N.m/g	85.74	105.98	119.92	124.75	130.59
TEA Index - DRY - HS - mJ/g	1,222.59	2,109.92	2,681.67	2,804.19	2,964.81
Elastic Modulus - DRY - HS - km	870	815	802	821	862
Z-Span B. length - DRY - HS - km	19.79	18.98	19.89	19.28	19.60
Gurley Air Res. - s/100 mL	<2s	3.4	6.5	18.4	115.8
Bright. – STD - %	30.81				
Bright. – TOP - %	29.65	26.60	24.87	23.84	22.82
Luminos. - TOP - %	42.29	39.42	37.75	36.57	35.28
Opacity (ISO) - TOP - %	95.94	93.45	92.47	90.61	89.32
Opacity (TAPPI) - TOP - %	89.66	83.25	80.52	76.09	72.86
L* - TOP	71.07	69.05	67.83	66.95	65.97
a* - TOP	4.54	5.19	5.47	5.62	5.86
b* - TOP	17.22	18.46	19.21	19.49	19.60
Lt. Scat. Coeff - TOP - m^2/kg	26.62	20.05	17.44	16.05	14.38
Lt. Abs. Coeff. - TOP - m^2/kg	10.48	9.34	8.96	8.83	8.53

Table II-34: Fibre and kraft pulp physical and optical properties of 75/25 green/kiln-dried mixture chips.

SAMPLE	7980-1	7980-2	7980-3	7980-4	7980-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	689	671	627	516	296
B-McNett R14 - %	72.1				
B-McNett 14/28 - %	10.9				
B-McNett 28/48 - %	9.5				
B-McNett 48/100 - %	2.8				
B-McNett 100/200 - %	1.0				
B-McNett P200 - %	3.7				
FQA Arith. - mm	1.56				
FQA L. Wtd	2.74				
FQA W. Wtd - mm	3.14				
FQA Coarse. - mg/m	0.119				
FQA P<0.2mm - %	28.07				
Grammage (O.D.) - g/m^2	60.2	60.5	59.7	56.9	59.1
Caliper - SS - um	116	102	95	89	90
Specific Volume - SS - cm^3/g	1.93	1.69	1.60	1.57	1.53
Apparent Density - SS - g/cm^3	0.52	0.59	0.63	0.64	0.66
Burst Index - kPm^2/g	5.33	7.87	8.71	10.08	10.78
Tear Index - 4PL - HS - mNm^2/g	20.43	17.69	14.57	13.75	13.23
Breaking Length - DRY - HS - km	8.41	10.85	11.50	13.18	12.89
Stretch - DRY - HS - %	1.95	3.14	3.14	3.69	3.65
Tensile Index - DRY - HS - N.m/g	82.46	106.36	112.79	129.23	126.42
TEA Index - DRY - HS - mJ/g	1,017.26	2,119.77	2,218.72	2,927.95	2,882.18
Elastic Modulus - DRY - HS - km	848	820	846	825	847
Z-Span B. length - DRY - HS - km	19.66	19.01	18.86	18.62	19.08
Gurley Air Res. - s/100 mL	<2s	4.1	4.4	13.2	93.1
Bright. – STD - %	30.99				
Bright. – TOP - %	30.06	26.12	24.85	23.40	22.57
Luminos. - TOP - %	42.73	39.07	37.79	36.20	34.96
Opacity (ISO) - TOP - %	96.08	94.68	91.94	90.07	89.22
Opacity (TAPPI) - TOP - %	90.07	85.98	79.39	74.83	72.50
L* - TOP	71.37	68.80	67.86	66.67	65.72
a* - TOP	4.56	5.39	5.63	6.00	6.05
b* - TOP	17.12	18.82	19.28	19.75	19.62
Lt. Scat. Coeff - TOP - m^2/kg	26.47	21.22	17.57	16.02	14.24
Lt. Abs. Coeff. - TOP - m^2/kg	10.16	10.08	9.00	9.01	8.61

Table II-35: Fibre and kraft pulp physical and optical properties of 50/50 green/kiln-dried mixture chips.

SAMPLE	7982-1	7982-2	7982-3	7982-4	7982-5
PFI Revs.	0	1,500	3,000	6,000	12,000
CSF - mL	681	661	616	501	287
B-McNett R14 - %	72.6				
B-McNett 14/28 - %	10.7				
B-McNett 28/48 - %	10.5				
B-McNett 48/100 - %	3.4				
B-McNett 100/200 - %	1.3				
B-McNett P200 - %	1.6				
FQA Arith. - mm	1.48				
FQA L. Wtd	2.65				
FQA W. Wtd - mm	3.10				
FQA Coarse. - mg/m	0.122				
FQA P<0.2mm - %	27.20				
Grammage (O.D.) - g/m^2	60.5	63.0	59.1	57.4	60.5
Caliper - SS - um	112	103	91	89	87
Specific Volume - SS - cm^3/g	1.86	1.63	1.54	1.55	1.43
Apparent Density - SS - g/cm^3	0.54	0.61	0.65	0.65	0.70
Burst Index - kPm^2/g	5.54	7.69	8.61	9.93	9.86
Tear Index - 4PL - HS - mNm^2/g	19.41	17.02	14.05	12.70	11.79
Breaking Length - DRY - HS - km	8.28	10.10	11.92	12.85	13.44
Stretch - DRY - HS - %	2.06	3.05	3.41	3.71	3.53
Tensile Index - DRY - HS - N.m/g	81.18	99.02	116.93	126.00	131.79
TEA Index - DRY - HS - mJ/g	1,063.89	1,906.60	2,488.62	2,901.39	2,886.68
Elastic Modulus - DRY - HS - km	849	804	807	818	895
Z-Span B.length - DRY - HS - km	18.19	17.05	18.76	18.22	18.85
Gurley Air Res. - s/100 mL	<2s	6.0	6.8	19.8	139.7
Bright. - STD - %	29.18				
Bright. - TOP - %	28.09	24.65	23.30	22.25	21.01
Luminos. - TOP - %	40.39	36.99	35.66	34.37	32.86
Opacity (ISO) - TOP - %	96.13	95.14	92.74	91.25	91.41
Opacity (TAPPI) - TOP - %	89.75	86.56	80.39	76.53	76.15
L* - TOP	69.74	67.27	66.26	65.25	64.04
a* - TOP	5.17	5.71	6.16	6.30	6.38
b* - TOP	17.30	18.62	19.16	19.38	19.53
Lt. Scat. Coeff - TOP - m^2/kg	24.65	19.71	17.29	15.79	14.32
Lt. Abs. Coeff. - TOP - m^2/kg	10.85	10.57	10.03	9.90	9.83