LOW CONSISTENCY REFINING OF MECHANICAL PULPS

by

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ABSTRACT

Mechanical pulping produces a much higher yield than its chemical counterpart. It has lower water and atmospheric effluent loads but requires a high level of energy input. There is a drive towards reducing energy use and costs through modifications to mechanical pulping equipment. The vast majority of research in the field of mechanical pulping focuses on the energy split between the first and second refiners in the production stages of pulping. This thesis examines an alternate process, low consistency refining, to see if there is a potential to improve mechanical pulp properties with this technique.

The experimental work included production and examination through fibre and paper test of several groups of mechanical pulps. The results indicate that low consistency refining of mechanical pulp can produce paper quality similar to that of high consistency refining at reduced energy input levels. However, the conditions for low consistency refining, namely number and intensity of refining impacts, must be chosen carefully as too high an impact intensity can damage fibres and reduce paper quality. Individual fibres show similar development for high consistency and low-intensity low consistency refining. Most notably, average fibre length and the number of long fibres are kept at high levels to maintain the network strength of paper.

Low consistency refining of latent thermomechanical (TMP) and chemi-thermomechanical (CTMP) pulps straightens fibres. If fibre curl is taken as a measure of latency removal, low consistency refining can achieve a delatent pulp without the separate step of latency removal. However, latent pulp may be more brittle resulting in lower paper strength. Low consistency refining of latent pulp may offer a usable alternative where a mill is limited by either space or latency removal equipment and lower paper strength is acceptable.

With regards to flexibility testing, LC-refined TMP and CMP show changes in flexibility distribution when compared to base pulps. The coarser summerwood fibres seemed to be more affected by refining as measured by changes in flexibility.

Much work was done to complete a fracture toughness analysis. The results proved to be strongly correlated to the tensile strength test results. Therefore this test may not offer new information regarding paper runnability and strength.

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"Two roads diverged in a wood, and I --
I took the one less traveled by,
And that has made all the difference."

Robert Frost: 'The Road Not Taken' 1916

For Beth
and Shelley

CHAPTER 1
INTRODUCTION

With the increasing cost of raw wood and the drive towards lower environmental impact associated with processing wood into pulp, there is a shift away from chemical pulp to mechanically produced pulp. Although mechanical pulp has replaced some of the chemical pulp needed in certain grades of paper, the potential exists for specifically engineered mechanical pulps to meet a higher quality standard and therefore find broader use. This could result in lower raw materials usage, lower environmental contaminants and lower cost pulp [Höglund et al. 1997, Sabourin et al. 1997].

This thesis explores two areas of mechanical pulp production, the first being to create a higher quality mechanical pulp through further mechanical processing. Specifically the process of low consistency secondary refining, a common operation for chemical pulp, is studied with regard to the possibility of raising the quality of mechanical pulp. Two groups of mechanical pulp from a single chip source, chemithermomechanical pulp, CTMP, and thermomechanical pulp, TMP, are studied for potential improvement with low consistency refining. The second part of the research builds on the first by determining if low consistency secondary refining of mechanical pulps can result in less total energy input and hence lower production costs. This research was started in 1992. During the course of this work several papers were published on the possibility of improving mechanical pulp quality through low consistency refining, none studying the procedure to the extent of this project. Engstrand and coworkers patented the low consistency refining of mechanical pulps without supplying any information regarding their research [Engstrand et al. 1993]. Sabourin et al. mention low consistency refining as an option in their pilot plant study of high-speed first stage refining [Sabourin et al. 1994]. Berger studies the idea in his lab scale work [Berger 1995]. Recent work by Hammer et al. [1997] studied low consistency refining following first stage high consistency refining of commercial TMP. Their pilot-plant scale work showed possible energy savings through the use of this refining configuration. Their work had similar objectives to this thesis but was narrower in scope both in the types of pulp tested and analysis of the changes. Lumiainen and

Partanen [1998] discuss low consistency refining of mechanical pulp to improve runnability.

An important distinction in this work is that between the two modes of secondary refining, namely high consistency (HC) secondary refining and low consistency (LC) secondary refining. The latter is also known as post-refining. In the case of HC secondary refining, pulp comes directly from the first stage refiners where the wood chips have been broken down into mechanical pulp. Normally the second stage refiner operates at approximately 20% consistency and uses an energy input of approximately 500 to 1000 kWh/t. In contrast, low consistency refiners operate at 3 to 5% consistency and a net energy input of 100 to 200 kWh/t. The refining machines themselves vary considerably between the two modes of secondary refining to process the differing pulp consistencies.

This thesis analyzes and quantifies the refining action and its impact on mechanical pulps, with a view to maximizing the potential of these pulps. As refining occurs on a microscale in a fraction of a second, the action of refining must be implied from the resultant fibre and paper properties. Thus, rather than studying the machinery itself, this research analyzes and then explains changes to the processed pulp. In pulp and paper manufacturing, the product must meet target values for tensile strength, tear index and bulk. These criteria will be used to evaluate the experimental results.

This research was carried out to study the following hypotheses:

1) Mathematical reconciliation of differing refining theories used for low consistency and high consistency refining can be achieved by examining the assumptions underlying each theory.

2) Similar paper properties can sometimes be achieved with mechanical pulp when secondary refining takes place with either low consistency or high consistency secondary refining.

3) Low consistency secondary refining of mechanical pulp can achieve desired paper properties at a lower energy input than high consistency secondary refining if the correct refining conditions are used.

CHAPTER 2
LITERATURE REVIEW

The first section of this chapter explains the terminology of wood. This is followed by a discussion of the refining process and a review of work to date in the field of refining.

2.1 FIBRE MORPHOLOGY

To minimize naturally caused variations in the pulps studied, only one wood sample of a single species, white spruce or *picea glauca*, was used for all experimental work. White spruce was chosen as it is a common pulp wood in Western Canada. It has an average fibre length of 3.5 mm, a wall thickness of 2.4 μm, and 25-30 μm fibre diameter. Its average chemical composition is 44% cellulose, 29% hemicellulose and 27% lignin [Saka 1984, Rydholm 1985]. A single sample was used since growing conditions such as soil, climate and age of the tree cause fibre variability (e.g. in terms of the amount of heartwood, juvenile wood and compression wood). Figure 2.1 shows representative elements of spruce wood. The terms *fibre* and *tracheid* are used interchangeably in this thesis.

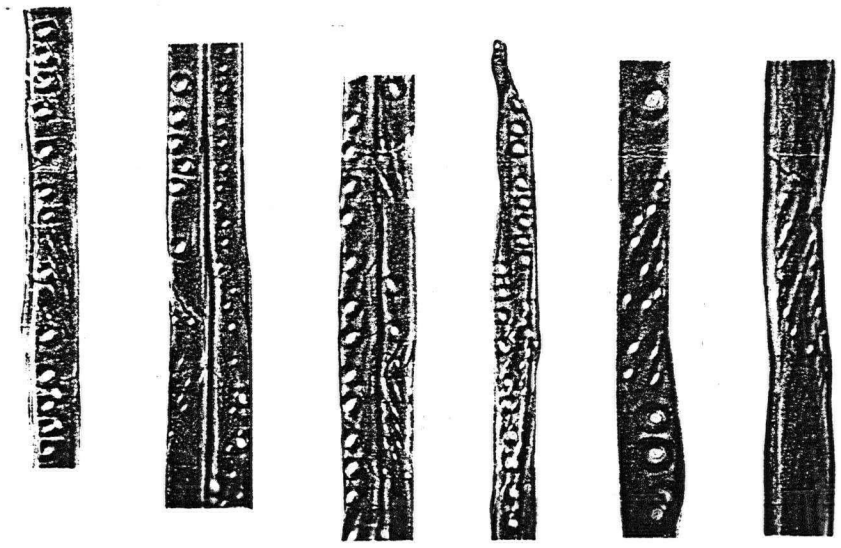
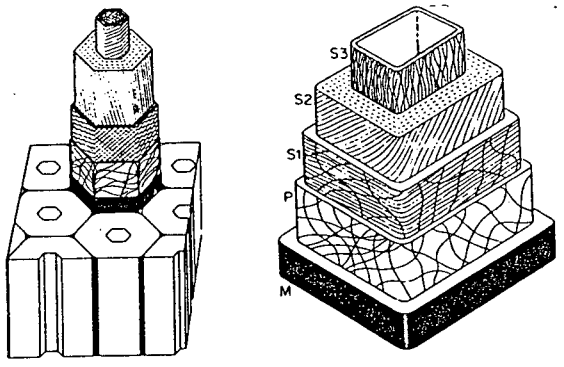


Figure 2.1: Spruce tracheid and other wood elements [Parham and Gray 1982]

Figure 2.2 shows an expanded view of one fibre resident in the cell wall. Lignin, a glue-like derivative of the benzene nucleus, is found throughout the tracheids reaching its highest concentration between fibres in the inter-fibre area known as the middle lamella (ML) [Emerton 1957]. Tracheids are slender tube-like structural elements composed of concentric layers. Each layer or lamellae consists of finer structural elements, fibrils, which are helically-wound bundles of cellulose. Primary and secondary layers of the cell wall are displayed on the right hand side of Figure 2.2. The central wall layer, S2, is the thickest cell wall layer with a fibril angle close to vertical. It is therefore responsible for most of the fibre strength [Page et al. 1971]. During processing the fibre structure may be damaged and individual fibril bundles pulled from the parent structure.



Cell-wall architecture, schematically. M middle lamella, P primary wall, S1 transition lamella, S2 main layer of secondary wall, S3 tertiary wall, or tertiary lamella of secondary wall (Wardrop (a), Meier (b))

Figure 2.2: Cell wall structure [Rydholm 1985]

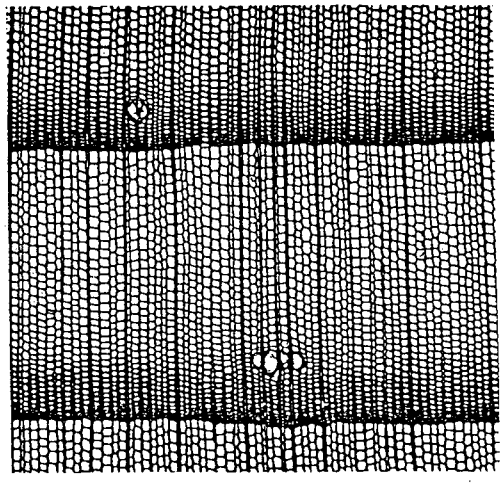


Figure 2.3: Softwood structure [Browning 1975]

In Figure 2.3 thin-walled springwood (earlywood or EW) tracheids and thick walled summerwood (latewood or LW) tracheids are visible in each annual growth ring. Due to their varying cell wall thicknesses, these two types of fibres behave differently in the paper sheet. This is a point of discussion in the analysis of the experimental results below. In white spruce there is a gradual transition from EW to LW and thus a portion of the fibres have properties between these two distinct groups. Definitions for all abbreviations and a glossary of variables are included in the Nomenclature.

In chemical pulping lignin is removed through the cooking and processing stages leaving the cellulose component largely intact. This process results in a loss of approximately 50 percent of the wood. In contrast, mechanical pulping of wood results in a much higher yield but more diverse pulp when viewed on a microscopic level. Bits of middle lamella and other small parts of the wood (e.g. pits, torn pieces of outer fibre layers, parenchyma, ray cells, resin duct particles) remain in the pulp. Mechanical pulps, especially those of high yield, are characterized by a broad range of particle sizes and high lignin content. Pulp yield values are shown in Table 2.1.

Table 2.1: Typical pulp yields [Seth 1991][1]

Classification	Process	Yield (%)
Mechanical	SGW	95+
	RMP	90+
	TMP	90-95
	CTMP	80-90
Chemimechanical	HYS	65-80
	NSSC	65-80
	CMP	70-80
Chemical	Kraft	40-50+
	Sulphite	45-55+

For many decades it has been realized that the actions and effects of refining are multifarious. During a fibre's path through the refiner it may be struck, bent and rubbed many times as it moves through the vortex action created by rapidly moving refiner plates [Cosler 1939]. Giertz postulated that in addition to the action of refiner

[1] For pulp type definitions, see Nomenclature: CMP has been added to the original table.

bars, the acceleration and deceleration of the water-fibre mass into and out of a refiner affects the pulp [Giertz 1958]. He further reasoned that as fibres pass over refiner bars, changes in water pressure act on the fibres. In support of internal changes in water pressure, Goncharov showed that pressure at the leading edge of refiner bars is thirteen times greater than the overall pressure in the refiner [Goncharov 1971]. The importance of refiner bar edge crossings and the resulting pressure increase have been seen as key components in refining [Atack et al. 1984, 1989].

Mechanical pulp fibres differ significantly from their chemical pulp counter-parts. Firstly, the fibres are stiff [Galley 1950, Jayme 1958, Forgacs 1963, Levlin 1980, Tam Doo and Kerekes 1982, Jauhari 1968]. Secondly, surface bonding activity is decreased due to the presence of hydrophobic lignin which interferes with cellulose bonding [Jayme 1958, Giertz 1962]. Thirdly, fibre swelling is inhibited [Giertz 1962, 1964]. Lastly, high yield pulp has a greater mass per fibre and hence a lower number of fibres per given weight. These factors explain the lower strength properties of high yield pulp. Although the fourth factor cannot be changed, the first three can be modified by refining [Giertz 1964] as discussed in the following paragraphs.

As a fibre is repeatedly bent and rubbed, its stiff outer layers are torn and the fiber swells. This permits intra-fibre bonds between fibrils to break resulting in a frayed or fibrillated surface [Campbell and Pidgeon 1930, Campbell 1932, Clark 1957, Van den Akker 1958, Asunmaa and Steenberg 1958, Giertz 1958 and 1964, Higgins and De Yong 1962, Jayme and Hunger 1962, Nordman 1968, Kibblewhite 1972, Atack 1978, Page 1989, Hietanen and Ebeling 1990]. This increase in fibre external surface area, known as external fibrillation, increases interfibre bonding [Levlin and Jousimaa 1988, Page 1989].

Adding to this idea of moving water affecting pulp fibres, Campbell [1932] realized that there was intimate contact between cellulose and water inside each fibre and that the internal loosening of lamellae and subsequent development of internal surface within the fibre would increase its volume. Galley [1949] postulated that repeated mechanical cycles of refining disrupt the crystalline fibre layer, thereby permitting the ingress of water. This internal disruption, or internal fibrillation, could improve both fibre flexibility and paper quality. This idea is supported by many others [e.g. Emerton 1957, Van den Akker 1958, Page and DeGrâce 1967, Atack 1978, Giertz

1980, Wahren 1980, Hartman and Higgins 1983]. In addition to delamination of the fibre core, outer fibre layers may separate or be removed with refining [Alexander et al. 1968, Kibblewhite 1972, Wardrop 1969, Nanko and Ohsawa 1989]. Examples of internal and external fibrillation are shown in Figures 2.4 and 2.5 below.

Figure 2.4: Internal fibrillation [Polan 1993]
top - Unrefined chemical pulp[1] bottom - Chemical pulp after LC refining

[1] Chemical pulp is used to illustrate external and internal fibrillation as the changes are more clearly shown in this type of pulp.

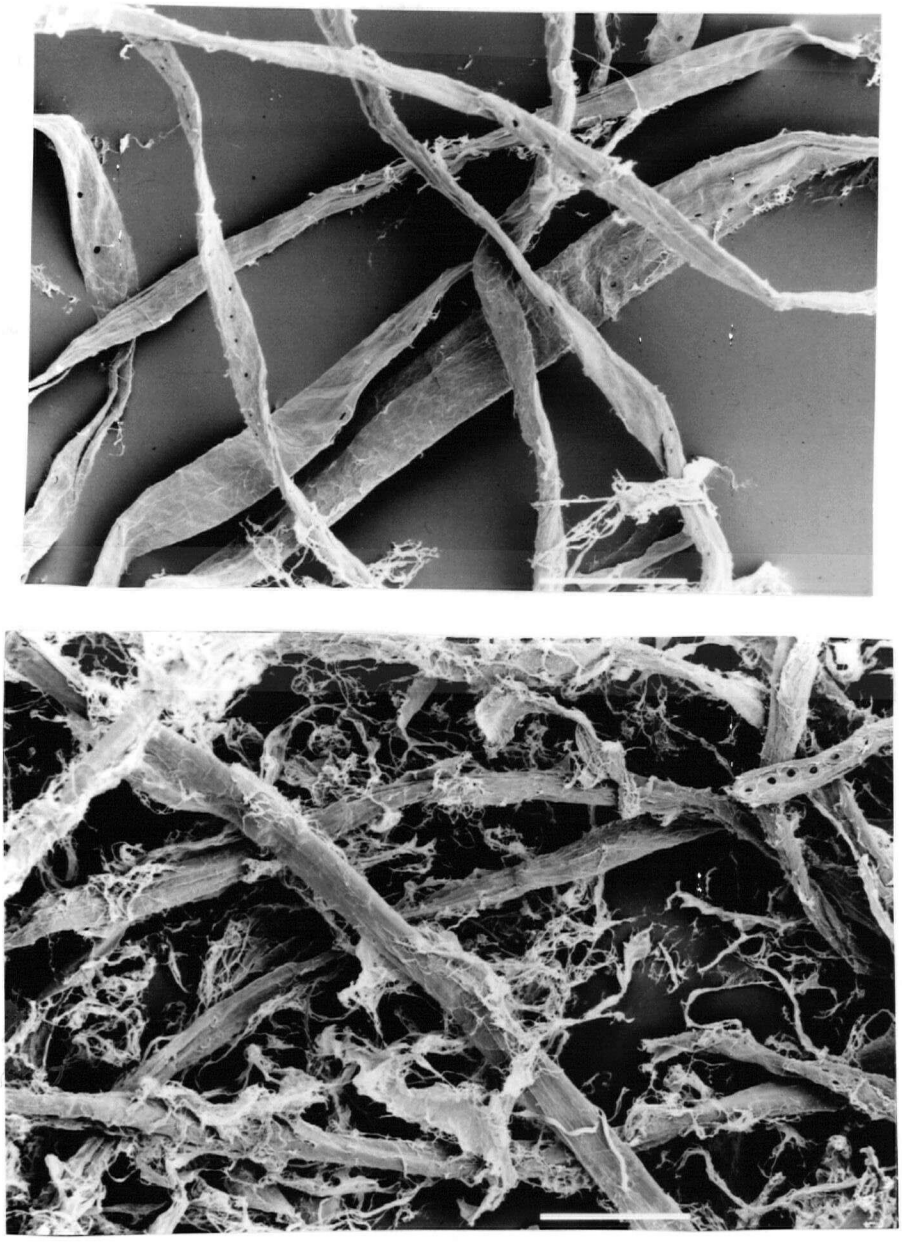


Figure 2.5: External fibrillation [Polan 1993]
top - Unrefined chemical pulp bottom - chemical pulp after LC refining

Part of the contribution of this thesis is to examine different low consistency refining conditions on mechanical pulp to elucidate the benefits, if any, of this method of processing high yield pulps. The thesis compares low consistency refining with the more commonly practiced high consistency secondary refining of mechanical pulp. This latter process is explained in section 2.2. To date the vast majority of low consistency refining research has used chemical pulps [Campbell 1932, Peckham and

May 1959, Halme 1962, Brecht and Siewert 1966, Stone et al. 1968, Fahey 1970, Leider 1977, Leider and Nissan 1977, Fox et al. 1979 and 1982, Lidbrandt and Mohlin 1980, Levlin 1981, Field 1986, Schmok 1987, Goyal 1989, Page 1989, Hietanen 1990 and 1991]. Comparatively little research has been performed on the refining of high yield pulps [Kurdin, 1974, Giertz 1977, Levlin 1980, Robinson et al. 1985, Engstrand et al. 1993, Sabourin et al. 1994, Berger 1995, Hammer et al. 1997, Lumiainen and Partanen 1998]. There are even those who say it cannot be done [Kurdin 1977].

2.2 REFINING

An important distinction in this work is that between high consistency (HC) refining and low consistency (LC) refining, also known as post-refining. In the case of HC refining, the pulp usually comes directly from the first stage refiners where the wood chips have just been broken down into mechanical pulp. Second stage HC refiners operate at approximately 20% consistency and an energy input of 500 to 1000 kWh/t. In contrast, LC refiners operate at 3 to 5% consistency and a net energy input of 100 to 200 kWh/t. The refining machines themselves vary considerably between the two modes of secondary refining.

2.2.1 High Consistency Refining

In the first refining stage of the mechanical pulping process, pretreated wood chips and water are sent through high speed rotating discs with a gap of less than one mm between disc plates. This produces a coarse mechanical pulp with many fibres still attached to one another. High consistency secondary refining usually takes place directly after first stage refining, reducing most of the remaining fibre bundles to separate fibres and modifying individual fibres.

2.2.1.1 High Consistency Refining Equipment

HC refiners are generally between 1.5 to 2 m in diameter. The plates are vertical and parallel with a gap of approximately 0.7 mm. Wood chips can be pretreated with steam and/or chemicals. The interior of a high consistency refiner is shown in Figure 2.6.

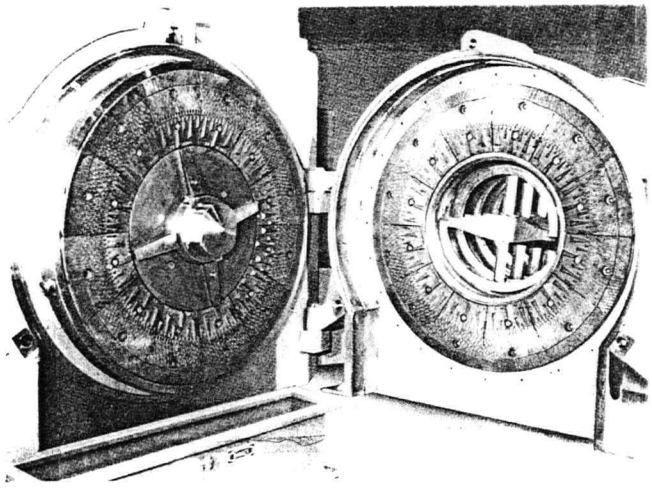


Figure 2.6: High consistency refiner [Biermann 1996]

2.2.1.2 High Consistency Refining Theory

Working with high-speed photographic equipment, Miles and May showed that wood chips entering the refiner are broken down almost completely while still in the feed hole and first section of the refiner, the breaker bar zone. Thus only pulp and fibre bundles enter the refining zone where they undergo additional mechanical work between the opposing bar patterns of the refiner plates [Miles and May 1990]. Using the forces acting on a point inside the refiner, Miles and May estimate the radial velocity of the pulp, the number of impacts experienced by a unit mass of pulp, and refining intensity [Miles 1990, 1991, Miles et al. 1991, Miles and May 1993].

Miles and May show that as inlet consistency is increased, the net accelerating force becomes weaker and residence time increases. The total number of bar impacts on the pulp increases so that for a given amount of specific energy, the energy per impact decreases [Miles and May 1990]. They show that the refining intensity can be changed by changing pulp consistency, rotational speed, steam pressure drop across the refining zone and density of refining bars [Miles et al. 1991, Miles and Karnis 1991]. With greater specific energy the residence time and number of impacts increases, but the specific energy per impact can remain unchanged.

Recently Ouellet et al. [1995] have compared residence times estimated by Miles and May's theory to measured residence times within a laboratory refiner. They found

that measured values were ten to fifteen times smaller than those predicted by theory. These differences may be due to the use of a smaller refiner by Ouellet et al. and the starting material being pulp, not chips, as in Miles and May's original work. Senger et al. [1998] have also estimated the ratio of friction coefficients in Miles and May's theory.

2.2.2 Low Consistency Refining

Low consistency refining normally takes place after the pulp is screened and cleaned and is on route to the machine chest of a paper machine. At this point pulp stock is dilute enough to act as a liquid and the movement of a pump carries it through the refiner. During LC refining, cyclic deformations are imposed on the pulp fibres as they pass through the refiner gap and encounter the bar and groove pattern of the rotating plates as seen in Figure 2.7. Even in low consistency pulp, fibres do not travel individually but aggregate into groups of fibres called *flocs*. As pulp moves through the refiner, there are many opportunities for fibre-fibre interactions as flocs are pulled apart and reformed [Page et al. 1962, Arjas 1980, Ebeling 1980, Hietanen and Ebeling 1983, Page 1989, Demler 1994].

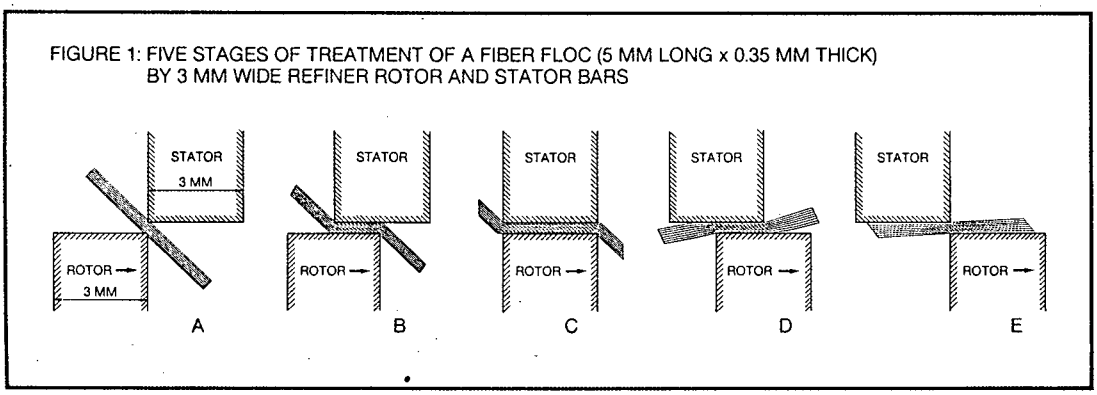


Figure 2.7: Action of LC refiner bars [Lumiainen 1990]

Espenmiller [1969] estimates that 90 percent of effective refining power is consumed at the leading bar edges. Thus most of the action on fibres occurs where fibre flocs are pressed between passing edges of rotor and stator bars. Most researchers agree with this position. Lumaianen [1995] also considers the energy expended as the bars pass one another. In analyzing refining action Giertz proposes that fibres are exposed to a range of forces as they pass through the refining zone

[Giertz 1964]. His summary is shown in Table 2.2. The intensity of the refining force increases, i.e. the impacts are more severe, as one progresses down the table.

Table 2.2: Effects of increasing refining force [Giertz 1964]

Treatment	Effect on fiber
internal friction in water causing elastic straining of the fiber	none
bond breaking in molecular structure of hemicellulose internal fibrillation	swelling fibre becomes flexible
fibre wall partly demolished	primary wall removed external fibrillation internal surfaces exposed
fiber demolished	cutting, crushing

2.2.2.1 Low Consistency Refining Equipment

Until the 1950s, large batch-type beaters were used to mechanically work pulp stock. The first continuous feed refiner introduced was the Jordan low-angle conical refiner. The 1970s saw a major move away from Jordans to disc refiners due to their wide range of applications and ease of maintenance. In a disc refiner two parallel plates rotate counter to one another as pulp stock moves from the central inlet to the outer area.[1] A simplified disc pattern is shown in Figure 2.8. The plate sections can be changed to effect different paper properties. When comparing the results from conical and disc refiners, Kerekes and coworkers found that a pulp refined at both an equal number of impacts and an equal intensity of refining, regardless of the type of refiner used, produced equal paper properties [Kerekes et al. 1993].

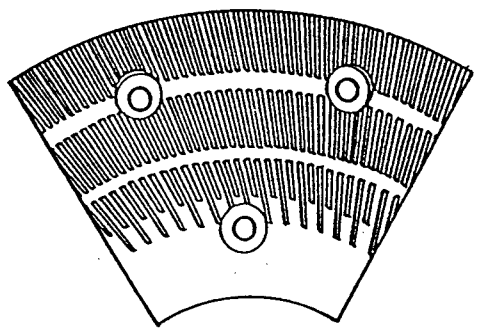


Figure 2.8: LC refiner plate

[11] One disc can be stationary and the other rotate. There can also be two outer stationary discs and a central, double-sided rotating centre disc.

2.2.2.2 Low Consistency Refining Theory

Table 2.3 shows the major contributions to low consistency refining theory.

Table 2.3: Chronological developments in the study of low consistency refining

Date - Name	Research Results
1922 Smith	Summarized the results of refining as cutting, splitting, external fibrillation and hydration
1932 Campbell	Postulated that increased flexibility of refined fibres was primarily due to internal fibrillation
1958 Van den Akker	Theorized that only 0.1% of refining energy is used to break fibre bonds
1957 Giertz	Used scanning electron microscope to show removal of primary cell wall layer during beating
1962 Halme	High speed film research: showed backflow in conical refiner
1966 Stone and Scallan	First micrographs showing internal delamination of fibre wall
1978 Atack	Postulated that fibres must first be constrained to be impacted, and discussed peristaltic action within fibres during refining
1979 Steenberg	Oozing and consolidation theory used to show that fibre concentration increases as load is applied
1979 Fox et al.	High speed photography in disc refiner showed flocs on leading edges of bars, secondary and tertiary flows
1990 Hietanen	Developed refiner to impact individual fibres operating at a very low SEL

Disc refiners can be used over a wide range of operating parameters. The rotor speed, throughput, plate configuration (e.g. plate diameter, bar arrangement and size, presence of dams, direction of rotation, plate age and surface material) can be changed to alter pulp quality. Control variables such as flow rate, pulp consistency and motor load also influence the final result. The large number of variables makes it difficult to fully understand how specific changes affect the system. Recently the C-factor was developed by Kerekes [1990] encompassing fibre, process and equipment variables in a comprehensive manner. Experience based equations are becoming more complex with the addition of new variables [Meltzer 1996]. A chronological summary of low consistency refining theory is shown in Table 2.4.

Table 2.4: Chronological development of quantitative theories of refining

Date - Name	Research Results
1922 - Smith	Fibrage theory - fibres cling to a rod moved through pulp
1958 - Wultsch and Flucher	First quantitative look at refining action
1966 - Brecht and Siewert	Amalgamated previous work into Specific Edge Load theory to define the intensity of refining energy transfer
1967 - Banks	The power loss of rotation is proportional to rpm^3, power loss of pumping proportional to rpm^2, horse power of work to rpm.
1969 - Espenmiller	Estimates 90% of effective refining power is consumed as the edges of the rotor and stator bars approach each other and hit compressed pulp between them with great force.
1969 - Danforth	Severity and number of impacts defined in two empirical parameters
1971 - Tappi Stock Prep. Committee	Intensity and amount of refining need to be defined to quantify refining action
1975 - Levlin	Combined SEL with specific energy to define refining action
1977 - Leider and Nissan	Examined number and energy of impacts on an individual fibre basis
1978 - Kline	Defines two empirical factors; amount and intensity of refining
1981 - Stevens	Inch cuts per minute defined to describe area of refining
1982 - Fox, Brodkey and Nissan	Fibers are stapled to the rotor or stator. . . the number of impacts a fiber will receive is 10^4.
1986 - Joris	Detailed mathematical analysis of plate crossing
1990 - Lumiainen	Incorporated width of bars into SEL theory to develop Specific Surface Load
1990 - Kerekes	C-factor developed to include fibre and plate geometry in determination of number and intensity of impacts
1995 - Meltzer and Sepke	Developed Modified Edge Load by adding bar angle, bar width and groove width to SEL equation

2.3 EXPERIMENTAL ANALYSIS OF REFINING

Optimum refining conditions are determined by maximizing resulting paper properties. To further understand the reasons behind paper property changes, modifications to individual fibres are examined. Experimental test details are discussed in Chapter 3. The following paragraphs explain the theory behind non-standard tests and points of research interest for common laboratory procedures.

2.3.1 Individual Fibre Properties

Fibre Length --Average fibre length is the most commonly used characteristic of individual fibres. It is determined by measuring the length of a large number of

individual fibres and then averaging the values either as the arithmetic average fibre length ($\Sigma n_i l_i / \Sigma n_i$ where n_i is the number of fibres in each class and l_i is the average length in class i), length weighted fibre length ($\Sigma n_i l_i^2 / \Sigma n_i l_i$) or weight weighted fibre length ($\Sigma n_i l_i^3 / \Sigma n_i l_i^2$). The long fibre portion influences the latter two numbers and hence the average length fibre lengths increase as one moves from the arithmetic average fibre length to the weight weighted fibre length. Unless otherwise stated, length weighted average fibre length is used for average fibre length in this work as it is the most commonly used fibre length term in pulp and paper research.

One problem with using an average fibre length is that as parts of fibres are pulled off the parent fibre, the smaller pieces are counted as individual fibres and thus lower average fibre length even in the case where original fibres may be largely intact. To compensate for this factor, normalized fibre length distributions are shown in the discussion of experimental results. Another concern with measuring average fibre length is that the equipment used for this work does not measure nonbirefringent material. This is critically discussed in section 3.4.1.

What is expected to happen to fibre length during refining? In the early stage of low-intensity refining the fibres lengthen [Atack 1978, Page 1985, Biasca 1989, Mohlin and Alfredsson 1990, Welch and Kerekes 1994]. The initial increase in fibre length is probably due to straightening of the fibre as a result of tensile forces acting on fibres. This stretching of fibres may be responsible for the removal of curls, kinks and microcompressions. With further refining, average fiber length decreases through cutting, curling, or increased fines quantity as discussed in the previous paragraph. In low consistency refining, the lignin-rich outer fibre layers are removed allowing the inner layers to swell [Alexander et al. 1968, Karenlampi 1992].

It has been suggested that the proportions of fibre length distribution, and not simply average fibre length, influence paper properties. This reflects an intuitive understanding that the sizes of the Bauer McNett fractions are important and that each fraction must be enhanced to produce optimal paper properties [Forgacs 1963]. In the Bauer McNett test, a 10 gram sample of pulp is placed in the top pulp chamber. Water flows through the device and the pulp is agitated causing it to flow across an outlet screen. Part of the pulp moves through the screen into the next chamber. The process is then repeated with a smaller screen hole size. Altogether there are five chambers

with decreasing screen hole sizes. After running for 20 minutes, the pulp chambers are emptied and the remaining pulp is collected. The pulp fractions are referred to as R14, R28, R48, R100, R200 and P200 where the "R" stands for "remaining" and the "P" for "past."[1] The P200 fraction is not collected and is calculated by subtracting the weight of the five pulp fractions from the original 10 grams of pulp. The long fibre fractions, R14 and R28, act as the fibre network backbone. The fines, R200 and P200, play a role in bonding and optical properties [Retulainen et al. 1993]. A certain amount of mid-size elements, in this work defined as R48 and R100 fractions, is required [Mohlin 1997]. Jackson and Williams [1979] found TMP pulp had a significantly larger amount of ribbon like material than CTMP in these middle fractions.

Giertz [1976] identified the following fines components in a study of spruce thermomechanical pulp.

> The fraction 100/200 contains mainly fibrils and fibrillar lamellae and also a few very short fiber fragments. The fibrils originate from the S1 layer of the secondary wall. The P200 fraction consists of:
> - ray cell fragments broken off as a result of tracheid separation
> - middle lamella debris, mostly from the cell corners
> - primary wall material, consisting of skin fragments of different size and the crater rings of the bordered pits
> - short and thin fibrils
> - some very short fibre fragments.

Fines play a very important role in determining paper sheet quality. They fill void spaces in the fibre network consolidating the sheet and thus contributing to its strength, water retention and optical properties [Giertz 1977, 1980, Corson 1979, 1980, Pelton et al. 1984, Sundström et al. 1993, de Silveira et al. 1996]. Ingmanson and Andrews [1959] estimated that external surface area of fines is more than ten times as great as that of the fibres. This extensive surface area greatly increases bondable area [Mohlin 1977, Giertz 1980, Paavilainen 1990]. However, very high levels of fines can be detrimental. Corson [1979] and Retulainen [1992] found a drop in tensile and tear strengths with high levels of fines as a result of load displacement from the fibre network. Although the fine material makes an essential contribution to consolidation of the fibre network, Corson [1979] concluded that the effect of fines fraction for TMP was secondary to that of fibre quality. Mohlin [1979] found that

[1] The pulp fractions are referred to by the Tyler series designation for the Bauer McNett. Some authors prefer the US designations for Bauer McNett fractions namely 16, 30, 50, 100 and 200.

quantity, not properties, of the fines was the dominant factor in her regression equations for determining paper properties.

Coarseness--Coarseness is defined as mass per unit length of fibre. Generally coarser fibres have thicker walls and fewer fibres per unit pulp mass. However a thick-walled, narrow fibre can have the same coarseness as a thin-walled wide fibre. The narrow fibre is very stiff whereas the wide fibre collapses readily [Seth 1990]. Even with this ambiguity, coarseness is seen as an important fibre characteristic [Clark 1962]. A recent correlation [Paavilainen 1993] showed that over 80 percent of the variation in tensile and tear strength of softwoods could be explained by changes in coarseness. Criticism of the coarseness test follows in section 3.4.1.

Forgacs [1963] found that coarser fibres are not as likely to unravel in the mechanical pulping process as finer ones and thus make weaker mechanical pulps. A number of researchers [Sundström et al. 1993, Karnis 1994, Jang et al. 1996] found that mechanical pulps produced with high-intensity first stage refining contain fibres of lower average coarseness than those produced with low intensity. Karnis [1994] put forward an earlier theory of Emerton [1957] postulating that a peeling-off mechanism decreases fibre coarseness as material is removed from the fibre wall. Material peeled from the fibres becomes fines. Corson [1993] agrees with this postulation. Corson and Ekstam [1994] also affirm a previous idea put forward by Kibblewhite [1989] who postulated that viscoelastic deformation of a fibre during refining could increase the density of the fibre wall material and thus reduce the fibre width. Figure 2.9 illustrates some of these fibre changes with refining.

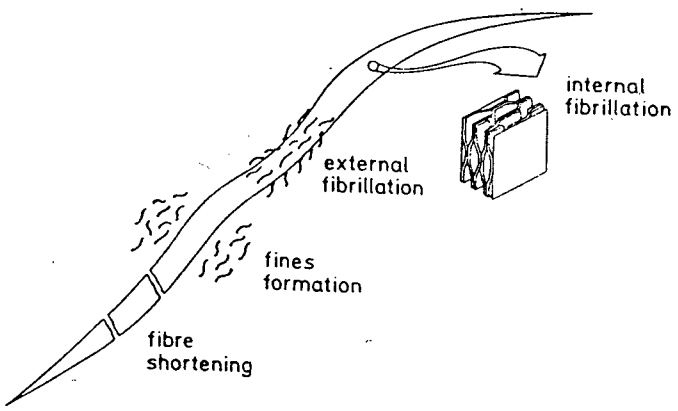


Figure 2.9: Some changes to fibres during refining [Lidbrandt and Mohlin 1980]

In parallel to what is observed with high consistency refining, low consistency refining of mechanical pulp may result in the production of fines from outer layers [Giertz et al. 1979, Kibblewhite 1983, Christensen 1987, Corson 1993]. This can be true even in cases the mass of R14 and R28 fractions decrease, as the number of fibres may remain constant but the mass per fibre is lower. An early study of chemical pulp found that the first fines produced with refining were membrane-like pieces originating from the S1 layer. With increased refining, fibril segments from the S2 layer were pulled off [Asunmaa and Steenberg 1958].

Fibre Strength--A zero span tensile test is often used as a measure of individual fibre strength. However, as the distance between the jaws is not exactly zero, other factors such as fibre bonding affect the test results [Boucai 1971]. Such complex interactions are common in tests designed to measure fibre properties as it is difficult to work on the microscale of individual fibres. El-Hosseiny and Bennett [1985] found zero span to be a function of fibre length distribution. Mohlin [1991] attributes zero span changes in refining to changes in fibre deformation.

Fibre Shape--Manual determination of kink and curl is tedious and often limited to small sample sizes. However, with the recent development of the Flow Through Fibre Analyzer (FTFA) both kink and curl can be calculated using a much larger sample size. Page et al. [1986] understand curl to be a dominant factor in both pulp and paper properties. A critique of the FTFA is included in section 3.4.2.

In addition to its affect on paper properties, fibre shape is particularly interesting in mechanical pulping analysis as it indicates the degree of latency removal. Pulp fibres exiting the refiner experience sudden cooling when air contact is made. This freezes fibre contortions resulting in curled and kinked fibres. The presence of the distorted fibres affects both pulp drainage and paper strength [Htun et al. 1988]. This research includes examination of latency removal through low consistency refining.

Mohlin and Alfredsson [1990] defined curl index as fibre contour length divided by the longest dimension. In this research curl index (CI) is specified by Olson et al. [1995] as illustrated in Figure 2.10. A straight fibre will have a curl of zero; the curl index increases as the fibre is deformed.

$$CI = \frac{L}{\ell} - 1 \qquad [2.1]$$

where CI = Curl Index, L = fibre length and ℓ = longest fibre dimension

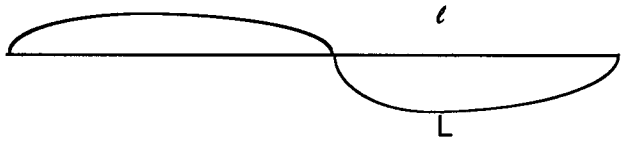


Figure 2.10: Fibre curl defined

Olson et al. [1995] define Kink Index, KI, as:

$$KI = \frac{n_{10-20} + 2n_{20-45} + 3n_{45-90} + 4n_{90-180}}{\ell} \qquad [2.2]$$

Where $n_{10\text{-}20}$ is the number of kinks with a kink of 10 to 20°, etc.

The kink index of every fibre is dependent on the magnitude and size of kinks and fibre length. In the computer program developed by Olson and coworkers for the FTFA, kink is measured with a twelve pixel hinged ruler. They found this to provide the best fit when used on a set of curved and kinked fibres orderly placed on a grid. All fibres less than twelve pixels, are assigned a zero kink index. If the fibres are longer than twelve pixels, but the irregularities are less than twenty degrees, they also have a kink index of zero. Fibres longer than twelve pixels may also have a calculated KI of zero if the fibre length exceeds a certain limit. As shown in Figure 2.11, fibres with small kinks that are straightened are also assigned a kink index of zero even though this small kink alters the fibre as much as a larger, measurable kink. These considerations show that the program results in measurable, not absolute, kink values.

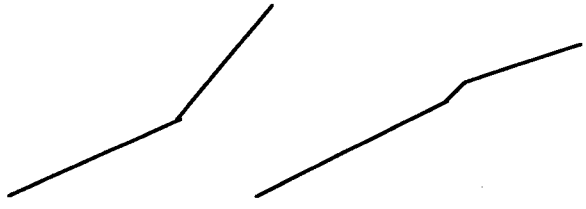


Figure 2.11: Examples of fibre kink

Kinks in fibres act as fibre ends and do not transmit load. Hence pulp with a high kink index behaves like a shorter length pulp. Shape factors such as curl and kink can greatly affect the pulp suspension and paper quality [Page and Seth 1980, Laamanen 1983, Page et al. 1985]. Properties of mechanical pulp can be changed by

fibre contortions, such as kink and curl, if latency removal is inadequate [Htun et al. 1988]. Tear index can be enhanced by increased fibre curl, although tensile strength decreases [Page et al. 1985, Jordan and Nguyen 1986]. On a single fibre heavily damaged areas may alternate with those of little distortion [Teder 1964, Ebeling 1980]. Two studies show that distortions appear to diminish with light refining [Atack 1978, Page et al. 1979]. However, as refining increases, so does the number of dislocations [Alexander et al. 1968].

Flexibility--Fibre flexibility is understood to be a major factor influencing the bonding ability of fibres and paper strength [Teder 1964, Mohlin 1975]. Flexibility is the reciprocal of the product of the modulus of elasticity and area moment of inertia. Small changes in fiber radius, as may happen in refining, greatly affect flexibility as the area moment of inertia is proportional to the difference of the outer and inner radius both raised to the fourth power. Flexibility increases with increasing hydrodynamic specific volume and the removal of the outer secondary wall [Forgacs and Mason 1958, Biasca 1989]. These two factors are key components in flexibility changes. Table 2.5 shows the chronological development of flexibility testing. The modulus of elasticity is affected by processing. Stone and Scallan [1965] postulate that splitting of the cell wall into many parallel layers may lower fibre modulus and thus increase flexibility. Page and DeGrace [1967] found the walls of chemically pulped fibres split into separate concentric layers when refined. They were not able to observe this phenomenon for groundwood and high yield chemical pulps.

High yield pulps, both from chemical and mechanical sources, have coarse and stiff fibres [Giertz 1962, Jauhari 1968, Tam Doo and Kerekes 1982]. Long fibres of CTMP exhibit a higher degree of conformability and a larger degree of lumen collapse than TMP [Jackson and Williams 1979]. Atack et al. [1980] conclude that increased interfiber bonding from sulfonation prior to refining is due to increased flexibility and collapse of long fibres, not to the development of new surface. As sulphonate groups are introduced, the middle lamella is softened and fibre conformability is increased [Atack 1987, Corson 1992, Dessureault and Barbe 1992].

Table 2.5: Chronological development of fibre flexibility testing

Date - Name	Flexibility Test
1941 - Seborg and Simmonds	Used a highly sensitive quartz spiral for applying stress to measure the stiffness in bending of single fibers in liquid media or in air.
1957 - Emerton	Noted that flexibility is proportional to the fibre width to the fourth power. ". . . if the equivalent diameter or thickness is halved, the flexibility of the fibre wall is increased 16-fold."
1958 - Forgacs et al.	Measured flexibility based on a classification of rotational orbits of the fibres in laminar shear.
1963 - Samuelsson	The fibre is fixed as a cantilever to the wall of a flow channel and loaded by the force from a water stream directed at right angles to the fibre axis.
1965 - Stone and Scallan	The ability of a wet fibre to deform under an applied load will depend upon two factors, 1) the moment of inertia which is related to the cross-sectional shape and 2) the modulus of elasticity of the cell wall material.
1975 - Mohlin	Conformability determined by measuring the ability of the pulp fibre to conform to a glass fibre placed on a glass plate.
1980 - Naito et al.	Tested torsional rigidity of individual fibres in pendulum device.
1981 - Shallhorn and Karnis	Long fibre fraction is sprayed by nozzle onto the underside of a screen which is subjected to vacuum on the upper side. The vacuum pulls some of the fibres through the screen and separates fibres out by their flexibility.
1981 - Tam Doo and Kerekes	Secured the fibre as a simply supported beam and measured its deflection while under hydrodynamic loading.
1985 - Steadman and Luner	Derived an equation for flexibility based on length of fibre not in contact with glass plate placed over a stainless steel wire.
1995 - Kuhn et al.	Flexible fibres are more able to conform to streamlines and exit through a slot in the side of the main channel.

2.3.2 Paper Properties

All common paper properties were measured in this study. Changes to paper properties are important since increased tensile strength, within a given tear and freeness specification, is often the objective of secondary refining [Fahey 1970]. A new test, fracture toughness testing, was completed to give additional information regarding this test.

Mechanical pulp is the primary component of newsprint. It is also used as part of the furnish in directory (telephone books), supercalendered (flyers, newspaper inserts, catalogues) and light weight coated (catalogues, magazines) papers [NLK Consultants

1996]. Higher grades of CTMP can be used to in office and printing papers [NLK Consultants 1996]. Typical pulp and paper properties as shown in Table 2.6.

Table 2.6: Typical values of pulp and paper properties [NLK Consultants 1996]

Property	Spruce Kraft	Spruce CTMP	Spruce TMP
Freeness (ml)	400	100	100
Breaking Length (km)	10.6	4.8	4.4
Tear (mNm^2/g)	10.0	7.0	8.0
Bulk (cm^3/g)	1.4	2.6	2.7
Yield (%)	45	92	94

Tensile Strength--Paper is a complex structure consisting of a three-dimensional network of paper fibres, fines and fillers. Tensile strength is measured by placing strips of paper into vertical holding clamps and slowly moving the clamps apart. The most common term for tensile strength, breaking length, is the self-supporting length of paper if the paper is hung vertically.

Paper strength depends on the strength of fibre-to-fibre bonding, strength of individual fibres and conditions used to make the sheet. When bonding strength increases through more bondable surface area or enhanced bonding strength, properties such as tensile strength and bursting strength increase. A simplified approach to paper strength consists of the following:

Paper strength = no. fibres contacting x area/contact x strength/contact area [2.3]

In equation [2.3], the number of fibres contacting is affected by stiffness of fibres [Robertson 1959]. The area per contact is also changed by stiffness and collapsibility. Strength per contact is affected by lignin on the surface and surface roughness [Lewis and Richardson 1939, Jayme 1958, Levlin and Jousimma 1986]. Secondary refining has the potential to affect all three aspects of paper strength. Page derived a quantitative relationship between paper strength and zero span, fibre cross sectional area, fibre length and relative bonded area [Page 1969]. It should be noted that Page considers only the whole fibre interaction and does not regard the contribution of fines to bonding

of paper. Nor does he consider the mode of paper failure [Shallhorn and Karnis 1979]. These considerations are part of the experimental analysis.

The development of tensile strength focuses on the breaking length information as this is the most commonly used indication of tensile strength. The burst test was performed but is not discussed as "there does not seem to be a strong correlation between bursting strength and any end-use requirement," [Scott and Abbott, 1995].

Tear Index--Tear Index results from an out-of-plane test and is understood to indicate paper's ability to resist crack propagation. For the tear test, four pieces of paper are clamped vertically together and cut to a given level. The pendulum of the tear tester is then released. The amount of work needed to completely tear the pieces in half is measured. Correcting this number for basis weight yields the tear index. Although it is a common test, it is not without controversy particularly since it measures crack propagation in a different plane than is usually encountered in a paper or printing machine [Seth 1991]. Tear is understood to be very dependent on fibre length, coarseness and zero span [Dadswell and Watson 1962, Dinwoodie 1965, Seth 1990, Yan and Kortschot 1996]. It decreases with increased bonding as the stress is more concentrated at the point of fracture and therefore less work is needed to continue the tear [Campbell 1932, Institute of Paper Chemistry Staff 1944, Page 1994].

Atack et al. [1978] found the tear indices of CTMP and TMP are significantly higher than those of corresponding CMP and RMP. They postulate presteaming enhances individual fibre properties. Richardson et al. [1990] found there was no difference between the tear indices of TMP and CTMP at all sulphite applications and preheating temperatures. Under normal conditions, low consistency refining reduces tear.

Bulk--Bulk, or its reciprocal, density, is often understood to be a rough measure of fibre flexibility as flexible fibres are able to conform to one another and create a cohesive mat [Mohlin 1979, Biasca 1989, Paavilainen 1993, Karnis 1994]. However surface bonding ability, total surface area, amount of fines and degree of fibre collapse may influence fibre to fibre contact and density [Jackson and Williams 1979, Hartman and Higgins 1983]. Tasman [1966] found that the apparent density decreased slightly with fibre length reduction brought about by fibre cutting.

Optical Properties--Incident light behaves as shown in Figure 2.12 or is absorbed as heat. The action of light is explained as follows.[1]

> The factors contributing to an increase in opacity are surface reflection, scattering, and absorption. Scattering is the most important of these factors with regard to opacity. . . light scattering is caused by multiple reflections and refractions occurring as light rays pass from air into the cellulosic fibers. Any activity which tends to reduce the number of air to fiber interfaces will thereby cause a reduction of scattering. . . The scattering coefficient is the fraction of light incident upon an infinitesimally thin layer of the material that is scattered backwards by that layer, divided by the (infinitesimal) basis weight of the layer.

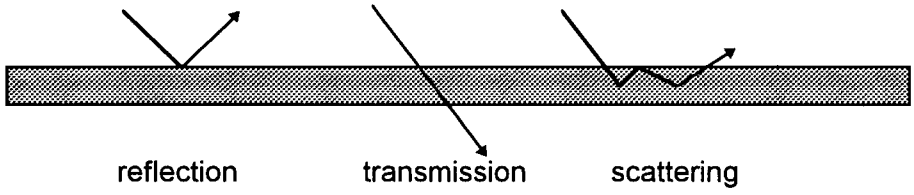


Figure 2.12: Behaviour of light incident on paper

Scattering coefficients and opacity are calculated based on absolute reflectance measurements and theories of Kubelka and Munk. The scattering coefficient is understood to be a function of free surface and is often used as a measure of bonded surface area [e.g. Ingmanson and Thode 1959, Rennel 1969, Sinkey 1984, Page et al. 1979, Skowronski and Bichard 1987, Paavilainen 1993]. This assumption is complicated by the large amount of fines present in mechanical pulps which was not considered in earlier studies. A large amount of fines increases the scattering coefficient while a high degree of network consolidation lowers it [Corson 1979]. A recent study of industrially produced mechanical pulps found that the light scattering coefficient of paper increased linearly with increasing fines content [Rundlöf et al. 1995]. They also found the increase in light scattering per mass of fines added was similar for all mechanical pulps tested, thereby concluding that the difference in light scattering ability between pulps was more closely related to properties of the fibre fractions than to the fines.

Marton et al. [1963] found scattering coefficients of CMP fractions to increase strongly with diminishing fibre length. Notably shorter fractions had a much greater scattering coefficient. In comparison, scattering coefficients of kraft pulp fractions are the same, implying that the chemical pulp fractions were composed of the same cellulosic

[1] Definitions taken from Technidyne BNL-3 Opacimeter manual, the instrument used for all optical tests.

base material whereas there is a variety of raw wood components present in mechanical pulp. Several studies have found that CMP had a lower light scattering coefficient than pure mechanical pulps [Mohlin 1987, Richardson et al. 1990]. Atack et al. [1978] found that scattering coefficients decrease in the order - TMP > RMP > CMP > CTMP.

Fracture Toughness--Fracture toughness has recently been introduced as a fundamental test for the runnability of paper. Fracture toughness is a measure of work consumed per unit area during crack propagation in a pre-notched sample [Seth et al. 1993, Seth 1995]. Although similar to tear strength as it analyzes the rate of flaw propagation, fracture toughness measures the flaw carrying capacity of paper in the same plane as normal sheet failure on a printing press. As it is an in-plane test, it may be a better prediction of crack propagation [Seth et al. 1993, Seth 1995]. Seth [1996] notes fracture toughness strongly correlates with tensile strength. Use of the same testing devise would intuitively suggest this. Two recent publications show that fracture resistance increases with LC refining [Shallhorn 1994, Seth 1996]. Details of the test are discussed in section 3.4.2. The results and discussion of fracture toughness testing are included in section 5.3.3.

2.3.3 Pulp Properties

Canadian Standard Freeness--Freeness measures drainage of pulp. El-Hosseiny and Yan [1980] found a change in CSF with refining to be a measure of the change in pulp specific surface area. Freeness is strongly influenced by fines content [Giertz 1968, Levlin and Jousimma 1986, Paavilainen 1990]. It is also a function of fibre flexibility as more flexible fibres form a more cohesive mat [Seth et al. 1993].

Freeness is frequently correlated to drainage time and desired paper properties [Lewis and Danforth 1962, Barnet et al. 1975, Flowers et al. 1979]. Additional specific energy is needed to produce CTMP than TMP of equivalent CSF [Atack et al. 1978].

Shives--Shives are bundles of wood fibres that have not separated during pulping. A low shive content is required for good runnability as shives act as weak points from which a paper flaw may propagate. In a mill study, Nordin et al. [1995] showed that the amount of shives was the most important variable in predicting some paper properties. Several studies have shown that low consistency refiners can effectively reduce shives from mechanical pulp [Bayliss 1984, Falk, et al. 1989,

Hietanen 1991, Sabourin et al. 1994]. Mill studies have shown that low-intensity LC refining is more effective than high-intensity LC refining for removing shives [Bonham et al. 1983].

2.3.4 Correlations between Fibre and Paper Properties

An early characterization of mechanical pulp was provided by Forgacs [1963] who developed Length and Shape (L and S) factors to characterize stone groundwood pulp. He defined S as the specific surface of the middle pulp fraction (later correlated to CSF for this part of the pulp) and L as the weight-weighted average fibre length of the middle pulp fraction. Forgacs used these two parameters to predict paper properties. Ölander et al. [1994] found that the specific surface area of all pulp types, mechanical and chemical, increased with refining.

Changes to fibres can be correlated to paper property changes. This is especially true in situations where either the wood supply or process conditions are constant as in a single mill. At present, the pulp and paper industry is undergoing an important change as on-line fibre analyzers are installed allowing a window into the pulp as it is being produced. As Table 2.7 shows, connections between fibre properties

Table 2.7
Chronological contributions correlating paper properties to fibre characteristics

Date - Name	Contribution
1962 - Clark	Gave equation for bulk, burst, tensile, fold and tear as a function of coarseness and length.
1963 - Forgacs	Developed shape factor, S = specific surface of 48/100 fraction (also substituted CSF for this), and length factor, L = WWA of R48 fraction to build equations for tear, burst, bulk and wet web.
1987 - Strand	Used factor analysis to resolve a large set of variables (pulp properties) in terms of a small number of common factors.
1987 - Levlin and Paulapuro	Stressed the importance of physical tests on single fibres as a starting point for understanding paper properties.
1991 - Paavilainen	The morphological properties have shown to explain from 70 to 90 percent of the paper property variations [for kraft].
1992 - Saltin and Strand	Used factor analysis to determine that fibre bonding, fiber length, unbonded surface area, fiber orientation and pressing are the five key independent variables.
1994 - Howard et al.	Three independent underlying factors were found to be responsible for the majority of the variation [in sheet and stock properties]: bonding, fibre length and microcompression.
1995 - Broderick et al.	Applied latent vector analysis to pulp characterization. Dominant factors are bonding area, fibre swelling and bond strength.

and paper properties have been studied for many years. Only recently however, has this type of study moved from an intuitive understanding to mathematical correlation. The majority of this work, particularly up to the 1980s, was performed with only chemical pulps in mind.

CHAPTER 3
EXPERIMENTAL METHODOLOGY

3.1 WOOD PREPARATION

White spruce, *picea glauca,* was used for the main part of the experimental work. Sections of two trees, approximately 80 years old, were obtained from the Gavin Lake area in British Columbia. I debarked the trees lengths and split them into manageable segments to prepare them for chipping. After chipping, I removed pin chips and oversize chips. The remaining wood chips were mixed, bagged and frozen prior to pulp production. The chips were set out one day before pulp production to bring them to room temperature. Mechanical pulps and a reference chemical pulp were then prepared.

3.2 PULP PRODUCTION

In this work, pulps which received only one stage of refining are labeled *base* pulps. First stage refining of TMP and CTMP was performed in Paprican's pressurized Sunds Defibrator refiner using a plate gap of 0.25 to 0.40 mm, a temperature of 135°C, 22 psi pressure and target outlet consistency of 15 percent. For CTMP the wood chips were treated for 90 seconds in a solution of sodium sulphite. Mechanical pulps were produced in the normal yield range of 90-96% for TMP and 80-93% for CTMP [Smook 1992].

After the first stage of refining the base pulps were treated for latency removal, except for the pulps in which latency effects were studied. All mechanical pulps were screened on a 6 cut screen with white water recycling as per standard procedure.

In addition to base CTMP and TMP, CMP and kraft were produced from the same chip source to yield an experimental database beyond that required to meet the thesis objectives. Results and analysis of CMP and kraft pulps as separate pulp groups are discussed in Appendix A. Differences between pulp groups are discussed in section 5.3.1.

3.3 SECONDARY REFINING

Base pulps were kept in the original form for further testing. TMP and CTMP were secondary refined both at high consistency and low consistency as shown in Figure 3.1.

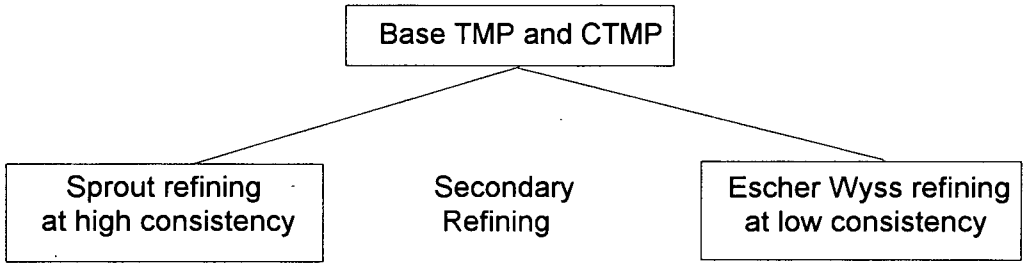


Figure 3.1: Simplified experimental program

Paprican's atmospheric pressure Sprout Waldron refiner was used for high consistency secondary refining of TMP and CTMP. A variety of TMP and CTMP pulps were produced by adjusting plate gap and power input. The refining temperature, 90°C, and consistency, 15%, were held as constant as possible. Paprican's Escher Wyss conical refiner was used for low consistency refining. It had previously been shown that the Escher Wyss refiner emulated industrial-scale disc refiners [Kerekes et al. 1993]. Each Escher Wyss pulp run was performed at room temperature, 3% consistency and targeted energy inputs of 100, 200 and sometimes 300 kWh/t. For both modes of secondary refining net power was calculated by subtracting the total power from the no-load power. Where applicable, the pulp was treated for latency removal prior to low consistency refining. All pulp types were also run in the PFI mill, the standard laboratory horizontal batch refiner, under standard operating conditions. The development of the C-factor refining theory for PFI refining is included in Chapter 4.

3.4 TESTING PROCEDURES

3.4.1 Standard Tests

The following C.P.P.A. Standard Testing Methods were used.

C.1 Determination of freeness

C.4 Forming handsheets for physical tests of pulp (see also C.2U)

C.6H Pulp evaluation--disintegrator method

C.7 Laboratory processing of pulp in a PFI mill

C.8P Latency removal by hot disintegration

D.4 Thickness and density of paper and paperboard

D.8 Bursting strength of paper

D.9 Internal tearing resistance of paper, paperboard and handsheets

D.12 Physical testing of pulp handsheets

D.16 Consistency of stocks

D.34 Tensile breaking properties of paper and paperboard

E1 Brightness of pulp, paper and paperboard

E2 Opacity of paper

G.9 Acid-insoluble lignin in wood pulp (Klason lignin)

G.13 Solvent extractives in wood and pulp

G.18 Kappa number of pulp

G.28 Total sulphur in pulp, paper and paperboard

Several C.P.P.A. Methods used:

C.1U Sommerville shives

C.2U British standard sheet machine preparation of mechanical pulps (mechanical pulp handsheets are made with recycled white water)

C.5U Fibre classification--Bauer-McNett method (using the normal Tyler series designation, namely 14, 28, 48, 100, 200)

D.27U Zero span breaking length of pulp (Pulmac zero span method)

Paprican Standard Procedures were used for the following:

B.2P Preparation of slides for microscopic examination of fibres

P-5-3 Screening of pulp

Fibre length and fibre coarseness were measured with the Kajaani FS-200. The FS-200 measures fibre length based on the birefringent property of cellulose to depolarize a polarized light beam. There has been much discussion regarding the fact that non-cellulosic fines are not captured by this method of measurement [Jackson 1988, Bentley et al. 1991]. During my FTFA work, a noticeable amount of small, dark pieces of nonbirefringent material could be seen on the monitor as pulp moved past the camera. As the FTFA visually outlines fibres as they are measured, one is able to determine that these nonbirefringent particles were never measured as part of the pulp sample. Jordan and O'Neill [1990] estimate that up to two-thirds of the fines are

invisible to the Kajaani. Due to this elimination of some fine particles, reported average fibre length is greater than the true fibre length, particularly where fine particles contain lignin-rich material as for mechanical pulps. However, this bias is consistent and does allow comparisons within pulp types.

Kajaani's FS-200 only measures the total fibre length and gives no indication of fibre deformation. For example, a fibre with broomed ends, a common effect of refining, would measure the total fibre length as shown in Figure 3.2. The effective fibre length is "a" but the length is measured as "b."

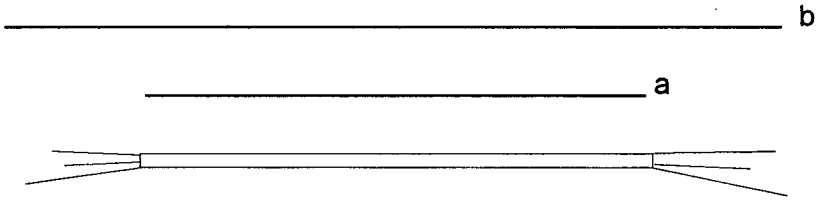


Figure 3.2: Fibre length measurement examples

For Kajaani coarseness measurements, the exact weight of sample is critically important. The FS-200 instruction manual recommends drying the sample, obtaining the exact oven-dry weight, reslurrying the sample and then running the test. I tried this method using a modified Hobart mixer to reslurry the mechanical pulp as per standard Paprican adaptation of the Kajaani instructions. However, a clean separation of the dried fibers was not possible without altering the sample through exposure to high shear. In addition, residual fibre bundles clogged the FS-200 testing tube which automatically terminated the test. I next tried the Paprican technique of determining an accurate consistency for a dilute pulp sample and carefully diluting and weighing out the portion to be tested. This provided repeatable measurements without damaging pulp fibres.

3.4.2 Non Standard Tests

3.4.2.1 Fibre Flexibility Tester

Flexibility of individual fibres is difficult to measure due to the complexity of clamping and flexing individual fibres. Further complications of wood and pulp variability add to the dilemma of measuring a statistically significant difference between samples. The flexibility tester developed by Tam Doo and Kerekes [1981] was used in

this work. The method involves placing a single fibre over a small opening and applying a concentrated hydraulic drag. Movement of the fibre and flow of water is recorded. Fibre flexibility is calculated using small deflection beam theory for a simply supported beam. The instrument was reassembled as per Figure 3.3.

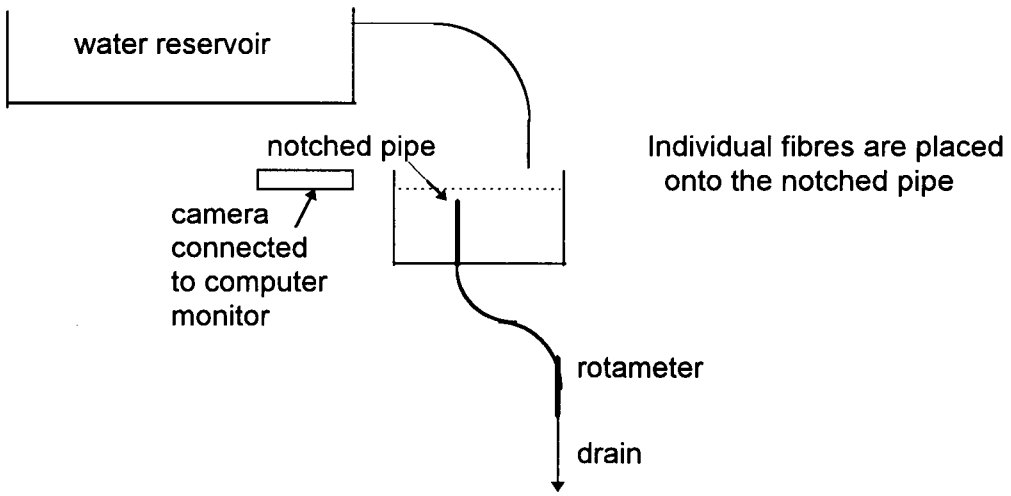


Figure 3.3: Schematic of fibre flexibility tester

Prior to the pulp fibre tests, the unit was calibrated with carbon fibres and an acceptable match between calculated and experimental values of carbon fibre flexibility was obtained as shown in Appendix D. Previously the unit had been calibrated with nylon fibres. However, there is a wide range in the literature for the elastic modulus of nylon, and it is believed that the elastic modulus is changed when nylon fibres are wet as required for the flexibility tester [Soszynski 1987]. Indeed when measuring flexibility of soaking wet and just wet nylon fibres, the latter were found to be statistically stiffer at a t-test confidence level of 99.9%. There was some concern regarding Tam Doo's choice of a circular fibre cross-section, as the flexibility calculation is proportional to the fibre radius to the fourth power. Thus any deviations from a circular cross-section would be significant.

For each test a single fibre is placed onto the notch. The water flow is then activated and flow rate and fibre displacement are measured. During flexibility testing wide variability of pulp fibres was seen. Within any given sample some fibres were stiff and inflexible, while others collapsed readily when hydrodynamic stress was applied. This variability reflects normal differences in springwood and summerwood

[Samuelsson 1964, Hattula and Niemi 1988, Abitz 1989]. There has been some criticism of the Tam Doo and Kerekes method in recent years, primarily with respect to the preselection of the tested fibres [Paavilainen 1993, Chatterjee and Dodson 1994]. However, I found that the task of grabbing and positioning a fibre across the testing notch is not simple. For every fibre successfully placed onto the notch, three other fibre were not seated accurately. The first 100 fibres to sit in the notch were measured. Each fibre was discarded after testing and therefore it could not be retested. Badly hinged or kinked fibres were not tested as they behaved abnormally when the hydraulic stress was applied. Some fibres, an estimated 10%, were too flexible, bent beyond the elastic limit of the test and were therefore discarded.

For the most part, my measured values for wet fibre flexibility were comparable to previous results with this apparatus as shown in Table 3.1. For all tests, the standard deviations were large, approximately equal to median values.

Table 3.1: Comparison of fibre flexibility results

Pulp Type	Species	Reported Flexibility [Kerekes and Tam Doo 1985]	Species	Measured Flexibility in this work
Kraft	hemlock	50 $N^{-1}m^{-2}$ x10^{10}	spruce	20 $N^{-1}m^{-2}$x10^{10}
TMP first stage refining	spruce	1 $N^{-1}m^{-2}$ x10^{10}	spruce	14 $N^{-1}m^{-2}$ x10^{10}
TMP second stage refining	spruce	1.3 $N^{-1}m^{-2}$ x10^{10}	spruce	9 $N^{-1}m^{-2}$ x10^{10}
CMP	unknown	9 $N^{-1}m^{-2}$ x10^{10}	spruce	11 $N^{-1}m^{-2}$ x10^{10}

3.4.2.2 Flow Through Fibre Analyzer

Paprican's Fibre Quality Analyzer, FQA, was still in its developmental stages when this research was done. At that time it was known as the Flow Through Fibre Analyzer or FTFA. It is thus referred to by that acronym in this thesis. As my project was the first to run mechanical pulp samples through the prototype, it was necessary that I validate the performance of the equipment by conducting a series of parallel tests on the FTFA and the Kajaani FS-200. This work is summarized in Appendix D.

Unlike the FS-200, the FTFA's computer monitor provides a window into the pulp. Magnified fibres appear clearly on the screen. Fibre damage and anomalies are readily seen. Previous to the development of this apparatus, fibre kink and curl were measured manually by preparing slides and then counting the visible characteristics. The FTFA provides a quick method of obtaining this information and eliminates bias on the part of a human operator.

3.4.2.3 Fracture toughness

At the time of this research, Paprican was standardizing its procedure for fracture toughness testing. A large number of varying width paper strips were tested, each having a standardized notch cut into the centre of each side of the test strip.

During fracture toughness testing, the gap widens on both sides of the notched area. Failure was very sudden and immediately followed by a complete, tortuous collapse across the ligament. This is different from paper failure in the tensile test where the paper usually snaps in a clean line across the strip. Fracture toughness results are included in section 5.3.3.

3.4.2.4 Microscopy Techniques

Toluene blue dyed microscope slides were prepared for the R14, R48, R100 and R200 Bauer McNett fractions of each pulp type. With this dying technique, higher lignin concentrations produce a darker shade of blue. Most microscopy work was done in phase contrast mode where phase differences in the refraction of light from the specimen are converted to wave length differences producing a sharper image [Delly 1980]. To quantify morphological changes, several hundred fibres were examined for each pulp type. The most commonly seen fibre anomalies are listed in Tables 5.4, 5.13, and 5.22 and shown in Figure 5.7. Polarized light microscopy was used to examine TMP and CTMP long fibre fractions.

3.5 EXPERIMENTAL ERROR

To minimize and understand the sources of experimental error, all laboratory work was completed by the author. Of particular interest is the comparison between the two base CTMP pulps. Two sets of paper sheets were created from this single pulp sample. The only difference was an eight month time lag during which the pulp was

kept in refrigerated storage. A summary of the test results is shown in Table 3.2. Detailed information on the statistical methods used in this work is found in Appendix E. Statistical significance is based on the assumption of a normal distribution and a 90% confidence level. The same alphabetical subscript indicates that the values are not statistically different.

Table 3.2: Fibre and paper properties of base CTMP

Fibre or Paper Property	CTMP Base Pulp #1	CTMP Base Pulp #2
LWA fibre length (mm)	2.08_a	2.09_a
Breaking Length (km)	4.24_a	3.49_b
Bulk (cc/g)	3.39_a	3.41_a
Tear (mNm^2/g)	9.8_a	10.8_b
Zero Span (km)	11.3_a	10.7_b
Scattering Coefficient (cm^2/g)	51.4_a	48.7_b
Fracture Toughness (Jm/kg)	14.2_a	14.4_a

The fibre length, bulk and fracture toughness are statistically the same. There is a loss of breaking length, zero span and light scattering coefficient due to the time delay and testing variables. This is taken into account in the discussion of experimental results.

CHAPTER 4
REFINING THEORY

As the theory of refining is an important part of this thesis, an examination of low consistency and high consistency refining theories form the first part of this chapter. To illustrate the similarities and differences between the two main theories, namely Miles and May's work in high consistency refining and Kerekes' work in low consistency refining, it is shown that with the appropriate substitutions and assumptions, these two theories can be reconciled. Section 4.3 is original work determining the C-factor for the PFI mill. This section was published in Appita, vol. 47, no. 5 (1994).

4.1 COMPARISON OF REFINING THEORIES

Further to the initial explanations of refining theories found in section 2.2, this section reviews Miles and May's characterization of high consistency refining and Kerekes' C-factor characterization of low consistency refining. Similarities and differences are highlighted to explain results obtained in the quantitative analyses and experimental results. A brief history of low consistency characterizations and a discussion of current theories are included.

4.1.1 Miles and May's Characterization of High Consistency Refining

In high consistency refining the pulp mass acts as a solid. The fibres are moved through the refiner by steam pressure and centrifugal force. Miles [1991] calculates the residence time inside a HC refiner, τ, as:

$$\tau = \frac{\mu_r}{\mu_t}\frac{aEc_{in}L}{\omega^3(L(r_2^2 - r_1^2) + c_{in}Er_1^2}\left[\ln\frac{r_2}{r_1} - \frac{1}{2}\ln\left(\frac{L - c_{in}E}{L}\right)\right] \qquad [4.1]$$

The component terms for equation [4.1] are defined as follows:

μ_r = radial coefficient of friction between the pulp and refiner disc

μ_t = tangential coefficient of friction between the pulp and refiner disc

a = 4 for single disc and 2 for double disc refiner

E = total specific energy applied to the refiner

c_{in} = inlet pulp consistency

L = latent heat of steam vaporization

ω = angular velocity of disc 2

r = refiner radius, r_1 = inner radius, r_2 = outer radius

The number of impacts experienced by the unit mass of pulp, n, is given as:

$$n = Nh\omega \frac{r_1 + r_2}{2} \tau \qquad [4.2]$$

where N = number of bars per unit length of arc.

h = 1 for single disc and 2 for double disc refiner

Miles defines refining intensity, e, as:

$$e = \frac{E}{n} \qquad [4.3]$$

Some of the values used by Miles et al. appear in Table 4.1 [Miles 1990, Miles and Karnis 1991, Miles, May and Karnis 1991]. These data are used in subsequent sections of this thesis.

Table 4.1: Miles' conditions and calculated values for HC refining

No.	Disc Speed (rpm)	Flow (t/d)	Consis-tency (%)	Residence Time (s)	Total Impacts (unspecified unit of pulp)	Average Specific Energy (MJ/kg)	Total Specific Energy (MJ/kg)
1	1200	11.8	C_{in}=20.5	1.13	21,418	1.93E-4	4.4
2	1200	11.8	C_{in}=20.5	1.25	11,898	3.77E-4	4.4
3	1200	-	C=23	0.55	9,970	2.13E-4	2.1
4	1200	-	C_{out}=20	1.7	31,800	2.55E-4	8.11

4.1.2 Kerekes' C-Factor Characterization

Kerekes derived the C-factor using fluid mechanics and the motion of a fibre inside a refiner. The C-factor is used to estimate the number and intensity of impacts imposed on fibres [Kerekes 1990]. It is similar to the simpler, empirically derived Cutting Edge Length discussed in section 4.2. The C-factor for a disc refiner is shown here.

$$C = \frac{8\pi^2 GD\rho C_F \ell n^3 \omega (1 + 2\tan\phi_r)(R_2^3 - R_1^3)}{3w(\ell + D)} \qquad [4.4]$$

G = groove width

D = groove depth

ω = rotational velocity

ϕ_r = angle of bars on rotor

ρ = density of water	R_2 = outer radius
C_F = consistency	R_1 = inner radius
ℓ = fibre length	w = fibre coarseness
n = bar density	F = flow rate

Number and intensity of impacts are calculated as shown. P_{net} is the net power used in refining.

$$N = \frac{C}{F} = \text{number of impacts} \qquad [4.5]$$

$$I = \frac{P_{net}}{C} = \text{intensity of impacts} \qquad [4.6]$$

Specific energy is defined as the product of N and I. For a given specific energy, a common measure used in refining, a large N and small I lead to fibre surface disruption as per Table 2.2. A small N and large I result in fibre cutting. With C-factor theory, equal refining occurs only when N and I are both equal.

4.1.3 Reconciliation of Characterization Theories

The main part of the experimental program for my thesis compares results using either high consistency or low consistency secondary refining for CTMP and TMP. Quantifying the number and intensity of refining impacts in these two modes of refining, and examining the assumptions used in each theory, provides more information for the experimental analysis. In high consistency refining, the pulp mass moves through the refiner as a solid. A mass and energy balance approach, as chosen by Miles and May, is appropriate in this case. In low consistency refining, pulp flowing through the refiner behaves as a continuous liquid. Fluid mechanics is used to define LC pulp behaviour. These fundamental differences demand different approaches in quantitative analysis. It is illustrative to compare the two approaches and resultant values.

I will start with Kerekes' derivation and modify it according to Miles and May's work. From the original C-factor work, "The number of impacts seen by a fibre passing through a refiner is proportional to the number of bar crossings at the location of the fibre and the likelihood that a bar crossing imposes an impact on the fibre. . . we may first note that the maximum number of impacts a fibre can see occurs when all the bar

crossings at the location of the fibre inflict an impact," [Kerekes 1990]. The number of impacts per unit time on a fibre is:

$$\frac{dN^*}{dt} = \frac{\ell n_1 n_2 \omega}{2\pi r} \qquad [4.7]$$

Here N^* = number of impacts per fibre

n_1 = number of bars on the rotor

n_2 = number of bars on the stator

ω = angular rotational velocity

Kerekes continues, "this condition is met if the full length of a fibre is oriented in a tangential direction between bars. To create this situation, the leading end of a fibre must be restrained at a bar tip. . . The probability of {fibres} coming into contact with the leading tip of a bar is dependent on the relative size of the fibre, ℓ, the groove depth, D, and the gap size, T. We assume here that this probability is represented by the fraction:"

$$\frac{\ell}{\ell + D + T} \qquad [4.8]$$

Then the number of impacts per unit time on a fibre is given by:

$$\frac{dN^*}{dt} = \frac{\ell}{\ell + D + T}\frac{\ell}{2\pi r} n_1 n_2 \omega \qquad [4.9]$$

Miles and May do not use a probability or, to state it another way, they assume a probability of one. This is logical if fibre length is approximately the same as groove width as is normal in high consistency refining. This is similar to the C-factor case where ℓ = W+G, W being bar surface width and G groove width. If the probability is taken as 1, then equation [4.7] is the same as equation [4.9].

Now consider the case "when the groove depth and bar clearance become very small compared to fibre length i.e. $(D+T) << \ell$. In this case fibres tend to not be in grooves, but rather in a plane between bar surfaces. This means that each bar crossing over a fibre produces an impact," [Kerekes 1990]. This is compatible with Miles and May's assumption that grooves are packed with pulp. This is further affirmed by the fact that plate dimensions (e.g. D, W,φ and G) do not enter into high consistency

refining equations. Indeed Miles and May state that, "No distinction is made between the configuration of the forces on the pulp as the bars and grooves on one side change position relative to those on the opposite plate. These cause cyclic changes in the forces. When a bar is opposite a groove, for instance, the forces are reduced, depending on the amount of packed pulp trapped in the groove," [Miles and May 1990]. Kerekes observes that this would allow only a single impact on a fibre from bar crossings of the opposing plate. This is shown by substituting $\ell = G_1+W_1$ in equation [4.7]. As $n_1 (G_1+W_1) = 2\pi r$, one obtains: [Kerekes 1990]:

$$\frac{dN^*}{dt} = n_2\omega \qquad [4.10]$$

Integrating equation [4.10] using average bar density and residence time, τ.

$$N^* = n_2\omega\tau \qquad [4.11]$$

Note that Kerekes defines bar density as the total number of bars on a circle at $2\pi r$ while Miles defines bar density as number of bars per unit length of arc. Therefore $n_{Kerekes} = 2\pi r N_{Miles}$.[1] Substituting this into equation 4.11:

$$N^* = 2\pi r N\omega\tau \qquad [4.12]$$

Miles introduces h to account for single or double disc refiners as there is a doubling effect where both discs are rotating; h=2 for double disc refiners and h=1 for single disc refiners.

$$N^* = Nh\omega 2\pi r\tau \qquad [4.13]$$

There is one more difference in notation, namely $\omega_{Miles} = 2\pi\omega_{Kerekes}$.

$$N^* = Nh\omega_{Miles} r\tau \qquad [4.14]$$

Equation [4.14] can be compared with Miles and May's equation for number of impacts, equation [4.2], shown here for ease of reference.

$$n = Nh\omega \frac{r_1 + r_2}{2}\tau \qquad [4.2]$$

Comparing equations [4.2] and [4.14], the C-factor equation uses r in place of r_{avg} in Miles and May's equation. This can be accounted for by the choice of r used when

[1] Notation correct as shown.

defining bar density. This difference comes from the fact that Kerekes looks at a single fibre of length ℓ sitting on a circle at $2\pi r$. Here the ratio $\ell/2\pi r$ is the maximum number of all impacts at radius $2\pi r$ which could hit a fibre oriented tangentially. In contrast, Miles and May start with the maximum number of bar crossings at r_{avg} for all points on the circle at $2\pi r$ during the time the unit mass is inside the refiner.

A more detailed look at the different radius terms follows. In the C-factor, n is calculated by integrating an equivalent form of equation [4.13] between r_1 and r_2. Miles and May's original paper proposes a similar equation, although they prefer the more approximate average radius. Before integration, equation [4.13] can be expressed as:

$$dN^* = Nh\omega 2\pi r dt \qquad [4.15]$$

Recognizing that dt = dr/v, one obtains:

$$dN^* = 2\pi Nh\omega r\frac{dr}{v} \quad \text{or} \quad N^* = 2\pi\int_{r_1}^{r_2} Nh\omega r\frac{dr}{v} \qquad [4.16]$$

For N, h, and ω = constant; $$N^* = 2\pi Nh\omega\int_{r_1}^{r_2} r\frac{dr}{v} \qquad [4.17]$$

The residence time, τ, is defined as; $$\tau = \int_{r_1}^{r_2}\frac{dr}{v} \qquad [4.18]$$

Transformation of equation [4.16] to Miles and May's equation [4.2] requires that:

$$\int_{r_1}^{r_2} r\frac{dr}{v} \approx \frac{r_1+r_2}{2}\int_{r_1}^{r_2}\frac{dr}{v} \qquad [4.19]$$

If v = constant then both sides of the equation are equal. Note that the derived equation is for N^*, number of impacts per fibre, whereas Miles' n is the number of impacts on the pulp. This difference accounts for part of the two orders of magnitude variance when calculating number of impacts in low consistency and high consistency refining.

In summary, this comparison of the number of impacts shows that high consistency refining can be seen as a specialized case of the C-factor application. Differences between the two methods of characterization are as follows:

1. Miles does not use a probability factor.

2. Miles assumes that a unit mass travels with one plate and therefore only sees impacts from the other plate.

3. Kerekes sees the number of impacts as proportional to fibre length divided by total circular measurement, $2\pi r$. In contrast, Miles and May estimate the number of impacts as being proportional to average radius and therefore include all impacts at this radius.

4. Miles uses a factor, h, to account for single or double disc refiners.

5. Miles uses radians per second, whereas Kerekes uses revolutions per second.

6. Different notation is used for the number of impacts and bar density.

4.1.4 Comparison of Residence Times

A look at residence time calculations in the two refining characterizations is illustrative. Miles' residence times vary from 0.55 to 1.7 seconds in the examples shown in Table 4.1. Residence time in a LC refiner can be calculated as shown:

$$\tau = \text{residence time} = \int_{R_1}^{R_2} \frac{dr}{v} = \int_{R_1}^{R_2} \frac{2\pi r A_R dr}{Q} \qquad [4.20]$$

where A_R = cross sectional area at $2\pi r$

Q = volumetric flow rate

Kerekes [1990] uses the subscript s to designate stator parameters and r for rotor:

$$A_R = 2\pi rT + 2\pi r n_s G_s D_s + 2\pi r n_r G_r D_r = 2\pi r\left(T + n_s G_s D_s + n_r G_r D_r\right) \qquad [4.21]$$

From Kerekes [1990] $n \approx \cos\varphi/(W+G)$. Assume $T \ll G$ or D, $n_s=n_r$, $G_s=G_r$, and $D_s=D_r$. Assume W = G, then:

$$A_R = 2\pi r D \cos\varphi \qquad [4.22]$$

$$\tau = \int_{R_1}^{R_2} \frac{dr}{v} = \int_{R_1}^{R_2} \frac{A_R dr}{Q} = \int_{R_1}^{R_2} \frac{2\pi r D \cos\phi}{Q} \qquad [4.23]$$

Let $Q = F/\rho C_F$

$$\tau = \frac{2\pi D \cos\phi C_F \rho}{F}\left(\frac{R_2^2 - R_1^2}{2}\right) \qquad [4.24]$$

Using the values from my mill trial for hemlock CTMP:

D = 0.00635 m	F = 4.9 kg/s	R_2 = 0.584 m
C_F = 0.032	φ = 12 degrees	R_1 = 0.356 m

Here τ = 0.027 s.

This is significantly less than the residence time in a high consistency refiner calculated by Miles and May. This difference in residence times accounts for some of the difference in number of impacts calculated by HC and LC refining theories. If we include the fact that Miles and May assume the grooves to be filled with pulp, then equation [4.22] becomes $A_R=2\pi rT$. After the appropriate integration and assuming T = 0.5 mm, the residence time is calculated to be 69 ms. This is approximately twenty times shorter than the residence time calculated for high consistency refining and accounts for most of the difference in number of impacts. A fibre is simply in an HC refiner for a much longer time than in a LC refiner.

4.1.5 Network and Individual Fibre Rupture Intensities

It is interesting to compare the calculated refining intensity of both high consistency and low consistency refining to network rupture and fibre rupture values. The intensity of refining should be greater than network strength in order to work the pulp fibres effectively. It should also be less than fibre rupture to avoid damaging fibres.

4.1.5.1 Comparison with Yield Stress on a Fibre Suspension

For effective refining to occur the network must be disrupted. Therefore the calculated intensity of refining must be greater than the calculated intensity of network

strength. Bennington et al. [1990] developed an equation [4.25] for the yield stress, τ_y, for TMP defined for the commercial TMP used in their study:

$$\tau_y = 1.38 \times 10^7 C_m^{3.56} \qquad [4.25]$$

where C_m = mass concentration (fraction) then τ_y = yield stress (N/m2)

For example at C_m=0.205, τ_y= 49,000 N/m^2 = 49 kJ/m^3.

From Table 4.1 for C= 0.205, average specific energy per impact = 0.193-0.377 kJ/kg or 193-377 J/kg. If we assume a density of 1000 kg/m^3, the average specific energy per impact is 193-377 kJ/m^3, almost an order of magnitude above the yield stress calculated for TMP and equivalent to low-intensity refining.

4.1.5.2 Comparison to Network Energy

The intensity of refining can also be compared to network energy. For this calculation, ℓ = 2.2 mm and w = 1.7 x 10^{-7} kg/m (hemlock). Using the specific energy value from Case 1 on Table 4.1:

Specific energy per fibre = 1.93 x 10^{-4} MJ/kg x l x w = 7.2 x 10^{-8} J/fibre

From Case 2 (highest SE) = 3.77 x 10^{-4} MJ/kg x l x w = 1.4 x 10^{-7} J/fibre

Compare network rupture strength at 20.5% consistency (consistency of both cases) using network rupture data from Kerekes et al. [1993].

SE network rupture = 1 x 10^{-9} J/impact x (20.5/3)$^{2.5}$ = 1.2 x 10^{-7} J/impact

Miles and May's specific energy per fibre and network rupture strength at 20.5% are about the same. According to their calculation, intensity of impacts is at the same level as energy required to break up a fibre network. This represents very low-intensity refining.

4.2 OTHER CHARACTERIZATIONS OF LOW CONSISTENCY REFINERS

In addition to Kerekes' C-factor, there are a number of empirically-derived characterizations for LC refining. The equation for Specific Edge Load (SEL) is included here as this terminology is used to describe experimental conditions [Wultsh

and Flucher 1958, Brecht and Siewert 1966, Brecht 1967]. Cutting Edge Length is defined as shown.

$$CEL = N_r N_s L\omega \qquad [4.26]$$

where N_r, N_s = number of bars on the rotor and stator respectively

L = length of refining zone

ω = rotational velocity

The Specific Edge Load is then defined as:

$$SEL = \frac{P_{net}}{CEL} \qquad [4.27]$$

where P_{net} = total power to refiner minus no-load power

As the number of bars or length of refining zone increases, CEL increases and SEL decreases. This results in lower intensity refining. Lowering net power or increasing rotational velocity have the same effect. Decreasing the number of bars, a shorter refining zone, lower rpm or increasing net power, increases SEL indicating more severe action on fibres.

The amount of energy put into refining per ton of pulp is defined as specific energy (kWh/t). In the Specific Edge Load theory, the combined use of SEL and specific energy allows quantitative comparisons between different refiners. Two parameters are necessary to characterize refining as the energy of refining can be used differently depending on the number and intensity of impacts received by each fibre. This concept is summarized in Figure 4.1. Note that this is a theoretical representation only and not the result of experimental work. This figure shows that the same amount of energy can be applied through a large number of low intensity impacts or through a small number of high-intensity impacts, resulting in different effects.

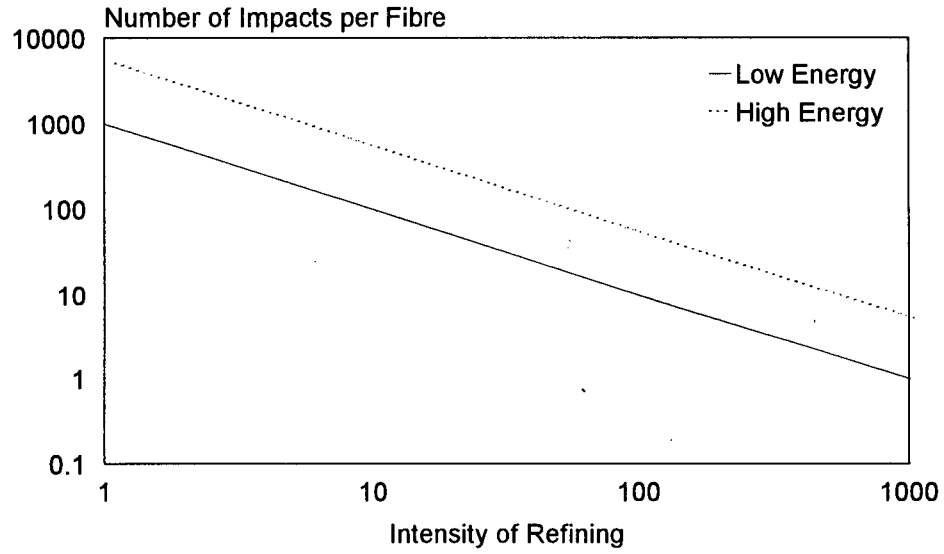


Figure 4.1: Summary of refining theories

When all other parameters besides those shown in equations [4.26] and [4.27] are kept constant, SEL is an excellent tool for designing and operating low consistency refining systems. However, in some cases the SEL is inadequate as it does not consider the following:

1. Consistency--as consistency increases refining action becomes less intense as more fibres are treated with the same total energy.
2. Angle of the bars--a larger angle decreases the cutting effect. A larger angle also increases pressure drop across the refiner. Too small an angle promotes fibre cutting and, in some cases, greatly increases noise from the refiner [Schmok 1987].
3. Depth of grooves-- important both for treatment and throughput considerations.
4. Width of the bars-- important where the bar width, not just the leading edge, contributes to the refining effect.
5. Fibre morphology--Fibre dimensions and pretreatment can greatly affect refining action.

Recently Meltzer added bar angle, bar width and groove width to the SEL equation in the derivation of his modified edge load (MEL) equation [Meltzer, 1996]. These five factors are incorporated in the C-factor analysis shown above.

4.3 LAB EQUIPMENT AND REFINING THEORY

As an extension of previous C-factor work, part of the original work for this thesis was to extend C-factor theory to a common laboratory refining devise, the PFI mill. This includes detailed derivations for number and intensity of impacts [Welch and Kerekes, 1994].

In North America the PFI mill is the most widely used laboratory refiner. It has long been recognized that qualitatively the refining action in the PFI differs from that of commercial units, but the degree and nature of the difference has never been quantified. In contrast, the laboratory Escher Wyss (EW) conical refiner is widely used in Europe and is gaining popularity in North America due to its similarity to commercial refiners. This similarity allows quantitative comparisons of the refining action. To date, such comparisons have not been possible with the PFI mill. Since the PFI remains a common analytical tool in the pulp and paper industry, there is a need to quantify its action to enable comparisons with other refiners.

There is much published literature on the changes in pulp properties induced by beating in a PFI mill. These studies have examined the effect of bar material [McKenzie 1980], use of higher than standard pulp concentrations [Watson et al. 1966], and the effect of speed, load, and gap size to standardize conditions [Murphy 1962, Phillips et al. 1970, Watson and Phillips 1964]. Energy of refining was measured in a number of studies [McKenzie 1980, Watson et al. 1966, Phillips et al. 1970]. In some cases experimental observations of the behaviour of pulp were made [Watson et al. 1966, McKenzie and Prosser 1981]. In other studies some expressions were presented for the force on fibres [Murphy 1962]. However, none of these studies attempted to quantify the action of a PFI mill on a basis that would allow comparison with other refiners. This is the objective of the present study.

An approach to characterize the refining action by a C-factor was developed by Kerekes [1990]. The C-factor measures a refiner's capability to inflict impacts upon fibres passing through it. In combination with mass throughput and power input, the C-factor is used to calculate the number, N, and intensity, I, of impacts on fibres. Once N and I are determined, different refiners can be compared at equivalent values of these parameters. A recent comparison of several mill disc refiners with an Escher Wyss refiner demonstrated the usefulness of this method [Kerekes et al. 1993]. Similar

changes in pulp properties were achieved at equal N and I despite dissimilar refining equipment and operating conditions of the refiners. In addition, values of I compared favourably with values estimated from other published scientific work [Kerekes et al. 1993].

4.3.1 Analysis

The C-factor is a defined parameter that relates net power input, P, and mass throughput, F, of a given refiner to the number, N, and intensity, I, of impacts imposed upon the fibres. N and I are derived from the relations:

$$N = C / F \qquad [4.28]$$

$$I = P / C \qquad [4.29]$$

The specific energy, E, is the product of N and I.

$$E = N \times I \qquad [4.30]$$

As a mechanical device, the PFI mill differs significantly from other refiners both in design and operation. To refine pulp the PFI is charged with 24 grams of medium consistency (10%) pulp. The pulp is packed into the inner circumference of the bedplate as shown in Figure 4.2. During refining the pulp is kept in place by centrifugal forces caused by the rotation of the bedplate. Inside the bedplate, roll bars press against the pulp imposing cyclic deformations upon the fibres. Because the roll rotates at a greater velocity than the bedplate and the fibres move with the bedplate, each fibre sees multiple bar passings for each revolution of the roll.

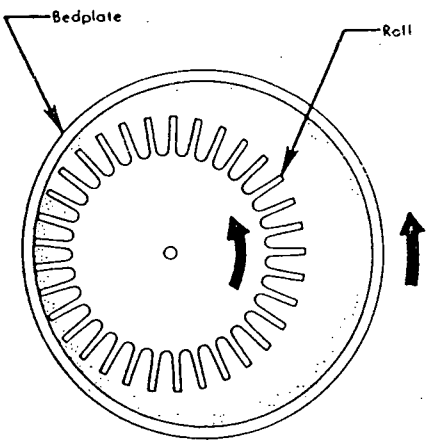


Figure 4.2: Elements of a PFI mill

Due to its geometry and operation, the PFI mill cannot be characterized in the same manner as disc and conical units. It is a unique device. Furthermore

assumptions must be made which are critical to its characterization. Because of these uncertainties, two limiting cases are considered.

4.3.2 Large Working Zone

In earlier work, Tam Doo and Kerekes [1989] derived an expression for the number of bending cycles imposed on fibres, N as a function of N_r, the number of rotations of the PFI roll. Their aim was to compare the action of a PFI mill to small amplitude bending, and therefore they considered the working zone to be the area that imposed any deflections in fibres. As a working zone, they chose the portion of the bedplate in which pulp mat thickness is less than the distance between the tip of the roll bars and the bedplate. They assumed that all fibres in this zone were subjected to cyclic deformation. On this basis, they related the number of cyclic deformations to revolutions of the roll as:

$$N = 2.5\ N_r \qquad [4.31]$$

Tam Doo and Kerekes [1989] found that on this basis, the PFI mill produced the same level of flexibilization of fibres as bending individual fibres cyclically through an amplitude of approximately 2% of the fibre span. This case therefore represents an upper limit of a large number of low intensity impacts. To represent it, equations [4.28] and [4.31] are combined to yield the C-factor for the PFI mill.

$$C = 2.5\ N_r M / t \text{ (kg/s)} \qquad [4.32]$$

The flow rate is represented by the mass charge of fibres, M, and t, the time of refining. Rather than time, the number of PFI roll revolutions is normally used to measure the duration of refining. Substituting the rotational speed of the roll (1440 r/min.) and expressing the mass in terms of fibre length, ℓ, and coarseness, w, yields an expression for the C-factor based on an individual fibre.

$$C = 1.44 / \ell w \text{ (s-1)} \qquad [4.33]$$

Similarly the intensity of impacts in the PFI mill can be calculated as:

$$I = P / C = P \ell w / 1.44 \text{ (J/impact-fibre)} \qquad [4.34]$$

4.3.3 Small Working Zone

The observations of McKenzie and Prosser [1981] through a transparent port in the bedplate of a PFI mill showed that some fibres are trapped between the roll bar tips and the bedplate. They concluded that most of the refining takes place in this region, although they acknowledged that some refining action can also occur outside this zone. In their work, the action of approximately three bars could be clearly seen at one time.

The above refining conditions can be approximated by a stator having one bar and the rotor as a refining zone extending over an arc of three bars. Based on this picture, use may be made of the basic equation for the C-factor derivation (equation [10] in Kerekes 1990) modified appropriately for this case.

$$\frac{dn}{dt} = \frac{\ell^2 n_1 n_2 \omega}{2\pi r(\ell + D + T)} \qquad [4.35]$$

We assume the working zone on the perimeter of the refiner ($2\pi r$) to be the arc of three bars, yielding 0.0571 m (note: there are 33 bars on the roll in total, and the diameter of the roll is 0.2 m). The factor, $\ell / (\ell + D+T)$, is a probability factor that a fibre will be impacted when in the working zone. D and T represent the depth of the groove and gap as per the original notation [Kerekes 1990]. In the PFI mill use was made of the depth of the pulp pad in place of D+T. This was calculated to be 6.1 mm [Tam Doo and Kerekes 1989].

Lastly the number of bars in the roll n_1, and the bedplate n_2, was set as 33 and 1. For the rotational speed, the relative rotational speed between the roll and bedplate was used. Thus:

$$N = 0.289 N_r \left[\frac{\ell^2}{\ell + 6.1} \right] \qquad [4.36]$$

The intensity per impact received per fibre is then calculated as:

$$I = 6 \times 10^{-6} [\ell + 6.1)\ wP] / \ell \quad \text{(J/impact-fibre)} \qquad [4.37]$$

If this case is assumed to represent a small working zone, it characterizes the other limit to Case 1. Without more precise knowledge of this device, the action of the PFI mill is defined as falling within these bounds.

4.3.4 Experimental Tests and Results

To test the above characterizations, a series of trials was conducted on a standard PFI mill and an Escher Wyss refiner. Separate Escher Wyss runs were made at a normal specific edge load (3.0 Ws/m) and at a very low SEL (0.5 Ws/m). The latter case was an attempt to approach the operating conditions of the PFI mill. A commercial blend of spruce and pine bleached kraft was used for all tests. Handsheets were made and tested according to standard CPPA procedures.

For this work power to the PFI was measured using a Dranetz wattmeter with a computer interface to give power as a function of time. The no-load power of refining was obtained by running the mill with the rotor backed off both before and after each refining run. The measured power input was in the range 0.6 to 0.7 joules per gram-revolution. This range compares favourably with previously reported work as shown in Table 4.2.

Table 4.2: Energy consumption in PFI refining

Reference	Pulp Type	Energy use (J/gram-revolution)
McKenzie 1980	eucalypt kraft pine kraft	0.55 0.80
Phillips, Bain and Watson 1970	unbleached eucalypt kraft #1 kraft #2	0.66 0.55
Hatton 1992	unbleached softwood kraft	0.72
Current work	bleached softwood kraft unbleached softwood kraft	0.59-0.68 0.69-0.72
Polan 1993	bleached softwood kraft	0.61-0.64

For the pulp in this study, the mean weight-averaged fibre length, ℓ, was 2.73 mm at 1000 PFI revolutions. The fibre coarseness, w, was 0.157 mg/m. Substituting these values into the above equations yields N and I values shown in Table 4.3.

Table 4.3: C-factor results for PFI mill

	Case 1 Large working zone	Case 2 Small working zone
Intensity of impact	1×10^{-7} J/impact-fibre	1×10^{-6} J/impact-fibre
Number of impacts after 1000 revolutions	2500 impacts per fibre	240 impacts per fibre

4.3.5 Discussion

Before comparing the above values with those of other refiners, it is useful to compare them with theoretical values estimated from pulp network strength, fibre rupture strength, and low amplitude flexing. For I, pulp network strength yields a useful lower limit since, in a PFI mill, the pulp network itself may play an important role in supplying the restraining force on fibres in the absence of stator bar edges. Without a restraining force, the action of the roll would simply accelerate the fibres rather than strain them. An estimate of the energy required to rupture a fibre network at the pulp concentration in the PFI mill is approximately 10^{-8} J/impact-fibre as shown in Table 4.4. With this in mind, the slight decrease in total refining power with time observed during the experimental work may be due to the decreasing network strength from increased fibre flexibilization as the pulp mass is beaten.

Table 4.4: Number and intensity of refining impacts [Kerekes et al. 1993]

	N Number of impacts per fibre	I Intensity of impact (J/impact-fibre)
MINIMUM Rupture of a 10% consistency fibre network	1	1×10^{-8}
MAXIMUM Fibre rupture	1	1×10^{-5}
PFI mill (per 1000 roll rev.) Case 1--Large working zone Case 2--Small working zone	 2500 240	 1.0×10^{-7} 1.1×10^{-6}
Low amplitude flexing of a single fibre	50,000	6.0×10^{-12}

Fibre rupture strength represents an upper limit of the intensity of impact on fibres. If I exceeds this value, the mechanical action would break fibres rather than develop their surface area. As shown above, fibre rupture occurs at approximately 10^{-5} J/impact -fibre. Table 4.4 also shows that small amplitude flexing of a single fibre is estimated at 6×10^{-12} J/impact-fibre [Kerekes et al. 1993].

The measured value of I for a PFI mill in the present work falls within 10^{-7} and 10^{-6} J/impact-fibre. This range is between the network rupture and fibre rupture values of 10^{-8} and 10^{-5} J/impact-fibre, suggesting that the fibre network is ruptured. Earlier work [Tam Doo and Kerekes 1989] showed that for equal N, the PFI mill yielded fibres of the same flexibility as single fibre flexing. In my work the levels of I are much greater than the intensity used in the original work suggesting that a substantial portion of the energy in a PFI mill is not used to make the fibres more flexible.

Having established the order of magnitude of N and I in the PFI mill, they can now be compared with values of these variables in mill scale refining. Estimates using the C-factor are shown in Table 4.5 for both disc and conical refiners [Kerekes 1990]. The calculation for the commercial disc refiner is based on the refiner dimensions for softwood pulp from Kerekes et al. [1993].

Table 4.5: Refiner characteristics

	C-factor (s^{-1})	N (impacts per fibre)	I (J/impact-fibre)
PFI			
Case 1	3.4×10^{9}	2500 per 1000 rev	1×10^{-7}
Case 2	3.3×10^{8}	240 per 1000 rev	1×10^{-6}
Escher Wyss			
3.0 Ws/m	2.1×10^{8}	31	6×10^{-6}
0.5 Ws/m	2.1×10^{8}	206	1×10^{-6}
Mill disc refiner	3.3×10^{10}	14	7×10^{-6}

The original objective was to increase the gap in the Escher Wyss refiner until refining was at the same low intensity as the PFI mill. This was achieved at 0.5 Ws/m (SEL) of the Escher Wyss for Case 2 of the PFI. For Case 1, the energy per impact for the low SEL of the EW refiner was an order of magnitude greater. At the higher SEL (3.0 Ws/m) the Escher Wyss had a refining intensity 60 times greater than the PFI mill for Case 1 and six times greater when compared to Case 2. Earlier work has shown

that the intensity level at 3.0 Ws/m in the EW refiner corresponds to some mill disc refiners [Kerekes et al. 1993]. Thus, depending on the model of PFI chosen, the PFI mill imposes impacts between 6 and 60 times milder than those of the particular mill refiner used in Kerekes' 1993 study.

This work yields another important observation: the PFI mill refines at a high specific energy. This is shown in Figure 4.3. At comparable specific energies, the PFI produces less strength development than the Escher Wyss refiner. This suggests that the PFI is not energy efficient. The higher I and lower N in the EW and commercial refiner develop superior sheet properties for a given specific energy. This helps explain some of the differences observed when comparing PFI mill results to those of commercial scale refiners.

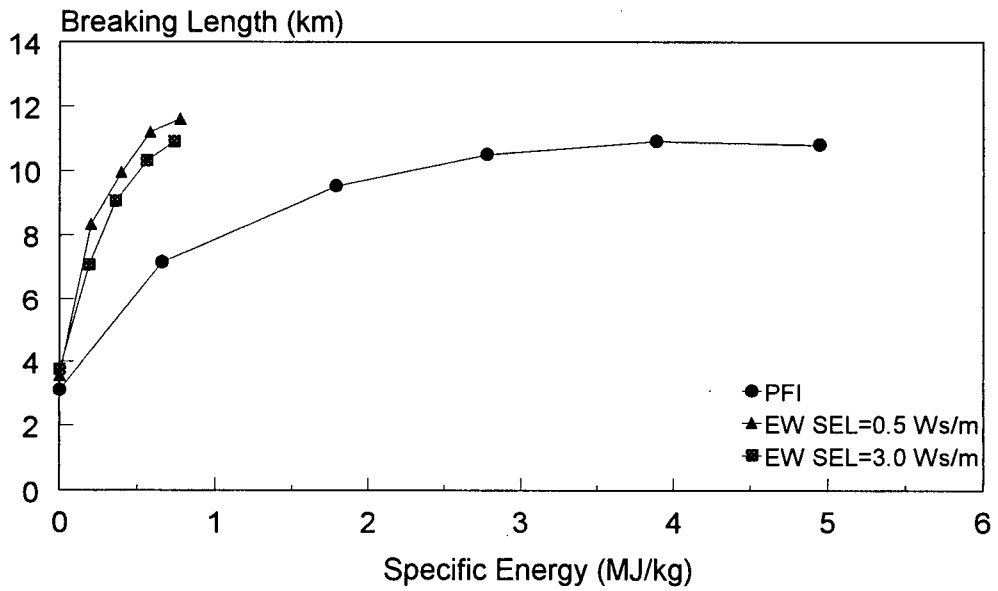


Figure 4.3: Breaking length development with energy input

It is also interesting to note that fibre cutting occurs only at the high SEL with the Escher Wyss. This is not surprising since an SEL of 3.0 Ws/m corresponds to I = 6.6 x 10^{-6} J impact-fibre, which approaches the energy of fibre rupture as shown in Table 4.4.

Changes in breaking length with increasing N for both the EW refiner and the PFI mill are shown in Figure 4.4. These data illustrate the rapid development of breaking length for the Escher Wyss, especially at a SEL of 3.0 Ws/m, in comparison to

slower development with the PFI. Similar data were obtained for burst strength development.

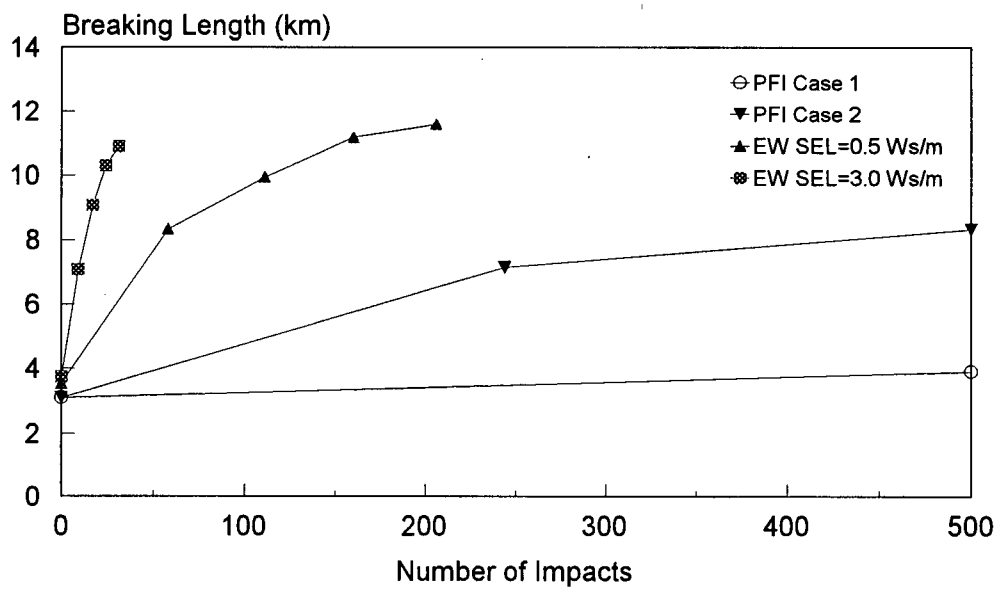


Figure 4.4: Breaking length development with the number of refining impacts

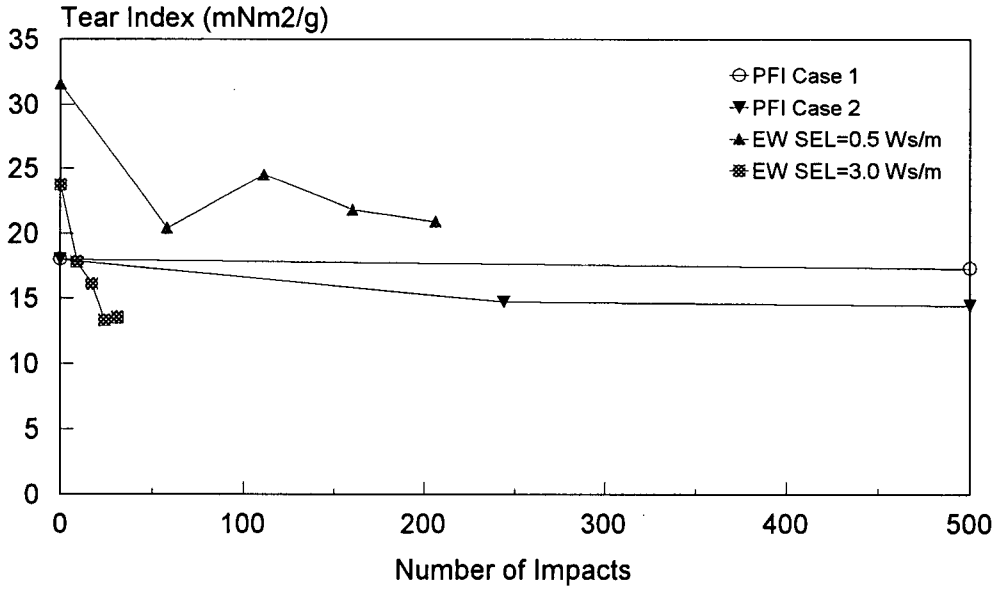


Figure 4.5: Tear index development with the number of refining impacts

Figure 4.5 shows the effect of refining on tearing resistance. The first observation here is that a sizable increase in tear was obtained at N = 0 in the EW refiner. This comes from pre-circulation of the pulp through the refiner to obtain the no-

load power level prior to applying the load. In this case the plates were fully backed off.

Figure 4.5 shows that at N = 500 impacts, the PFI reduces the tear to a value lower than obtained at N = 206 impacts for the Escher Wyss refiner at an SEL of 0.5 Ws/m (for both Case 1 and Case 2). In contrast, the Escher Wyss at SEL = 3.0 Ws/m and N = 31 impacts reduced tear to approximately the level of N = 500 impacts in Case 2 for the PFI mill.

From Figure 4.3 it can be seen that approximately the same tensile strength is produced after full refining in the PFI and the EW at SEL = 3.0 Ws/m, even though the N and I are vastly different (Case 2 for PFI N = 2200, I = 10×10^{-6} J/impact; EW N = 31, I = 6×10^{-6} J/impact). In contrast, at the same N (N = 200) Figures 4.4 and 4.5 show that the PFI produces substantially lower tensile strength and a somewhat lower tear when compared to the EW at SEL = 0.5 Ws/m. This finding is in direct contrast to earlier work which compared the EW to mill refiners [Kerekes et al, 1993]. They found that at equal N and I, the resultant sheet properties were equal regardless of the refiner used. This suggests that even at similar N and I there is a substantial difference in the refining action of a PFI mill compared with disc or conical refiner. While part of the difference may result from the difficulty in estimating N and I in the PFI mill, the more probable conclusion is that the refining action in a PFI mill is significantly different.

4.3.6 Conclusions

The number and intensity of impacts on fibres in a PFI mill have been estimated to permit quantitative comparisons to conical and disc refiners. The value of I found for the PFI mill falls within a range expected from previous studies, suggesting that the estimates are sound. Thus, for the first time, it is possible to quantify the action of a PFI mill in a manner that allows comparison with other refiners.

For the conditions tested, the PFI mill imposes a far greater number of impacts than do refiners. For example, during 5000 revolutions, the PFI mill imposes between 40 (Case 2) and 400 (Case 1) times the number of impacts of a conical or disc refiner operating at standard specific edge load. However, the intensity of the impacts is only about 1.5 (Case 1) to 15% (Case 2) of those imposed in a disc or conical refiner operating at a specific edge load of 3.0 Ws/m. The energy expenditure of the PFI mill is significantly larger than for a typical disc refiner.

The principal conclusion to be drawn from this work is that the PFI mill is dissimilar in several fundamental respects from disc or conical refiners, apart from the obvious dissimilarity in geometry and operation. It uses more specific energy, imparts far more impacts on fibres, and the impacts are of lower intensity. Lastly, even if all of these are were to be equivalent to commercial refiners, its refining action produces significantly lower tensile strength and therefore is different from commercial refiners.

4.4 VALIDATION OF C-FACTOR THEORY

The C-factor theory predicts the average number of impacts per fibre as pulp passes through a low consistency refiner [Kerekes 1990]. In order to test this theory, dyed nylon fibres were added to bleached kraft pulp and fed to a pilot plant disc refiner at known N and I as calculated by C-factor theory. This was similar to, but more extensive than, the work done by Dharni [1990]. After refining, the nylon fibres were collected and mounted on microscope slides. This was done with great care in order to minimize the changes resulting from handling the fibres. The number of kinks was then counted. If a fibre had more than one kink, each kink was included in the total. To form a true base of comparison, unrefined nylon fibres were also examined to determine the base level of deformation. The difference in the number of kinks was compared with the calculated number of impacts during refining. Examples of nylon fibres are shown in Figure 4.6.

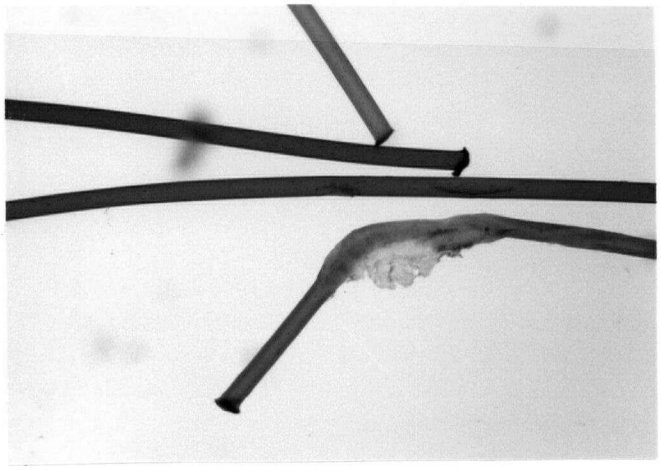


Figure 4.6: Micrograph of refined nylon fibres (x100)

Four trials were conducted. In 100 fibres, the base or unrefined nylon had seven kinks smaller than 10 degrees, seven larger kinks, four curled fibres and one

unraveled fibre. The only run that produced a statistically significant different number of fibre deformations from the base nylon fibres had twelve small kinks, five large kinks, four curled fibres and three unraveled fibres. Counting all fibre deformations, one can conclude, with an 80% confidence level, that the nylon fibres were deformed during refining. Refining variables for this run are shown in Table 4.6. One hundred fibres were examined. If every possible fibre impact calculated by C-factor theory was recorded by a change in shape to nylon fibres, the change in the number of fibre deformations should be 140, not five as shown in Table 4.6 (calculated as outlined in section 4.1.2).

Table 4.6: Results from synthetic fibre validation of N and I

Variable	Calculated value from C-Factor theory
N	1.4
I	3.2 E -5 J/impact
Δ deformations in 100 fibres compared to base pulp	5

The resulting observable changes to fibre shape were lower than calculated. One of the reasons for the low number of countable impacts is that the nylon fibres are robust and may not permanently change shape every time they are hit. Impact intensity is beyond that of wood fibre rupture which is estimated as 1×10^{-5} J/impact. As this was the only run to show any difference in the number of kinks in nylon fibres this suggests that nylon is more difficult to kink than wood fibres. In addition, impact intensity may cover a range of values with only the strongest impacts leaving a mark.

Kink information is part of a FTFA analysis. For the FTFA data from this thesis, in almost every case of mechanical pulp secondary refining the number of kinks dropped. For kraft pulp, kinks tripled with LC refining. The calculated number of impacts was an order of magnitude higher than number of kinks introduced. These findings for the synthetic fibres suggest that there must be a threshold impact intensity needed to create a kink.

CHAPTER 5
EXPERIMENTAL RESULTS AND DISCUSSION

Groups of pulp were produced from the same chip source as explained in section 3.1. The first pulp group tested was CTMP.

5.1 CTMP

Base CTMP pulp was divided into a number of identical samples. One sample was refined at high consistency (HC) as per normal industrial practice. As shown in Figure 5.1, two other samples were separately refined at low consistency (LC), one at a refining intensity of 24 x 10^{-6} Joules/impact-fibre or 3.0 Ws/m and the other at a lower intensity, 7.7 x 10^{-6} J/impact-fibre (1.0 Ws/m). Each of these three refining runs, one in the HC refiner and two in the LC refiner, generated a number of test pulps as sampling points occur at several energy inputs in each run.

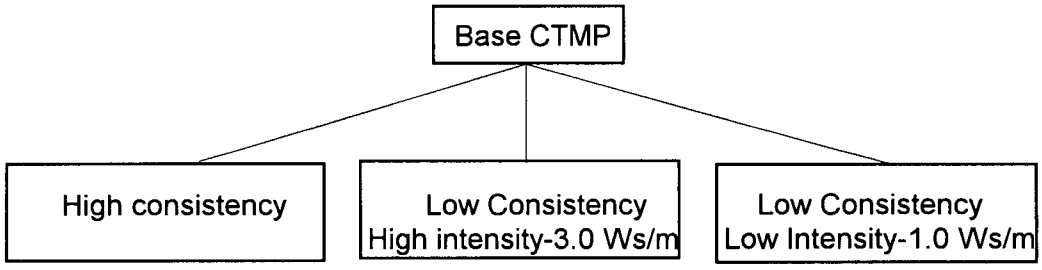


Figure 5.1: Simplified CTMP experimental program

In addition to the three main refining runs, three more refining runs were completed as shown in Figure 5.2. Firstly, low-intensity LC refining was repeated to obtain a higher energy input sample. Secondly, a high-intensity LC run was carried out without the normal latency removal process. Finally, CTMP was refined in the PFI mill to study the effects of midrange refining intensity and the number of impacts as per section 4.3. For clarity, the pulps are labeled using a descriptive prefix and incremental energy input (e.g. HC for high consistency, Low for low-intensity LC refining and High for high-intensity LC refining). Complete results of CTMP testing are shown in Table 5.1. In all tables, non-significant differences are shown by the same alphabetical subscript as determined by the Duncan multiple-range test [Walpole 1982]. Thus if two numbers are not statistically different in value, they are assigned the same letter.

Midrange values are sometimes given two or more alphabetical subscripts to show that they are not significantly different from both a lower and higher value, yet the latter two values differ significantly. The alphabetical subscripts are kept the same for CTMP and TMP throughout the discussion as first seen in Tables 5.1 and Table 5.10.

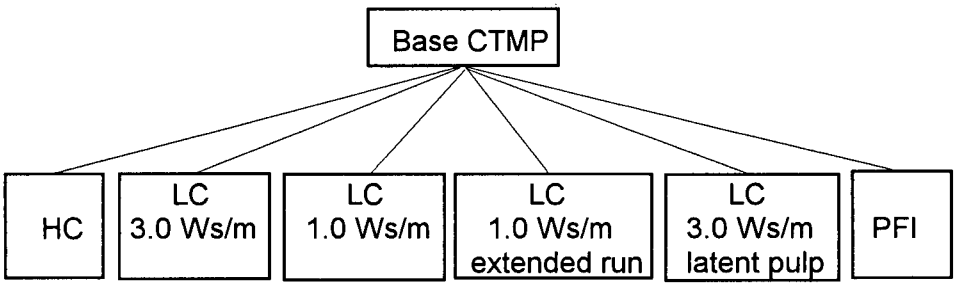


Figure 5.2: Complete CTMP experimental program

From the literature review it was anticipated, but not certain, that lower refining intensities would result in stronger pulps. This proved to be the case. In keeping with the thesis objectives of maximizing refining results, section 5.1.1 focuses on the comparison of low-intensity LC-refined CTMP to that of HC-refined CTMP. To keep the tables and graphs as readable as possible, only these two pulp groups are shown in the tables and graphs of section 5.1.1. Other CTMP pulps are discussed in section 5.1.2.

Table 5.1: Complete experimental results for CTMP pulps (page 1 of 2)

	HC Refining				Extended LC refining			
	Base #1	HC520	HC880	HC1560	Base #2	Low100	Low200	Low310
Refining Variables								
Sec. Energy (kWh/t)	0	520	880	1560	0	100	200	310
No. Impacts (fibre-1)	0	4940	8550	14,500	0	38	77	116
Impact Itensity (J 10^{-6})	0	0.33	0.34	0.35	0	8.0	7.1	8.1
Handsheet Test Results								
Breaking Length (km)	4.24_a	5.04_b	5.40_c	5.71_d	3.49_e	4.33_a	4.39_a	4.35_a
Tear (mNm^2/g)	9.8_a	10.9_b	8.6_c	8.4_c	10.9_b	9.0_{ac}	8.4_c	8.2_c
Bulk (cc/g)	3.39_a	2.74_b	2.70_b	2.60_c	3.41_a	2.80_d	2.78_{bd}	2.64_c
Zero Span (km)	11.3_a	11.4_a	12.2_b	12.6_b	10.7_c	11.1_{ac}	11.5_a	10.8_c
Scat. Coef. (cm^2/g)	51.4_a	49.4_b	50.4_c	54.2_d	48.7_e	47.2_f	45.8_g	46.7_h
T.E.A. Index (mJ/g)	469_a	634_b	631_b	712_c	316_d	437_a	457_a	440_a
Tensile Index (Nm/g)	41.6_a	49.5_b	52.9_c	56.1_d	34.2_e	42.4_a	43.1_{ae}	42.6_a
Burst Index (kPa m^2/g)	-	-	-	-	2.52_a	2.54_a	2.61_a	2.81_b
Brightness	56.8_a	56.1_b	55.9_b	54.9_c	58.7_d	57.1_e	57.0_{ae}	59.1_d
Opacity % (ISO)	93.6_a	93.7_a	93.3_a	94.5_b	91.6_c	92.1_{cd}	91.4_c	91.3_c
Fracture Tough. (Jm/kg)	14.2_a	-	18.9_b	-	14.4_a	-	-	14.6_a
Fibre Properties								
Fibre Length (NA mm)	0.82_a	0.82_a	0.77_b	0.73_c	0.82_a	0.70_d	0.71_{cd}	0.73_c
Fibre Length (LWA mm)	2.08_a	2.11_a	2.01_b	1.95_c	2.09_a	1.84_d	1.80_e	1.83_{de}
Fibre Length (WWA mm)	2.84_a	2.88_a	2.76_b	2.72_b	2.81_a	2.60_c	2.50_d	2.54_{cd}
Flexibility ($1/Nm^2 x 10^{10}$)	1.5_a	-	-	2.3_b	-	-	-	-
Curl Index (LF)	-	0.051_a	0.052_a	0.053_a	0.061_b	-	-	0.055_a
Kink Index (LF)	-	0.43_a	0.45_a	0.49_a	0.75_b	-	-	0.50_{ac}
Coarseness(mg/m)	0.367_a	0.250_b	0.280_c	0.264_{bc}	-	-	-	-
Pulp Properties								
Screen Rejects (%)	0.28	0.02	0	0	0.21	0.11	0.08	0.04
Screened CSF (ml)	341_a	247_b	181_c	107_d	-	292_e	267_f	236_g
Sommerville Shives (%)	0.36_a	0.13_b	0.07_c	0_d	-	0.16_e	0.13_b	0.11_b
Bauer McNett R14 (g)			2.43		2.57			1.08
R28 (g)			2.97		3.02			3.11
R48 (g)			1.73		1.66			2.14
R100 (g)			0.71		0.68			0.89
R200 (g)			0.32		0.27			0.36
P200 (g)			1.84		1.8			2.42
Sulphonation (mg/kg)	1584	-	-	1510	-	-	-	-
Lignin Content (%)	27.2_a	-	-	27.1_a	-	-	-	-
Lignin fines free (%)	24.7_a	-	-	24.3_b	-	-	-	-

Table 5.1: Complete experimental results for CTMP pulps (continued)

	Low Consistency Refining						
	Low110	Low200	High100	High200	Lat100	Lat210	PFI
Refining Variables							
Sec. Energy (kWh/t)	110	200	100	200	100	210	1330
No. Impacts (fibre-1)	41	81	14	27	14	28	1560
Total Energy (kWh/t)	2360	2450	2350	2450	2350	2460	3580
Impact Itensity (J 10^{-6})	9.1	7.5	23.9	24.6	23.6	24.6	3.26
Handsheet Test Results							
Breaking Length (km)	4.96_{b}	5.23_{c}	4.41_{a}	4.34_{a}	4.23_{a}	4.16_{a}	4.87_{b}
Tear (mNm^2/g)	5.7_{d}	5.6_{d}	3.2_{e}	5.2_{d}	7.8_{c}	7.6_{c}	5.1_{d}
Bulk (cc/g)	2.61_{c}	2.28_{e}	2.65_{c}	2.41_{f}	2.73_{b}	2.42_{f}	2.89_{g}
Zero Span (km)	11.4_{a}	11.8_{ab}	11.5_{a}	12.3_{b}	11.4_{a}	11.8_{ab}	11.9_{ab}
Scat. Coef. (cm^2/g)	47.1_{f}	48.5_{e}	45.6_{g}	49.1_{b}	50.2_{c}	51.5_{a}	46.2_{h}
T.E.A. Index (mJ/g)	497_{a}	504_{a}	446_{a}	336_{d}	434_{a}	329_{d}	552_{ab}
Stretch (%)	1.55_{c}	1.50_{c}	1.56_{c}	1.24_{d}	1.57_{c}	1.26_{d}	1.75_{a}
Tensile Index (Nm/g)	48.7_{b}	51.3_{c}	43.3_{ae}	42.6_{a}	41.5_{a}	40.7_{a}	47.8_{b}
Burst Index (kPa m^2/g)	-	-	-	-	-	-	-
Brightness	57.6_{f}	58.5_{d}	56.4_{a}	55.8_{b}	57.7_{f}	57.8_{f}	$57.0a_{e}$
Opacity % (ISO)	91.6_{c}	91.2_{c}	91.8_{cd}	93.8_{ab}	92.6_{d}	93.1_{a}	91.3_{c}
Fracture Tough. (Jm/kg)	-	-	-	-	-	9.7_{c}	15.1_{d}
Fibre Properties							
Fibre Length (NA mm)	0.61_{e}	0.50_{f}	0.58_{g}	0.48_{f}	0.59_{eg}	0.48_{f}	0.77_{b}
Fibre Length (LWA mm)	1.47_{f}	1.10_{g}	1.36_{h}	1.01_{i}	1.37_{h}	1.01_{i}	1.90_{j}
Fibre Length (WWA mm)	2.12_{e}	1.56_{f}	1.97_{g}	1.44_{h}	1.96_{g}	1.42_{h}	2.64_{c}
Flexibility ($1/Nm^2x10^{10}$)	-	1.4_{a}	-	1.7_{a}	-	1.3_{a}	-
Curl Index (LF)	0.059_{b}	0.062_{bc}	0.059_{b}	0.062_{bc}	0.064_{c}	0.063_{c}	0.055_{a}
Kink Index (LF)	0.55_{c}	0.57_{cd}	0.62_{d}	0.51_{ac}	0.60_{cd}	0.60_{cd}	0.53_{c}
Coarseness(mg/m)	0.288_{cd}	0.305_{d}	0.271_{c}	0.277_{c}	0.284_{c}	0.284_{c}	0.290_{cd}
Pulp Properties							
Screen Rejects (%)	0.02	0.02	0.04	0.03	0.08	0.03	0.08
Screened CSF (ml)	167_{h}	102_{i}	188_{c}	120_{j}	192_{k}	116_{j}	277_{f}
Sommerville Shives (%)	0.12_{b}	0.03_{f}	0.15_{e}	0.09_{c}	0.13_{b}	0.08_{c}	0.20_{g}
Bauer McNett R14 (g)							
R28 (g)							
R48 (g)							
R100 (g)							
R200 (g)							
P200 (g)							
Sulphonation (mg/kg)	-	-	-	1585	-	-	-
Lignin Content (%)	-	-	-	27.7_{b}		27.4_{c}	-
Lignin fines free (%)	-	-	-	24.5_{ab}	-	24.4_{b}	-

5.1.1 Key CTMP Pulps

Table 5.2 shows key properties for HC refined CTMP and low-intensity LC refined CTMP. In the following analysis, the optimum pulp from each type of secondary refining is discussed. As the results for HC880 and HC1560 are close, HC880 is used in comparisons of energy use as it has the lower energy input. The breaking length of HC1560, however, is higher and will be used in the discussion of this property. Low200 is the optimum LC refined CTMP. Note that the breaking length values for the first low-intensity LC refining run are shown for Low100 and Low200 as they were not exposed to the aging effects discussed in section 3.5. For all other paper properties, the values from the extended LC run are shown unless otherwise stated.

Table 5.2: Properties of key CTMP pulps

CTMP Pulp	Base CTMP	HC520	HC880	HC1560	Low100	Low200	Low310
Incremental Energy (kWh/t)	0	520	880	1560	100	200	310
Total Energy (kWh/t)	2250	2770	3130	3810	2350	2450	2560
Breaking Length (km)	4.2_a	5.0_b	5.4_c	5.7_d	5.0_b[1]	5.2_c[1]	4.4_a
Tear Index (mNm^2/g)	9.8_a	10.9_b	8.6_c	8.4_c	9.0_{ac}	8.4_c	8.2_c
Bulk (cm^3/g)	3.39_a	2.74_b	2.70_b	2.60_c	2.80_d	2.78_{bd}	2.64_c
No. of Impacts ($fibre^{-1}$)	0	4900	8600	14,500	40	80	120
Intensity of Impact ($Jx10^{-6}$)	0	0.33	0.34	0.35	8.0	7.1	8.1

As seen in Table 5.2 and Figure 5.3, with HC refining there is a consistent trend of increased breaking length with increased energy input. In the case of LC refining, breaking length increases with increased energy input up to a given value, which coincidentally corresponds to the breaking length of HC880, and then decreases from

[1] see note in first paragraph above

the maximum at Low200. Within LC refined pulps, there is no noticeable change to either zero span or average fibre length to explain this phenomenon. Both are significantly lower than HC880 and HC1560 as shown in Table 5.3. Zero span continues to increase with HC refining. Zero span is lower for Low310, as is breaking length. As discussed in Chapter 2, zero span of mechanical pulps is not an absolute reading of individual fibre strength. It is, however, a measurement of tensile strength at the lowest achievable gap.

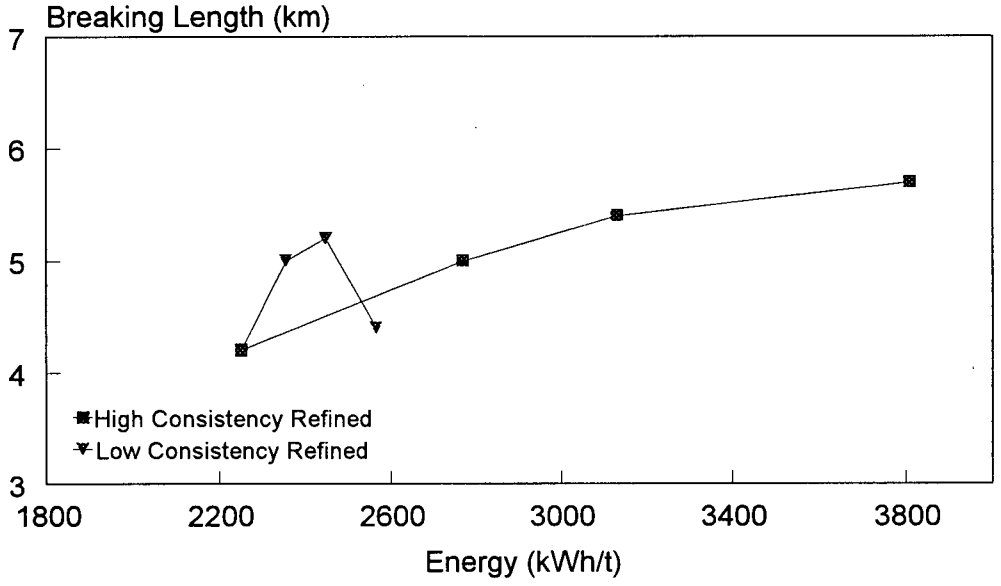


Figure 5.3: CTMP breaking length development with energy input

Table 5.3: Breaking length factors for key CTMP pulps

CTMP Pulp	Base CTMP	HC520	HC880	HC1560	Low100	Low200	Low310
Breaking length (km)	4.2_a	5.0_b	5.4_c	5.7_d	5.0_b	5.2_c	4.4_a
Zero span (km)	11.3_a	11.4_a	12.2_b	12.6_b	11.1_{ac}	11.5_a	10.8_c
LWA fibre length (mm)	2.08_a	2.11_a	2.01_b	1.95_c	1.84_d	1.80_e	1.83_{de}

Subtle changes in fibre size distribution are seen in the normalized fibre length distribution charts, Figures 5.4 and 5.5. Figure 5.4 shows that the decrease in the number of long fibres, 2 to 4 mm in length, is most rapid with LC refining. Figure 5.5

illustrates the corresponding increase in the number of short fibres and birefringent particles, 0.2 to 1.0 mm in length, with LC refining. This is consistent with changes in the Bauer McNett fractions, Figure 5.6, where there is a large drop in the R14 fraction and an increase in shorter pulp fractions for Low200.

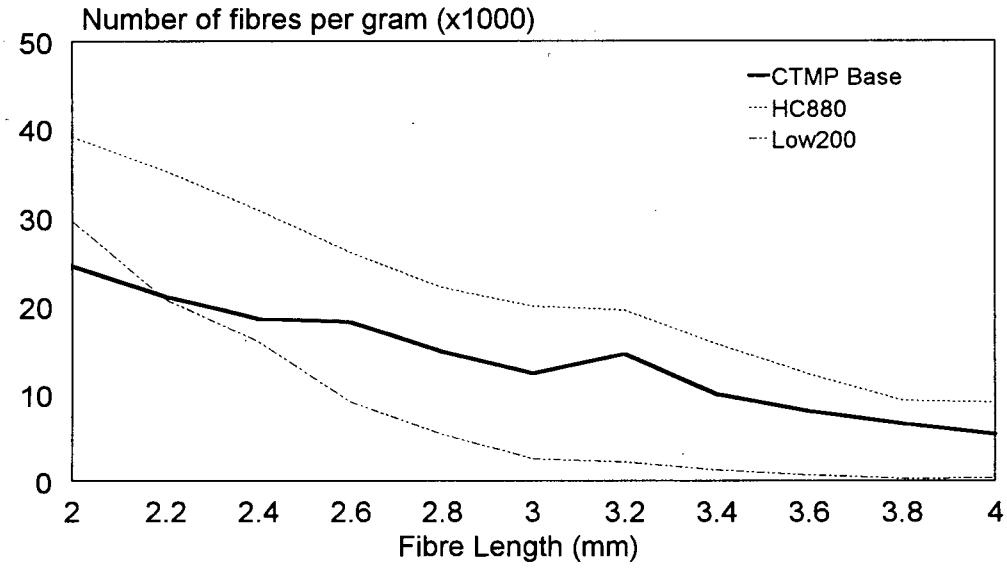


Figure 5.4: CTMP normalized long fibre distribution

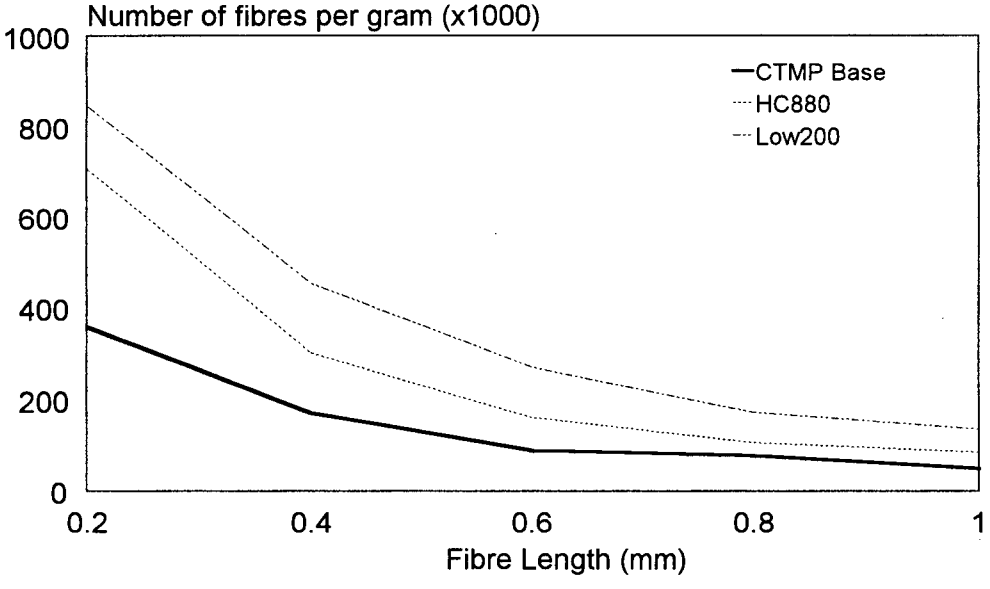


Figure 5.5: CTMP normalized fine fibre distribution

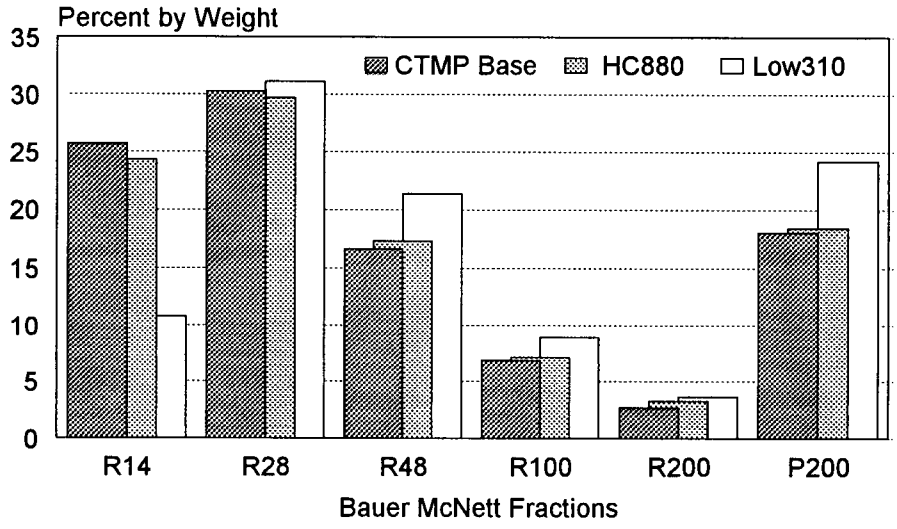


Figure 5.6: CTMP Bauer McNett fractions

Even with this decrease in long fibre, LC refining increases breaking length of CTMP up to a given energy input. Other factors, such as increased bonding seen in the lower bulk, counteract the effect of lower average fibre length to maintain this high breaking length.

Table 5.4 shows the microscopic changes to CTMP pulps with refining. Alphabetic subscripts indicate if the change is proportionally different from that of Base CTMP [Walpole and Myers 1978]. These data were obtained by systematically examining slides of the R14 fractions of each pulp. Where a fibre had multiple

Table 5.4: CTMP microscopy results

Fibre Data	Base	HC1560	Low200
Number of fibres tested	200	200	200
Number of fibres with an unraveled end	12_a	42_b	18_a
Pulled back to a point	0_a	7_b	1_a
Large fibre segments pulled back	15_a	31_b	37_b
Sleeve condition	6_a	21_b	6_a
Large kink	2_a	1_a	6_a
Percent fibres showing damage of any kind (%)	19_a	53_b	35_c

conditions, each anomaly was counted. Examples of these changes are shown in Figure 5.7

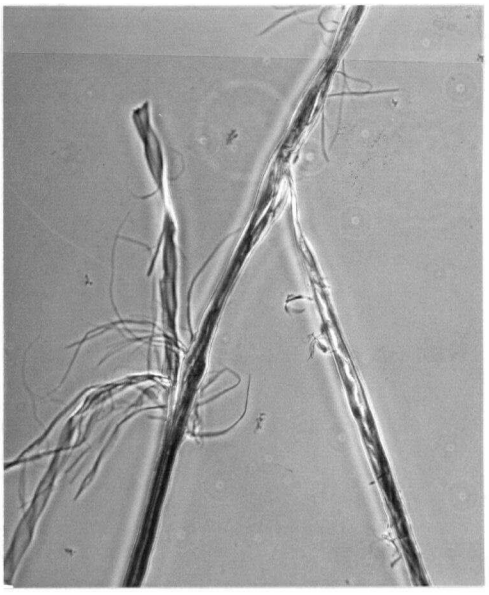


Figure 5.7: Examples of fibre damage (x100)
a. Unraveled end b. Pulled back to a point

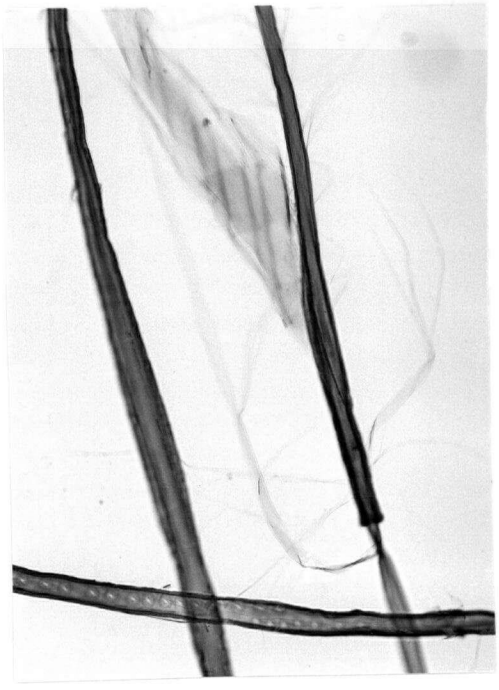


Figure 5.7: Examples of fibre damage (x100)
c. Large fibre segments pulled back d. Sleeve condition

As shown in Table 5.5, reductions in kink index and curl index are greatest for the HC refined CTMP pulps and Low310. Straightening of the fibres adds to tensile strength. The reduction of shives also increases breaking length.

Table 5.5: Curl, kink and shives of key CTMP pulps

CTMP Pulp	Base CTMP	HC520	HC880	HC1560	Low100	Low200	Low310
Breaking length (km)	4.2_a	5.0_b	5.4_c	5.7_d	5.0_b	5.2_c	4.4_a
Curl Index	0.061_b	0.051_a	0.052_a	0.053_a	0.059_b[1]	0.062_{bc}[1]	0.055_a
Kink Index	0.75_b	0.43_a	0.45_a	0.49_a	0.55_c[1]	0.57_c[1]	0.50_{ac}
Sommerville Shives (%)	0.36_a	0.13_b	0.07_c	0_d	0.16_e	0.13_b	0.11_b

Another factor influencing breaking length is fibre flexibility. Most CTMP fibre flexibility mean results are close to one another with wide standard deviations in data for all refining methods. Because of this, of the pulps tested, only HC1560 showed a significant increase in fibre flexibility. Lack of changes to flexibility may, in part, be due to the testing method, as discussed in section 3.3.2.

CTMP data for tear index, as well as average fibre length and zero span, are shown in Table 5.6 and Figure 5.8. Both of the key CTMP pulps, HC880 and Low200 show a similar decrease in tear index from Base CTMP even though Low200 has a lower average fibre length and zero span.

Table 5.6: Tear index factors for key CTMP pulps

CTMP Pulp	Base CTMP	HC520	HC880	HC1560	Low100	Low200	Low310
Tear Index (mNm^2/g)	9.8_a	10.9_b	8.6_c	8.4_c	9.0_{ac}	8.4_c	8.2_c
Zero span (km)	11.3_a	11.4_a	12.2_b	12.6_b	11.1_{ac}	11.5_a	10.8_c
LWA fibre length (mm)	2.08_a	2.11_a	2.01_b	1.95_c	1.84_d	1.80_e	1.83_{de}

[1] Where data for extended LC run is unavailable, those from the shorter LC run are shown.

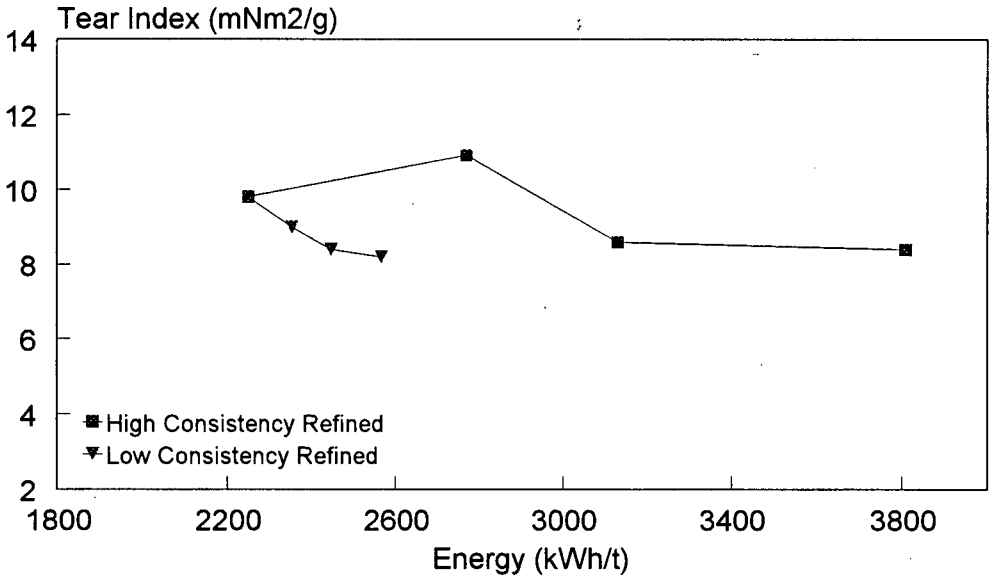


Figure 5.8: CTMP tear index development with energy input

As shown in Table 5.7, all of the CTMP pulps lose bulk with refining. Even with the different energy inputs of HC and LC refining, bulk decreases in a similar fashion due to the potential for increased relative bonded area through the creation of fines and external surface area, although these factors may contribute to different degrees in each CTMP. For example, Low200 CTMP has more fine material, as seen in Figure 5.5, and HC1560 has more discernible surface disruptions, as categorized in Table 5.4. HC1560 has the highest scattering coefficient, which is sometimes interpreted as a decrease in relative bonded area. However, the high flexibility of HC1560, the only HC CTMP sample tested for flexibility, indicates a trend in the opposite direction.

Table 5.7: Bulk and related properties of key CTMP pulps

CTMP Pulp	Base CTMP	HC520	HC880	HC1560	Low100	Low200	Low310
Bulk (cm^3/g)	3.39_a	2.74_b	2.70_b	2.60_c	2.80_d	2.78_{bd}	2.64_c
Scattering Coeff. (cm^2/g)	51.4_a	49.4_b	50.4_c	54.2_d	47.2_f	45.8_g	46.7_h
Flexibility ($1/Nm^2 x 10^{10}$)	1.5_a	-	-	2.3_b	-	1.4_a	-

In summary, HC refining of CTMP improves breaking length and bulk, although there is a drop in tear index with high energy input. High zero span, only a slight decrease in average fibre length, reduction in curl and kink, an increase in external fibrillation and a slight increase in fines quantity contribute to the high strength. Low200 has the same breaking length, tear index and bulk as HC880, even with its shorter average fibre length and higher curl and kink indices. Although the breaking length value for Low200 is not as great as that of HC1560, some increase in breaking length is achieved with LC refining and tear strength is improved at a lower energy input with a corresponding higher intensity and lower number of impacts.

5.1.2 Secondary CTMP Pulps

In addition to HC and low-intensity LC secondary refining of CTMP, Base CTMP, in both the normal delatent state and the latent state, was LC refined at high-intensity. Base CTMP was also refined in a PFI mill to study the effect of this intermediate N and I process. Figure 5.2 is shown again for clarity.

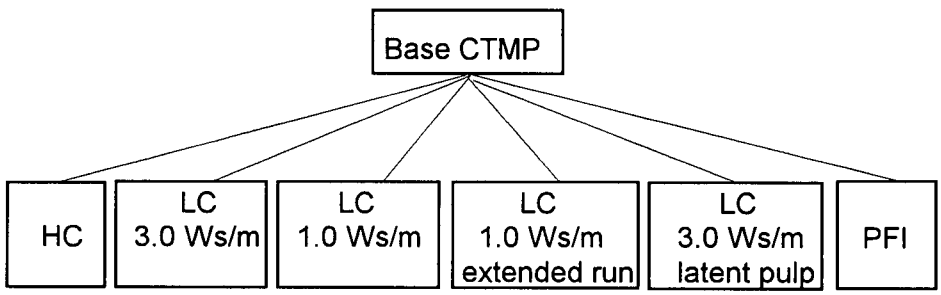


Figure 5.2: Complete CTMP experimental program

The first low consistency refining trials for mechanical pulp used a standard refining intensity of 3.0 Ws/m or 24 x 10^{-6} Joules/impact-fibre. This high LC intensity proved detrimental to the development of paper properties as shown in Table 5.1 and summarized in Table 5.8. For High100 and High200, breaking length is unchanged and tear strength is greatly reduced when compared to Base CTMP. Loss of long fibre and corresponding shorter average fibre length contribute to these changes. Twenty-four x 10^{-6} Joules/impact-fibre was too harsh on the CTMP fibres, and thus further experimental work was performed at reduced refining intensity.

The ability of LC refining to remove latency from CTMP was studied by omitting the standard hot water treatment before one LC refining run. All other parameters,

such as refining intensity and energy input, were held constant. As shown in Table 5.8, the breaking length and bulk of latent CTMP are the same as those of delatent CTMP pulp, shown as High100 and High200. At the given energy levels, average fibre lengths are identical. These results suggest that LC refining may have potential to replace part or all of the latency removal process. High refining intensities and experimental inaccuracies with the tear test negate further conclusions.

Table 5.8: Comparison of latent vs. delatent CTMP

CTMP Pulp	Base CTMP	High100	High200	Lat100	Lat210
Incremental Energy (kWh/t)	0	100	200	100	210
Breaking Length (km)	4.2_a	4.4_a	4.3_a	4.2_a	4.2_a
Tear Index (mNm^2/g)	9.8_a	3.2_e	5.2_d	7.8_c	7.6_c
Bulk (cm^3/g)	3.39_a	2.65_c	2.41_f	2.73_b	2.42_f
LWA Fibre Length (mm)	2.08_a	1.36_h	1.01_i	1.37_h	1.01_i
No. of Impacts ($fibre^{-1}$)	0	14	27	14	28
Impact Intensity ($Jx10^{-6}$)	0	24	25	24	25

CTMP pulp was processed in the PFI mill to complete the refining program. As shown in Table 5.9, PFI refining of CTMP produces an inferior pulp to HC880 and Low200 at a much greater energy cost.

Table 5.9: Results of PFI refining CTMP

CTMP Properties	Base CTMP	HC880	Low200	PFI
Incremental Energy (kWh/t)	0	880	200	1330
Breaking Length (km)	4.2_a	5.4_c	5.2_c	4.9_b
Tear Index (mNm^2/g)	9.8_a	8.6_c	8.4_c	5.1_d
Bulk (cm^3/g)	3.39_a	2.70_b	2.78_{bd}	2.89_g
LWA Fibre Length (mm)	2.08_a	2.01_b	1.80_e	1.90_j
No. of Impacts ($fibre^{-1}$)	0	8600	80	1600
Impact Intensity ($Jx10^{-6}$)	0	0.34	7.1	3.3

In summarizing CTMP pulps as a whole, Low200 had a lower breaking, equal tear strength and higher bulk compared to HC1560. Compared to HC880, however, Low200 is equal in all three key paper properties. High intensity LC refining of CTMP, both latent and delatent pulp, did not improve breaking length and lowered tear. Although the refining intensity used in making High200 is normal for chemical pulp, it is too high for refining CTMP. Even the lower refining intensity used for CTMP, 1.0 Ws/m, may be too high for this type of pulp. As a result of this finding, LC refining of TMP was performed at lower refining intensities.

For CTMP, if we look at the paper properties for the highest values in each case, it appears that HC1560 is the "best" one. However, using the best results in each case, the differences between LC and HC pulps are not large and, in both cases, greater than those shown for "typical spruce CTMP" on Table 2.6. In terms of energy input, HC1560 gained 0.0094 km per kWh/t, and Low200 gained 0.0050 km per kWh/t. HC880, the lower energy HC refined CTMP, gained 0.0013 km per kWh/t. If LC-refined CTMP can meet the required level of paper properties, there is a cost-saving potential for this mode of refining.

5.2 TMP

After the CTMP results were evaluated, it was decided to lower the LC refining intensities for the TMP program. As for CTMP, Base TMP was divided into a number of identical samples. One of these TMP samples was refined in the HC refiner. Two separate LC refining runs were performed at different refining intensities, one at 8.7×10^{-6} Joules/impact-fibre (1.0 Ws/m) and the other at 4.1×10^{-6} Joules/impact-fibre (0.6 Ws/m). The latter intensity was the lowest available at the time this work was done. LC refining was terminated at a target energy input of approximately 200 kWh/t input, the high point for breaking length development for CTMP. As with CTMP, lower-intensity refined TMP pulp produced stronger paper and is compared to HC refined TMP in section 5.2.1. Figure 5.9 shows the simplified experimental program for secondary refining of TMP. Table 5.10 shows the complete results of TMP tests. As with CTMP, a number of secondary TMP pulps were produced. These are evaluated in section 5.2.2. The TMP discussion follows, to a large extent, the same pattern as the CTMP one. However, some points are made in a different order to simplify the presentation of material.

Table 5.10: Complete experimental results for TMP

	High Consistency			Low Consistency						
	Base	HC620	HC740	Low80	Low170	High90	High190	Lat80	Lat160	PFI
Refining Variables										
Sec. Energy (kWh/t)	0	620	740	80	170	90	190	80	160	1330
No. Impacts (fibre^{-1})	-	5560	7080	61	122	26	52	58	105	1170
Impact Itensity (J 10^{-6})	-	0.33	0.30	4.1	4.2	8.7	8.8	3.9	4.4	3.03
Handsheet Test Results										
Breaking Length (km)	3.32_a	3.73_b	3.89_b	3.24_{ac}	3.52_d	3.26_{ac}	3.40_{ad}	3.32_a	3.50_d	3.15_c
Tear (mNm^2/g)	9.1_a	9.5_{ab}	10.1_b	10.4_b	10.1_b	8.3_a	6.1_c	9.6_{ab}	8.6_a	7.8_d
Bulk (cc/g)	3.11_a	3.04_b	2.96_c	3.40_d	3.24_e	2.98_c	2.55_f	3.11_a	2.86_g	2.90_g
Zero Span (km)	10.2_a	10.9_b	11.7_c	10.3_{ab}	10.3_{ab}	10.2_a	10.3_{ab}	10.2_a	10.4_{ab}	10.6_{ab}
Scat. Coef.(cm^2/g)	63.2_a	55.4_b	57.1_c	52.7_d	54.2_e	51.7_f	57.1_c	52.3_d	51.1_f	50.2_g
T.E.A. Index (mJ/g)	339_a	384_{ab}	393_{ab}	340_a	410_b	296_{ac}	289_{ac}	390_{ab}	368_{ab}	249_c
Stretch (%)	1.65_a	1.65_a	1.64_a	1.66_a	1.83_a	1.45_b	1.36_b	1.82_a	1.67_a	1.31_b
Tensile Index (Nm/g)	32.5_a	36.5_b	38.2_b	31.7_{ac}	34.5_d	32.0_{ac}	33.3_a	32.5_a	34.3_{ad}	30.9_c
Burst (kPa m^2/g)	2.24_a	2.41_b	2.61_c	2.14_{ad}	2.13_{ad}	2.01_d	1.85_e	2.03_d	2.20_a	2.03_d
Brightness	59.2_a	56.0_b	56.3_{bc}	55.3_d	56.6_c	54.7_e	56.6_c	55.6_d	55.7_d	54.5_e
Opacity % (ISO)	95.4_a	95.1_a	95.2_a	94.4_b	94.1_b	94.3_b	95.3_a	94.2_b	94.0_b	94.0_b
Frac. Tough. (Jm/kg)	12.6_a	-	15.1_b	-	13.2_c	-	8.5_d	-	13.2_c	-
Fibre Properties										
Fibre Length (NA mm)	0.63_a	0.66_{bc}	0.65_b	0.69_c	0.68_{bc}	0.60_{ad}	0.47_e	0.65_b	0.66_{bc}	0.59_d
" " (LWA mm)	1.76_a	1.92_b	1.90_b	1.95_b	1.94_b	1.63_c	1.13_d	1.86_e	1.82_e	1.51_f
" " (WWA mm)	2.56_a	2.74_b	2.71_b	2.74_b	2.72_b	2.36_c	1.67_d	2.61_a	2.60_a	2.22_e
Flex. (1/Nm^{2}x10^{10})	6.7_a	-	6.0_a	-	15_b	-	-	-	-	-
Curl Index (LF)	0.079_a	0.061_b	0.063_b	0.072_c	0.071_c	0.068_{bc}	0.062_b	0.082_a	0.070_c	0.066_b
Kink Index (LF)	1.03_a	0.70_b	0.79_{bc}	0.85_c	0.81_{bc}	0.80_{bc}	0.69_b	1.00_a	0.87_c	0.79_{bc}
Coarseness(mg/m)	0.308_a	0.306_a	0.293_a	0.339_b	0.316_{ac}	0.322_c	0.311_{ac}	0.335_b	0.310_a	0.308_a
Pulp Properties										
Screen Rejects (%)	1.16	0.90	0.60	0.75	0.68	0.54	0.45	0.98	0.67	0.87
Screened CSF (ml)	290_a	174_b	145_c	249_d	218_e	179_b	94_f	238_g	172_b	185_h
Som. Shives (%)	1.78	1.50	1.27	1.73	1.64	1.26	0.88	1.80	1.68	1.23
Bauer McNett R14 (g)	1.68±.03		1.99±.07		2.46		0.04		1.54	0.63
R28 (g)	2.79±.01		2.90±.12		3.04		2.00		3.06	3.12
R48 (g)	1.91±.03		1.64±.01		1.72		3.03		1.94	2.54
R100 (g)	1.04±.09		0.71±.01		0.71		1.61		0.86	1.10
R200 (g)	0.39±.05		0.32±.05		0.35		0.70		0.39	0.41
P200 (g)	2.20±.11		2.40±.06		1.70		2.63		2.20	2.20

5.2.1 Key TMP Pulps

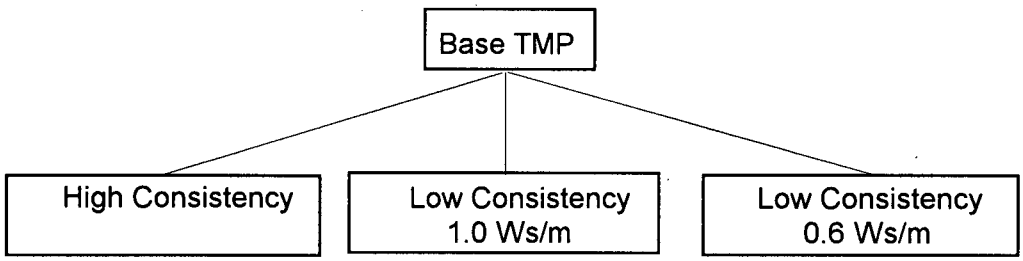


Figure 5.9: Simplified TMP experimental program

As seen in Table 5.11 HC refining of TMP increases breaking length to a greater extent than LC refining. As with CTMP, breaking length increases with increasing energy input. HC refined TMP is the only TMP pulp to show an increase in zero span over that of Base TMP. Length weighted average fibre length increases for both LC and HC refined TMPs as discussed in section 2.3.1. Little variation in fibre length distribution can be discerned between the three TMP pulps shown in Figures 5.10 and 5.11.

Table 5.11: Properties of key TMP pulps

TMP Pulp	Base TMP	HC620	HC740	Low80	Low170
Incremental Energy (kWh/t)	0	620	740	80	170
Total Energy (kWh/t)	1920	2540	2660	2000	2090
Breaking Length (km)	3.3_a	3.7_b	3.9_b	3.2_{ac}	3.5_d
Tear Index (mNm^2/g)	9.1_a	9.5_{ab}	10.1_b	10.4_b	10.1_b
Bulk (cm^3/g)	3.11_a	3.04_b	2.96_c	3.40_d	3.24_e
Zero Span (km)	10.2_a	10.9_b	11.7_c	10.3_{ab}	10.3_{ab}
LWA Fibre Length (mm)	1.76_a	1.92_b	1.90_b	1.95_b	1.94_b
No. of Impacts ($fibre^{-1}$)	0	5560	7080	60	120
Impact Intensity ($Jx10^{-6}$)	0	0.33	0.30	4.1	4.2

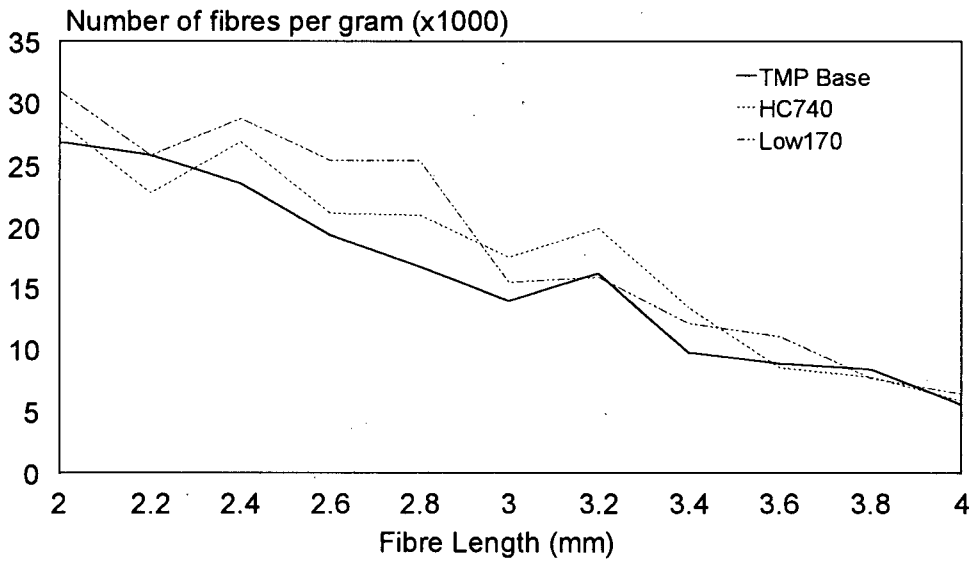


Figure 5.10: TMP normalized long fibre distribution

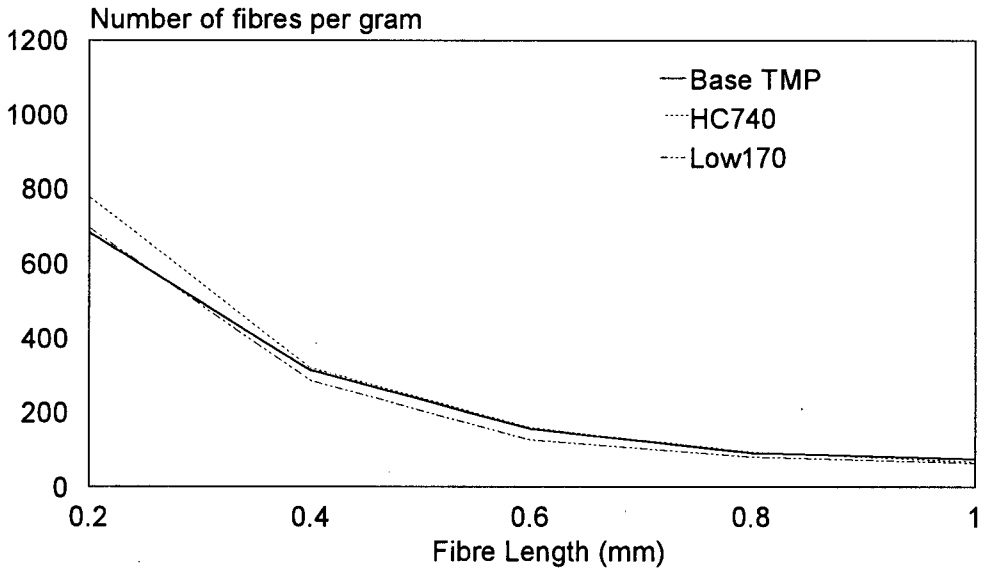


Figure 5.11: TMP normalized fine fibre distribution

As shown in Table 5.12, curl indices are lowest for HC refined TMP which is consistent with the gentle action of multiple low intensity impacts. Curl decreases to a lesser degree for the LC refined TMPs. Both HC and LC refined TMPs have lower kink indices than Base TMP. This reduction in kinks is seen in the microscopic examination of TMP long fibres, summarized in Table 5.13, where both modes of refining reduced large fibre kinks. Lower kink and curl indices contribute to increased tensile strength [Page 1985 and 1989]. Table 5.13 shows that the greatest morphological change with

TMP refining was an increase in the number of large segments of the fibre pulled back as shown in Figure 5.7c. These changes are fewer than those seen with CTMP, as discussed in section 5.3.

Table 5.12: Curl, kink and shives for TMP

TMP Pulp	Base TMP	HC620	HC740	Low80	Low170
Breaking Length (km)	3.3_a	3.7_b	3.9_b	3.2_{ac}	3.5_d
Curl Index	0.079_a	0.061_b	0.063_b	0.072_c	0.071_c
Kink Index	1.03_a	0.70_b	0.79_{bc}	0.85_c	0.81_{bc}

Table 5.13: TMP microscopy results

Fibre Data	Base	HC620	Low170
Number of fibres tested	200	200	200
Number of fibres with an unraveled end	12_a	16_a	20_a
Pulled back to a point	2_a	2_a	1_a
Large fibre segments pulled back	6_a	15_b	12_{ab}
Sleeve condition	10_a	11_a	13_a
Large kink	10_a	2_b	1_b
Percent fibres showing damage of any kind (%)	18_a	19_a	18_a

One factor affecting area available for bonding is increased fibre flexibility. One study found that even for a single species, the flexibility-tensile relationship is highly dependent on refining conditions [Abitz and Luner 1989]. The flexibility of Low170 is greater than that of Base TMP and HC740. Figure 5.12 shows that Base TMP and HC740 have similar flexibility distributions. The flexibility distribution of Low170, has however, shifted to the right, indicating an increase in fibre conformability and suggesting that the change in flexibility is due to increased flexibility of the stiffer, summerwood fibres.

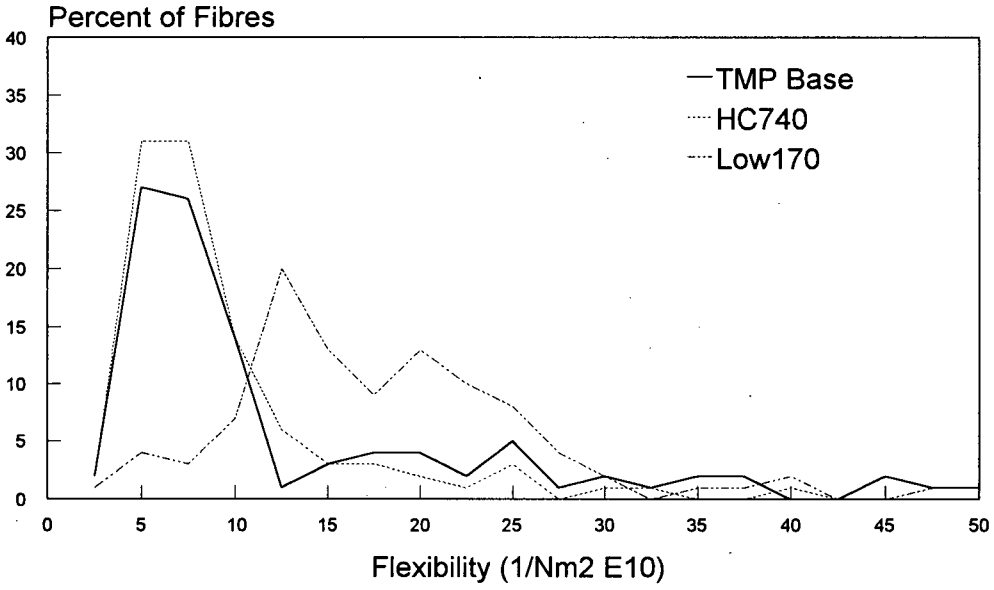


Figure 5.12: TMP wet fibre flexibility distribution

As shown in Table 5.14, low-intensity low consistency refining increases bulk. Scattering coefficients for both LC and HC refined TMPs decrease to a greater extent than seen with CTMP suggesting a greater bonding. This is contradictory to the observed increase in bulk for LC refining. The increased flexibility of Low170 should work to decrease bulk [Mohlin 1979, Biasca 1989, Paavilainen 1993, Karnis 1994]. The decreased fines content should increase bulk [Jackson and Williams 1979, Hartman and Higgins 1983].

Table 5.14: Bulk and related properties for TMP

TMP Pulp	Base TMP	HC620	HC740	Low80	Low170
Bulk (cm^3/g)	3.11_a	3.04_b	2.96_c	3.40_d	3.24_e
Scattering Coeff. (cm^2/g)	63.2_a	55.4_b	57.1_c	52.7_d	54.2_e
Flexibility ($1/Nm^2x10^{10}$)	6.7_a	-	6.0_a	-	15_b
Bauer McNett Fines (g) (R200 + P200)	2.59 ± 0.16	-	2.72 ± 0.11	-	2.05

As shown in Table 5.15, both HC and LC refined TMP tear indices increase due to longer average fibre length and reduced kink indices. The increased zero span of HC refined TMP is a positive factor for tear strength.

Table 5.15: Tear index factors for TMP

TMP Pulp	Base TMP	HC620	HC740	Low80	Low170
Tear Index (mNm^2/g)	9.1_a	9.5_{ab}	10.1_b	10.4_b	10.1_b
Zero Span (km)	10.2_a	10.9_b	11.7_c	10.3_{ab}	10.3_{ab}
LWA Fibre Length (mm)	1.76_a	1.92_b	1.90_b	1.95_b	1.94_b
Curl Index	0.079_a	0.061_b	0.063_b	0.072_c	0.071_c
Kink Index	1.03_a	0.70_b	0.79_{bc}	0.85_c	0.81_{bc}

In summary, the high consistency refined TMPs, HC620 and HC740 have the highest breaking length. Low170 has a lower breaking length and equal tear strength compared to HC740 at a lower energy input--170 kWh/t vs. 740 kWh/t respectively.

5.2.2 Secondary TMP Pulps

Base TMP was processed into five pulp groups as shown in Figure 5.13 using lower LC refining intensities as a result of the CTMP findings. PFI refining was included to see how TMP would respond to this refining treatment and to study the effects of the PFI N and I values.

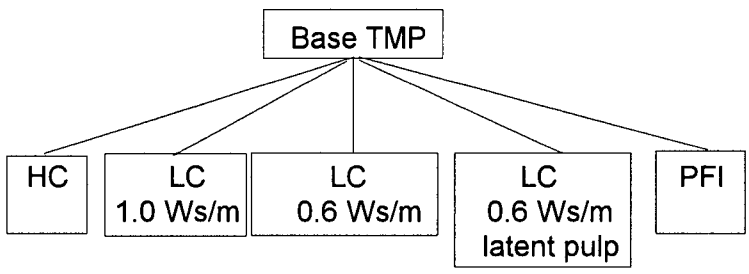


Figure 5.13: Extended TMP experimental program

As discussed in section 5.1, HC-refined TMP has the greatest breaking length of the TMP pulps and a high tear index. LC-refined pulp, at the lower refining intensity of 0.6 Ws/m, has the same tear index and lower breaking length at one-third to one-quarter of the incremental energy input. The other TMP pulps did not respond as well to refining.

For example, as shown in Table 5.16, High190 has a lower tear index and no gain in tensile strength compared to Base TMP. This correlates to the dramatic drop in long fibre fraction for High190 where the longest fibre fraction, Bauer McNett R14, is virtually eliminated. The quantity of fines is greatest for High190. The handsheets for this TMP pulp were visibly choppier than those of the other TMPs. Earlier work [Laamanen et al. 1986, Karnis 1996] claiming that low consistency refining of TMP cuts fibres is validated for high-intensity LC refining.

Table 5.16: Key properties of TMP pulps

TMP Pulp	Base TMP	HC740	Low170	High190
Incremental Energy (kWh/t)	0	740	170	190
Breaking Length (km)	3.3_a	3.9_b	3.5_d	3.4_{ad}
Tear Index (mNm^2/g)	9.1_a	10.1_b	10.1_b	6.1_c
Bulk (cm^3/g)	3.11_a	2.96_c	3.24_e	2.55_f
LWA Fibre Length (mm)	1.76_a	1.90_b	1.94_b	1.13_d
Bauer McNett R14 (g)	1.68±0.03	1.99±0.07	2.46	0.04
Bauer McNett Fines R200 + P200 (g)	2.59±0.16	2.72±0.12	2.05	3.33
No. of Impacts ($fibre^{-1}$)	0	7080	120	50
Impact Intensity ($Jx10^{-6}$)	0	0.30	4.2	8.8

Is there any benefit in eliminating the latency removal step in TMP pulp processing? As shown in Table 5.17, compared to Low170, Lat160, the LC low-intensity refined TMP with latent pulp, has the same breaking length, but lower tear strength. Curl indices, seen as a measure of latency removal, are the same.

PFI refining of TMP produces an inferior pulp to both HC740 and Low170 at a greater energy cost because of a large reduction in long fibre fraction. Interestingly, the long fibre has become part of the middle fraction as fines quantity has not increased above that seen with Base TMP as shown in Table 5.18.

Table 5.17: Comparison of latent vs. delatent TMP

TMP Pulp	Base TMP	Low80	Low170	Lat80	Lat160
Incremental Energy (kWh/t)	0	80	170	80	160
Breaking Length (km)	3.3_a	3.2_{ac}	3.5_d	3.3_a	3.5_d
Tear Index (mNm^2/g)	9.1_a	10.4_b	10.1_b	9.6_{ab}	8.6_a
Bulk (cm^3/g)	3.11_a	3.40_d	3.24_e	3.11_a	2.86_g
LWA Fibre Length (mm)	1.76_a	1.95_b	1.94_b	1.86_e	1.82_e
Curl Index	0.079_a	0.072_c	0.071_c	0.082_a	0.070_c
Kink Index	1.03_a	0.85_b	0.81_{bc}	1.00_a	0.87_c
Bauer McNett R14 (g)	1.68 ± 0.03	-	2.46	-	1.54
No. Impacts ($fibre^{-1}$)	0	60	120	60	110
Impact Intensity ($Jx10^{-6}$)	0	4.1	4.2	3.9	4.4

In summary for TMP, as with CTMP, the highest breaking length and lowest bulk were obtained with HC refining at a higher energy consumption. The lower refining intensity showed promising results for latency removal of TMP, although tear was lower than the delatent counterpart. As with CTMP, the PFI refined TMP had a lower tear index and, in this case, lower breaking length than both Low170 and HC740 at a greater energy input.

As with CTMP, if we look for the "best" TMP, the high consistency refined pulps are stronger. However, both HC740 and Low170 have higher bulk, higher tear and lower breaking length than "typical spruce TMP." For HC740 the breaking length development was 0.00077 km per kWh/t. For Low170, breaking length development was 0.0012 km per kWh/t. There is therefore a choice between energy input and maximum breaking length. If minimum standards for paper properties can be met with the LC pulp, then this mode of refining may offer a cost-effective way to develop TMP.

Table 5.18: Results of PFI refining TMP

TMP Pulp	Base TMP	HC740	Low170	PFI
Incremental Energy (kWh/t)	0	740	170	1330
Breaking Length (km)	3.3_a	3.9_b	3.5_d	3.2_c
Tear Index (mNm^2/g)	9.1_a	10.1_b	10.1_b	7.8_d
Bulk (cm^3/g)	3.11_a	2.96_c	3.24_e	2.90_g
LWA Fibre Length (mm)	1.76_a	1.90_b	1.94_b	1.51_f
Bauer McNett R14 (g)	1.68±0.03	1.99±0.07	2.46	0.63
Bauer McNett Fines R200 + P200 (g)	2.59±0.16	2.72±0.11	2.05	2.61
No. of Impacts ($fibre^{-1}$)	0	7080	120	1170
Impact Intensity ($Jx10^{-6}$)	0	0.30	4.2	3.0

5.3 GENERAL EXPERIMENTAL RESULTS

5.3.1 Comparisons between Pulp Groups

To investigate broader aspects of low consistency refining, CMP and kraft pulps from the same wood source as used for TMP and CTMP were made and tested. As they are not part of the central part of the thesis work, CMP and kraft pulps are discussed in Appendix A. Only a brief summary of the experimental conditions and results is given at this point.

5.3.1.1 CMP

CMP spruce chips were first cooked at 140°C for 30 minutes at a liquor-to-wood ratio of 5:1 in a 1.6% sodium sulfite solution, then HC refined to form Base CMP. Secondary refining of CMP was carried out only in the LC mode using the same refining intensities as TMP.

Table 5.19 shows results of CMP low consistency refining. Although breaking length increased greatly with low-intensity LC refining, tear index fell due to loss of long

fibre and a corresponding decrease in average fibre length. Perhaps CMP requires a lower intensity than 0.6 Ws/m to maximize its potential.

Table 5.19: Key properties of CMP

CMP Pulp	Base CMP	Low90	Low180	High90	High190
Incremental Energy (kWh/t)	0	90	180	90	190
Breaking Length (km)	3.0_a	4.1_b	4.6_c	3.3_d	3.7_e
Tear Index (mNm^2/g)	11.6_a	8.7_b	7.0_c	5.7_d	4.1_e
Bulk (cm^3/g)	3.54_a	2.97_b	2.47_c	2.56_d	2.16_e
LWA Fibre Length (mm)	2.11_a	1.87_b	1.50_c	1.14_d	0.76_e
Flexibility ($1/Nm^2x10^{10}$)	6.2_a	-	20_b	-	-
Curl Index	0.055_{ab}	0.052_a	0.054_a	0.059_b	0.067_c
Kink Index	0.48_a	0.48_a	0.50_a	0.54_b	0.55_b
Bauer McNett R14 (g)	2.99	-	0.42	-	0
No. Impacts ($fibre^{-1}$)	0	50	110	20	40
Impact Intensity ($Jx10^{-6}$)	0	4.1	4.1	8.4	8.8

5.3.1.2 Kraft

Kraft pulp was processed with an H-factor of 1350 at a maximum temperature of 170°C, liquor-to-wood ratio of 4.5:1 and an effective alkali of 16%. This resulted in a 49% yield and Kappa number of 28.9, representing a typical kraft cook. The kraft pulp was low consistency refined at an intensity of 3.0 Ws/m and energy levels as shown in Table 5.20, which reflect normal refining conditions for kraft pulp. This is also the higher of the two intensities used for CTMP low consistency refining.

Breaking length of kraft pulp increased and the bulk decreased with LC refining due to higher bondable area from increased flexibility and creation of fines. Tear index decreased due to the small decrease in average fibre length and increased fibre bonding. These changes are as expected.

Table 5.20: Key properties of kraft pulps

Kraft Pulp	Base Kraft	High100	High200
Incremental Energy (kWh/t)	0	100	200
Breaking Length (km)	7.1_a	10.0_b	12.1_c
Tear Index (mNm^2/g)	22.2_a	15.3_b	11.5_c
Bulk (cm^3/g)	1.74_a	1.48_b	1.39_c
LWA Fibre Length (mm)	2.95_a	2.76_b	2.63_c
Flexibility ($1/Nm^2x10^{10}$)	16_a	-	32_b
Curl Index	0.057_a	0.118_b	0.111_c
Kink Index	0.37_a	1.00_b	0.94_b
Bauer McNett R14 (g)	7.17	-	6.14
Bauer McNett Fines R200 + P200 (g)	0.18	-	1.04
Number of Impacts ($fibre^{-1}$)	0	17	35
Impact Intensity ($Jx10^{-6}$)	0	13	13

5.3.1.3 Inter-pulp Comparison

To study the broader aspects of pulping and refining variables, all pulp types are compared to one another. Understanding the effects of manufacturing and processing, coupled with desired paper properties and manufacturing costs, could help to optimize wood resources. The pulps were made as shown in Figure 5.14. CTMP and TMP were

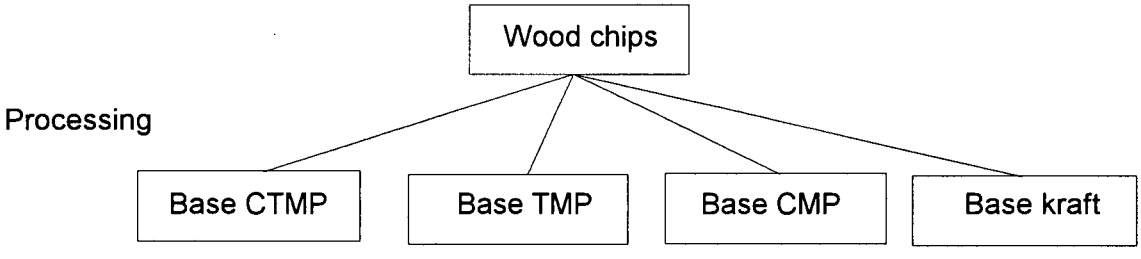


Figure 5.14: Manufacturing of base pulps

refined at high consistency. All four base pulps were refined at low consistency. Table 5.21 shows the key paper properties of the optimum pulps in each category. For Table 5.22, the Duncan multiple-range analysis was redone for these data. Thus the alphabetical subscripts differ from those shown in the individual pulp group tables.

Table 5.21: Key properties of all pulp types

Pulp Type	Breaking Length (km)	Tear Index (Nm^2/g)	Bulk (cc/g)	Fibre Length (mm)
CTMP				
Base	4.2_a	9.8_{ab}	3.39_a	2.08_a
HC1560	5.7_b	8.4_{ac}	2.60_b	1.95_b
Low200	5.2_b	8.4_{ac}	2.78_c	1.80_c
TMP				
Base	3.3_c	9.1_a	3.11_d	1.76_d
HC740	3.9_a	10.1_{ab}	2.96_e	1.90_e
Low170	3.5_c	10.1_{ab}	3.24_f	1.94_b
CMP				
Base	3.0_c	11.6_b	3.54_g	2.11_a
Low180	4.6_a	7.0_c	2.47_h	1.50_f
Kraft				
Base	7.1_d	22.2_d	1.74_i	2.95_g
High200	12.1_e	11.5_b	1.39_j	2.63_h

When looking at the highest value obtained for each pulp type, breaking length increases in the following order, TMP < CMP < CTMP << kraft. This agrees with Atack et al. [1978] who found that chemical pretreatment, as with CTMP and CMP, results in higher breaking lengths for chemically treated pulps compared to those of TMP. In another study, Atack et al. [1981] state, "Softening of wood by steaming as in the TMP process is temporary and produces stiff, poorly bonded fibres."

Figure 5.15 shows Bauer McNett fractions of all base pulps. Base TMP has the lowest long fibre fractions, consistent with its low breaking length. Even though CMP has a greater long fibre content than CTMP, it has a lower breaking length. Perhaps lack of other fibre length components is an important aspect in mechancial pulp strength. Average fibre lengths for base pulps are as follows; kraft 2.95 mm., CMP 2.11 mm., CTMP 2.08 mm. and TMP 1.76 mm. These numbers show the expected trend and concur with the theory that chemical treatment increases long fibre content since fibre separation takes place in the middle lamella rather than in the secondary

wall when chemicals are used in the mechanical pulping process [Mackie and Joyce 1987, Heitner and Hattula 1988, Miles and Karnis 1993].

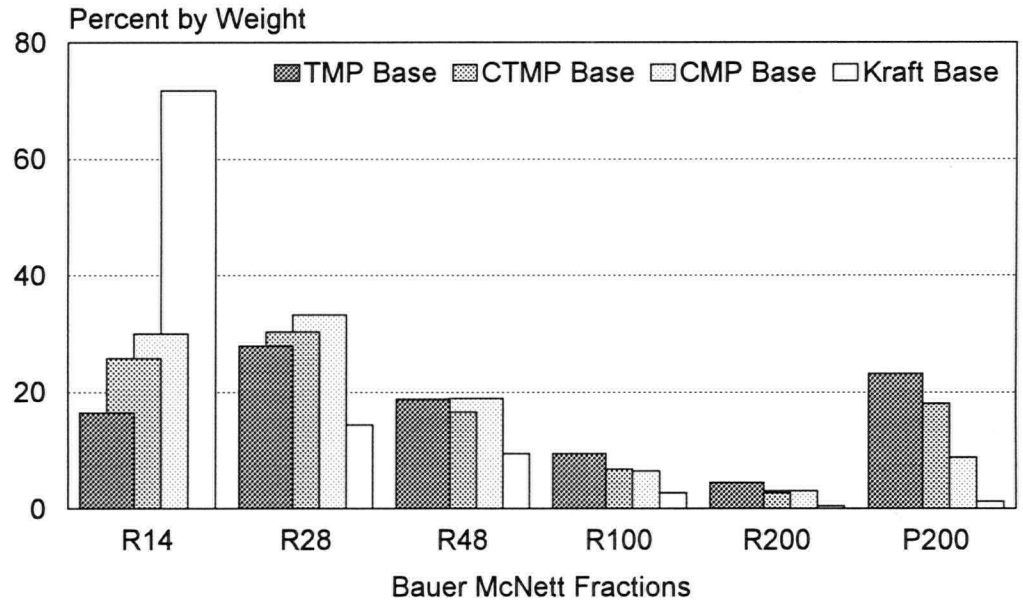


Figure 5.15: Base pulps Bauer McNett fractions

Zero span shows the strongest correlation of all individual fibre properties to breaking length. Breaking length = -2.43+0.567(zero span) or BL = -2.44(zero span)^2 both at r^2 = 80 at a 90% confidence level. Additionally BL = -2.4 + 0.58(zero span) - 0.093 (LWA) at r^2 = 0.80. Appendix E outlines the linear regression methods used to obtain these numbers.

Jackson and Williams [1979] noted that TMP differs considerably from kraft and CTMP by displaying large amounts of ribbon-like material in conjunction with some long fibres showing few or no signs of surface fibrillation. As expected, in this work there is very little fibre deformation in base kraft. The three mechanical base pulps have a comparable level of fibre damage as shown in Table 5.22. With secondary refining, kraft fibres are pulled apart and kinked. TMP and CMP fibres remain at approximately the same level of deformation. CTMP shows a significant increase in fibre deformation, particularly with HC and PFI refining where there is a dramatic increase in unraveled ends, sleeve-like formations and, for PFI refining only, kinks. The effects of refining on CTMP are more closely related to those of kraft than TMP and CMP.

Table 5.22: Complete microscopy results

Pulp Type	Percent damaged (%)	Unraveled end	Pulled to a point	Large fibrils pulled back	Sleeve	Kink	Partially attached to another fibre
TMP							
Base	18_a	12_a	2_a	6_a	10_a	10_a	6_a
HC610	19_a	16_a	2_a	15_b	11_a	2_b	9_a
Low170	18_a	20_a	1_a	12_{ab}	13_a	1_b	3_{ab}
Lat160	16_a	17_a	2_a	10_{ab}	6_a	4_b	9_a
PFI	14_a	7_a	2_a	12_{ab}	8_a	6_{ab}	7_a
CTMP							
Base	19_a	12_a	0_a	15_b	6_a	2_b	0_b
HC1560	53_b	42_b	7_b	31_c	21_b	1_b	0_b
Low200	35_c	18_a	1_a	37_{cd}	6_a	6_{ab}	1_b
High200	42_{bc}	17_a	1_a	31_c	7_a	23_c	3_{ab}
Lat210	37_c	16_a	4_a	44_d	5_a	2_b	0_b
PFI	61_b	26_c	0_a	37_{cd}	17_{ab}	36_d	1_b
CMP							
Base	20_a	13_a	4_a	11_{ab}	10_a	2_b	1_b
Low180	23_a	15_a	3_a	15_b	7_a	3_b	0_b
Kraft							
Base	5_d	0_d	0_a	3_a	0_c	5_{ab}	0_b
High200	25_a	8_a	3_a	3_a	0_c	33_d	0_b

On the topic of fibre deformation, while working with the FTFA, I observed regular-spaced microcompressions on the long fibre fractions of both CTMP and TMP. A simplified diagram showing this effect is provided in Figure 5.16a. Microcompressions occurred for an estimated 4% of the R14 fraction in these two base pulps. Dumbleton [1972] saw the same effect on axially compressed fibres obtained by laying fibres between two stretched rubber mats and then releasing the mats. The resultant fibres had distinct buckled zones of disoriented fibrils and relatively intact segments in which fibrils maintained their helical arrangement. He postulated that the disorientation occurred due to stress concentrations. It is interesting that this stress, applied over the length of the fibres, should result in such regular-spaced compressions. This seems to imply that the material in the fibre walls is of a consistent strength throughout the length of the fibre.

I observed that incremental refining, both in HC and LC refiners, reduced this phenomenon to an estimated 1% of fibres. More work is needed to see if the fibre has

been axially compressed or merely twisted, as in Figure 5.16b. Note that twisted fibres alter the fibre silhouette somewhat which was not seen during FTFA work.

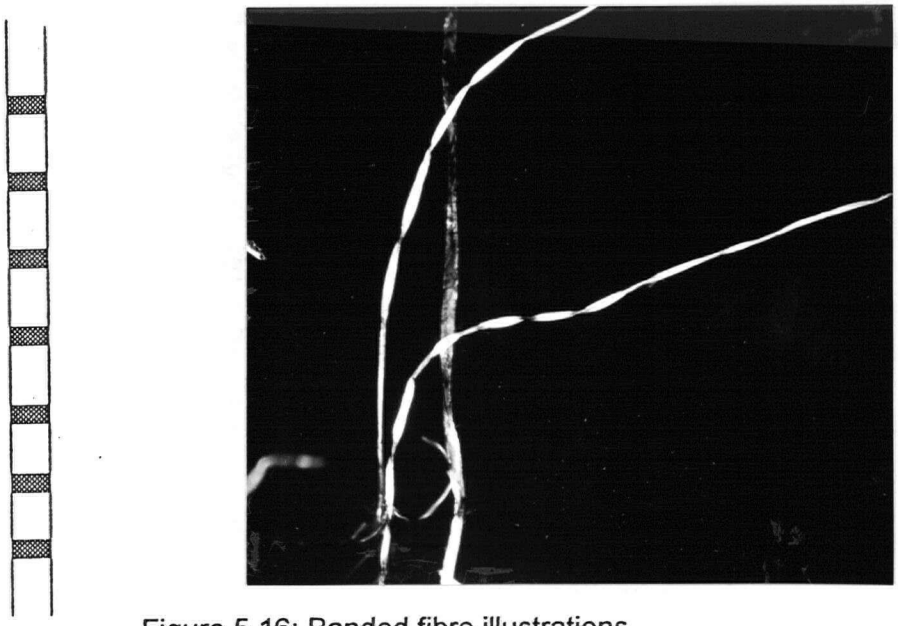


Figure 5.16: Banded fibre illustrations
a. Simplified section of a banded fibre b. Polarized image (x40)

As shown in Table 5.21, all three mechanical pulps had tear indices within 3.1 units of each other. All LC refined CTMP pulps lose tear due to high LC refining intensity. CMP tear index drops dramatically because of long fibre loss. Kraft tear decreases by almost half due to increased bonded area and lower fibre length. Both HC refining and low-intensity LC refining of TMP improve tear. The results of this work agree with Richardson et al. [1990] who claim that tear indices of TMP and CTMP are similar. With 200 kWh/t of LC refining, the kraft pulp tear index was reduced to that of the stronger mechanical pulp samples. Atack et al. [1978] found that at given energy levels, tear indices of CTMP and TMP were higher than those of CMP. They postulate that presteaming preserves fibre length, thus increasing tear. I found that the tear strength of CMP is greater than that of TMP, with CTMP close to that of TMP, dependent on the energy input during manufacturing.

Tear index had a strong correlation to fibre length for all pulp types: tear = -0.809 + 5.65(LWA) at $r^2 = 0.68$; tear = 6.35 + 0.180 $(LWA)^4$ at $r^2 = 0.79$; tear = 1.57 + 1.70 (long fibre content (R14 + R28)) at $r^2 = 0.72$; tear = 4.57 + 0.191$(\text{long fibre})^2$ at $r^2 = 0.82$

and tear = -8.9 + 0.51(zero span) + 4.0(LWA) +16.1 (coarseness) at $r^2 = 0.72$ all at a confidence level of 90%.

Bulk values of TMP, CTMP and CMP are within one unit of each other. Kraft is more dense, particularly with refining. Low-intensity LC refining of TMP yields a small increase in bulk. HC refining and low-intensity LC refining of latent TMP show a small decrease in bulk due to increased fines. The densest CTMPs were high-intensity LC refined pulps, both latent and delatent, with increased fines quantity being a dominant factor. Bulk decreased by over 30% for CMPs from loss of long fibres and creation of fines. The only fibre characteristic that shows a linear correlation to bulk is coarseness despite the experimental uncertainty of the coarseness measurements. Bulk = -0.50 + 11.1 coarseness at $r^2 = 0.74$ and a confidence level of 95%.

The light scattering coefficient increases as chemical application decreases, kraft < CMP < CTMP < TMP. This agrees with other work [Atack et al. 1980, Richardson et al. 1990] where increased sulfonation led to a decrease in scattering coefficient. For kraft pulp there is a dramatic reduction of scattering coefficient with refining, a finding which is very different from the behaviour of mechanical pulps. Atack et al. [1978] write, "One useful practical criterion of mechanical character is the simultaneous increase of breaking length and scattering coefficient of the pulp on beating or refining." This was seen for HC-refined TMP and CTMP, low-intensity LC-refined TMP and both LC-refined CMPs. The only fibre characteristic to show a linear correlation to scattering coefficient is coarseness, with scattering coefficient = 84.6 - 3.04 coarseness, at $r^2 = 0.84$ at 95% confidence level.

Freeness increases for base pulp types as follows--TMP < CTMP < CMP << kraft. With secondary refining, all three mechanical pulps covered the same range of freeness. With LC refining, kraft freeness dropped from 770 ml to 478 ml. The amount of fines increases in the following order--kraft < CMP < CTMP < TMP. This trend is the same for decreasing freeness as the quantity of fines, and their large external surface area is a dominant factor for CSF.

5.3.2 Mill CTMP Low Consistency Refining Trial

On June 16, 1993, in combination with a mill study on shive reduction, work was carried out at MacMillan Bloedel's Powell River mill to expand this research to mill scale. Pulp samples were collected before and after a low consistency refiner in a CTMP line. Mill conditions, at the calculated N and I, were then used to refine the same commercial CTMP pulp in Paprican's pilot plant scale LC refiner. Standard fibre, pulp and paper tests and FTFA analyses were performed.

As shown in Table 5.23, two separate trials were conducted on the mill LC refiner. The intensity of impacts was increased in each case and the number of impacts held constant. The trials are designated Mill Trial #1 and Mill Trial #2. Trial #1 had a slightly higher refining intensity and lower number of impacts compared to trial #2. The two trials were closer to each other than originally planned due to imprecise readings on the mill-scale consistency sensors. The error in the consistency reading caused the pilot plant N and I values to differ from those at the mill. Three samples were taken for each mill-scale trial, the first at zero kWh/t (i.e. refiner plates backed off

Table 5.23: Key properties of mill CTMP

Pulp	Incremental Energy Input (kWh/t)	Breaking Length (km)	Tear Index (mNm^2/g)	Bulk (cm^3/g)	Average Fibre Length (LWA)(mm)
Base CTMP	0	4.4_a	8.0_a	2.81_a	1.46_a
Mill refined #1 $N = 60$ fibre^{-1} $I = 3.0 \times 10^{-6}$ J $I = 4.7 \times 10^{-6}$ J	 74 114	 4.0_b 4.0_b	 6.2_b 5.5_{bc}	 2.61_b 2.53_c	 1.23_b 1.10_c
Mill refined #2 $N = 75$ fibre^{-1} $I = 2.0 \times 10^{-6}$ J $I = 3.4 \times 10^{-6}$ J	 67 117	 4.2_{ab} 4.2_{ab}	 4.4_c 4.3_c	 2.57_{bc} 2.51_c	 1.18_d 1.07_{ce}
Pilot Plant #1 $I = 8.6 \times 10^{-6}$ J $N = 30$ fibre^{-1} $N = 40$ fibre^{-1}	 91 139	 4.1_b 4.4_a	 7.5_{ab} 5.7_b	 2.52_c 2.46_d	 1.19_d 1.04_e
Pilot Plant #2 $I = 16 \times 10^{-6}$ J $N = 15$ fibre^{-1} $N = 20$ fibre^{-1}	 88 134	 4.0_b 4.1_b	 7.6_a 8.5_a	 2.53_c 2.48_d	 1.03_e 0.90_f

completely) to establish the net energy input of the remaining samples. Two further samples were taken per run at differing plate clearances.

For the first mill trial breaking length decreased slightly. Increased bonded area counteracted loss of average fibre length. Note that the commercial CTMP was heavily refined entering the LC refiner and therefore the maximum potential for further property development had passed. At the time of this trial, the mill was interested in using the LC refiner to eliminate shives and not to develop the pulp properties. Had they wanted to study the latter, the incoming pulp should have received less energy input in the production stages.

Two separate runs were performed on the pilot plant LC refiner to mirror the two mill trials. However, since the on-line consistency readings at the mill were inaccurate, the pilot plant work was not as close to the mill conditions as planned. The breaking length values were the same. Tear degraded more in the commercial refiner.

5.3.3 Fracture Toughness Analysis

Much effort was put into producing comprehensive data for the new fracture toughness test developed by Paprican. The results are seen in Table 5.24. For fracture toughness TMP = CMP = CTMP << kraft. In the kraft samples, fibres were

Table 5.24: Fracture toughness results

Pulp Type	Fracture Toughness (Jm/kg)	Breaking Length (km)	Tear Index (Nm/g)	Fibre Length (mm)
CTMP				
Base	14.2_a	4.2_a	9.8_{ab}	2.08_a
HC880	18.9_b	5.7_b	8.4_{ac}	1.95b
Low300	14.6_a	4.4_a	8.2_{ac}	1.83_c
TMP				
Base	12.6_a	3.3_c	9.1_a	1.76_d
HC740	15.1_a	3.9_a	10.1_{ab}	1.90_e
Low170	13.2_a	3.5_{ac}	10.1_{ab}	1.94_e
CMP				
Base	12.5_a	3.0_c	11.6_b	2.11_a
Low180	11.4_a	4.6_a	7.0_c	1.50_f
Kraft				
Base	21.8_b	7.1_d	22.2_d	2.95_g
High200	36.4_c	12.1_e	11.5_b	2.63_h

visibly pulled from each side of the fracture. This was not seen in the mechanical pulp samples. TMP fracture toughness increases by 20% with HC refining and by 5% for both latent and delatent low-intensity LC refining. High-intensity LC refined TMP has a 32% drop in fracture toughness. The only CTMP pulp to show a significant increase in fracture toughness was HC880. Kraft High200 fracture toughness increases by 67% over that of base kraft because of increased bonded area. Not surprisingly, due to common elements in testing, fracture toughness shows a strong correlation to tensile strength. Breaking length = 0.028 + 0.313 fracture toughness or BL = 0.028 + 0.156(fracture toughness)^2 both at r^2 = 90 and 95% confidence level. No linear correlation was found with tear index. In terms of general trends, fracture toughness increases with increasing zero span in agreement with other research [Seth and Page 1975]. It also correlates to increasing average fibre length [Peng 1995].

5.3.4 Flexibility Analysis

Wet fibre flexibility distributions are shown in Figures 5.17 and 5.18. Figure 5.17 shows a dramatic difference between flexibility distributions of TMP and kraft fibres. Even with refining, many TMP fibres remain stiff. The kraft pulp has a broader distribution of fibre flexibility, particularly after refining.

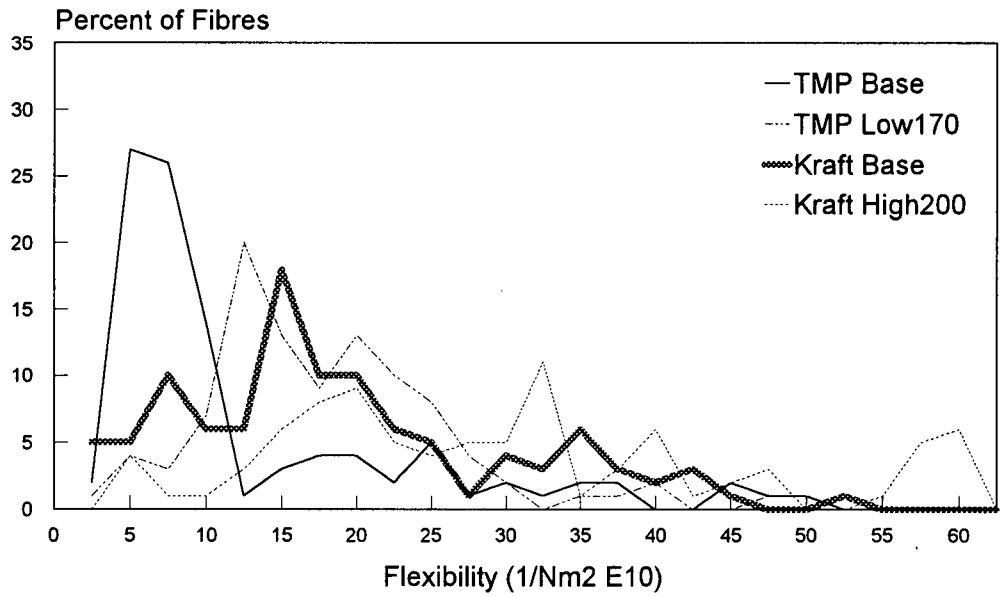


Figure 5.17: Flexibility distribution of TMP and kraft pulps

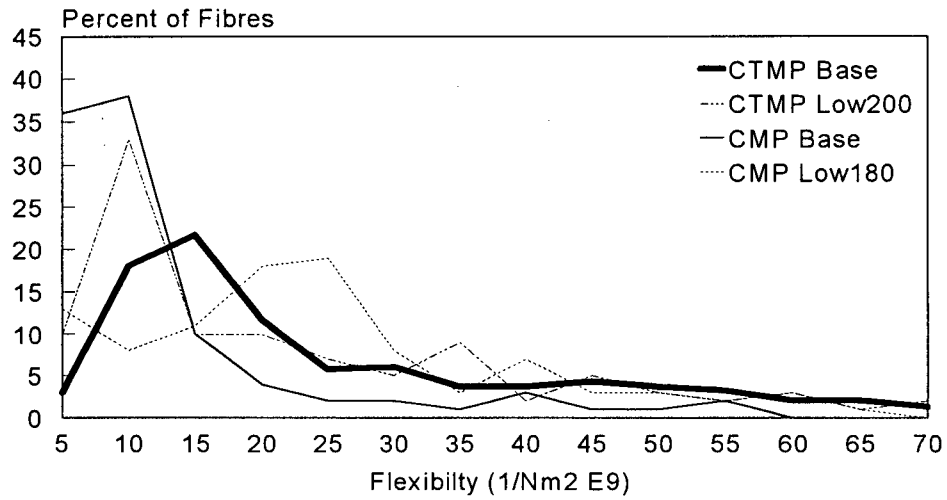


Figure 5.18: Flexibility distribution of CTMP and CMP pulps

Atack et al. [1980] conclude that increased interfibre bonding of CTMP over that of TMP is due to greater fibre flexibility and not to increased external area. In my work the CTMP fibre flexibility distribution is more similar to that of kraft flexibility than that of either TMP or CMP.

CHAPTER 6
SUMMARY and CONCLUSIONS

The comparison of low consistency and high consistency refining theories completed in section 4.1, showed that the differences in the Miles and May [1990] and Kerekes [1990] theories result from the physical differences between low consistency and high consistency modes of refining and the assumptions used in each theory. In addition to the experimental work with TMP and CTMP, refining theory was extended through this work by developing a C-factor for the PFI mill.

For low-intensity LC-refined TMP, Low170, the breaking length was lower than HC refined TMP, HC740, and tear values were the same. Both properties were greater than those of Base TMP. For HC740 the breaking length development was 0.00077 km per kWh/t. For Low170, breaking length development was 0.0012 km per kWh/t. There is therefore a choice between energy input and maximum breaking length. If minimum standard paper properties can be met with the LC value, then this mode of refining may offer a cost-effective way to develop TMP.

For CTMP, Low200 had the same breaking length and tear as HC880. The breaking length for HC1560 was greater than for HC880 and Low200. In terms of energy input, HC1560 gained 0.00094 km per kWh/t, and Low200 gained 0.0050 km per kWh/t. HC880, the mid energy HC refined CTMP, gained 0.0013 km per kWh/t. Again, if the minimum standard paper properties can be met, there is a cost-saving potential for LC-refined CTMP.

This work extended the concept of producing high quality CTMP and TMP with a reduction in energy usage through LC refining. This result was achieved for low-intensity refining conditions. At these conditions, individual wood fibres were subject to both internal and external changes; yet, for the most part, they maintained their length and the number of long fibres, as with HC refining. Low consistency refining at higher intensities or higher energy input proved detrimental to paper property development. Low consistency refining of latent TMP and CTMP pulps straightens fibres and may contribute to latency removal. However, latent pulp may be more brittle, resulting in lower paper strength. Low consistency refining of latent pulp may offer a usable alternative where a mill is limited by either space or latency removal equipment.

In terms of the microscopy work, CTMP fibres displayed the highest levels of unraveled ends, large fibrils pulled back, sleeves and kinks. LC-refined kraft also had a large kink count. TMP displayed these attributes to a lesser degree and had a higher level of fibres partially attached to each other. Coarseness measurements, although repeatable with Paprican's modified method for mechanical pulp, were not precise enough to support an overall peeling off of external fibres [Karnis 1994] or to indicate whether or not there was a true change in average fibre coarseness. This agrees with recent findings by Seth and Chan [1997].

Wet fibre flexibility testing of low consistency refined TMP and CTMP showed a change in both the median values. Low170 TMP showed a shift in the flexibility distribution. The coarser, summerwood fibres seemed to be more affected by refining.

Fracture toughness does not seem to add any new information to paper testing results, as it is strongly correlated to breaking length.

PFI refining of both TMP and CTMP produces pulp which is inferior to both HC and LC refining at a greater energy cost. PFI refining did not mirror the changes to mechanical pulp in either the HC or LC refiner and cannot be used as a lab-scale estimation of behaviour in mill-scale refiners.

In the inter-pulp comparison, linear regression equations were developed for breaking length, tear, bulk and scattering coefficient. Although these show the expected trends, the low degree of quantifiable correlation between fibre and paper properties illustrates that the relationship between the micro fibre level and the macro paper level is complex.

For the mill trial, the commercial CTMP was already heavily refined entering the LC refiner, and therefore there was little opportunity for further property development. This explains the fact that only small changes were observed both in fibre and paper properties. The mill-scale work should be expanded with careful consideration to the energy input level during base CTMP manufacturing.

CHAPTER 7

SUGGESTIONS FOR FURTHER RESEARCH

The lowest LC refining intensity used in this work, 0.6 Ws/m, was able to improve the quality of resultant paper. The optimum refining intensity for low consistency refining of mechanical pulps, however, has not yet been found and needs further research as it may be equipment and species dependent. With regard to species considerations, the main experimental part of this thesis focused on the effects of refining white spruce. Other species will respond differently to refining and further research is needed in this area.

Some of the equipment and test procedures used in this study, for example the fracture toughness test and the Flow Through Fibre Analyzer, are relatively new or untested. The data generated in this thesis may prove beneficial in improving the scientific understanding of these two tests, the meaning of their results, and the validity of the tests. The Kajaani FS-200 should not be used to determine the coarseness of whole mechanical pulps. However, coarseness determination on mechanical pulp fractions, as opposed to whole pulp, may generate helpful information.

NOMENCLATURE

Symbols

a	4 for single disc and 2 for double disc refiner
A	average fibre cross- sectional area (m)
$A_p(r)$	aerodynamic specific surface of the pulp (cc/g)
A_R	cross sectional area at $2\pi r$
c_{in}	inlet pulp consistency (%)
c(r)	average consistency of pulp (%)
C_F	consistency (%)
dm(r)	oven dry mass of pulp in the annulus (kg)
dM(r)	wet mass of pulp in the annulus at radius r (kg)
D	groove depth (m)
e	refining intensity (J/impact)
E	total specific energy applied to the refiner (J/kg)
F	flow rate (kg/s)
g	acceleration due to gravity (m/s^2)
G	groove width (m)
h	variable used to indicate single disc or double disc refiner
I	intensity of refining impacts (J/impact)
ℓ	fibre length, or longest fibre dimension [Olson et al. 1995] (m)
L	latent heat of steam [Miles and May 1990], or length of refining zone [SEL theory] (m), or fibre length [Olson et al. 1995, Page 1969] (m)
m	oven dry throughput (kg)
n	number of impacts experienced by a unit mass of pulp [Miles and May 1990], or bar density [Kerekes 1990] (bars/m)
N	number of bars per unit length of arc [Miles and May 1990], or number of refining impacts [Kerekes 1990] (impact/kg)
N_r, N_s	number of bars on the rotor and stator, or N_r is number of PFI revolutions
P	perimeter of the fiber cross section (m)
P_{net}	net power (W)
Q	volumetric flow rate (cc/s)
r	refiner radius (m)

R	R_1 inner radius, R_2 outer radius (m)
RBA	relative bonded area of the sheet
SE	specific energy (W/kg)
t	residence time inside the refiner (s)
T	gap size [Kerekes 1990] (m), or tensile strength [Page 1969]
w	fibre coarseness (kg/m)
W	bar surface width, W_{fr} is rotor width factor, W_{fs} is stator width factor (m)
Z	zero span tensile strength (km)
θ	angle of conical refiner (rad)
μ_r	radial coefficient of friction between the pulp and refiner disc
μ_t	tangential coefficient of friction between the pulp and refiner disc
ρ	density of water [Kerekes 1990], density of fibrous material [Page 1969] (kg/m^3)
$\rho_s(r)$	density of the steam at radius r (kg/m^3)
τ	residence time (s)
τ_y	yield stress (J/m^3)
ϕ_r	angle of bars (degree)
ω	angular velocity of disc 2 [Miles and May 1990], or rotational velocity [Kerekes 1990] (rev/s)

Definitions

AWA	Fibre length based on Arithmetic Weighted Average
CEL	Cutting Edge Length
CI	Curl Index
CIPM	Contact Inches Per Minute
CMP	Chemimechanical Pulp
CSF	Canadian Standard Freeness
CTMP	Chemithermomechanical Pulp
EW	Earlywood or Escher Wyss refiner
FQA	Fibre Quality Analyzer
FS-200	Kajaani's fibre length and coarseness tester
FTFA	Flow Through Fibre Analyzer, an earlier name for the FQA
HC	High consistency

HYS	High Yield Sulphite pulp
ICPM	Inch Cuts Per Minute
IIPM	Impact Inches Per Minute
IQR	Inter Quartile Range
KI	Kink Index
Kraft	Standard method of producing chemical pulp
LC	Low Consistency
LF	Long Fibre
LW	Latewood
LWA	Fibre length based on Length Weighted Average
MEL	Modified Edge Load
ML	Middle Lamella
NSSC	Neutral Sulphite Semi Chemical process
P	Primary layer of the fibre cell wall
PFI	From the Norwegian term "Papirindustriens Forskningsinstitutt"
Postrefining	Low consistency secondary refining
RMP	Refiner Mechanical Pulp
S1	Transition lamella in the fibre cell wall
S2	Main layer of fibre cell wall
S3	Tertiary layer of the fibre cell wall
SE	Specific Energy
SEL	Specific Edge Load
SEM	Scanning Electron Microscope
TMP	Thermomechanical Pulp
WWA	Fibre length based on Weight Weighted Average

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APPENDIX A

DATA TABLES AND DISCUSSION OF CMP AND KRAFT PULPS

The primary focus of this thesis is the potential benefit of low consistency refining for CTMP and TMP. However, to investigate broader aspects of low consistency refining, CMP and kraft pulps were made and tested from the same wood source. CTMP and TMP are discussed in sections 5.1 and 5.2. Tables A.1 and A.2 present the complete information for these two pulp groups. The results from CMP and kraft in comparison to those of CTMP and TMP are discussed in section 5.3.1. The following is a brief look at the effects of refining on CMP and kraft pulp.

A.1 CMP

Spruce chips were first cooked at 140°C for 30 minutes at a liquor to wood ratio of 5:1 in a 1.6% sodium sulfite solution, then refined in a high consistency refiner under multi-pass conditions to form Base CMP. Figure A.1 shows the basic classifications of the CMPs. All secondary refining of CMP was performed at low consistency using the same refining intensities as TMP.

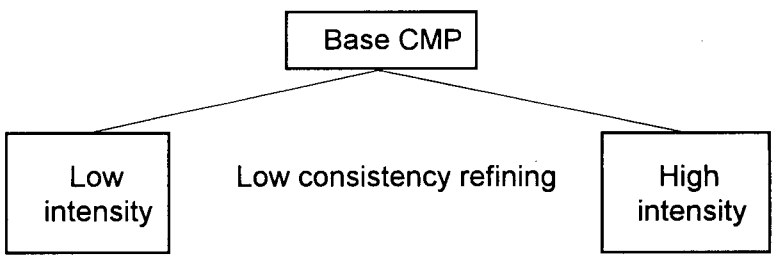


Figure A.1: CMP experimental program

Table A.3 is a summary of the CMP results with alphabetic subscripts used to show that two values are not statistically different. Breaking length increases by 55% for Low180. With high-intensity refining, breaking length of High190 increases by only 26%. This difference is due to lower average fibre length, elimination of the R14 fraction and creation of additional fines. The dramatic reduction in long fibre is seen in the elimination of the R14 Bauer McNett fraction with high-intensity refining of CMP. Note that the breakdown of the R14 Bauer McNett fraction increases the middle fraction of the pulp, not just the fines content. This may explain some of the increase in strength, even with the loss of long fibre.

Table A.1: Complete experimental results for CMP

	Base	Low90	Low180	High90	High190
Refining Variables					
Energy Postrefining (kWh/t)	0	88	176	94	192
Total Energy (kWh/t)	1440	1530	1620	1530	1630
Impact intensity (J 10^{-6})	-	4.1	4.1	8.4	8.8
No.Impacts (1/fibre)	-	54	110	20	41
Handsheet Test Results					
Breaking Length (km)	2.96_a	4.06_b	4.58_c	3.27_d	3.74_e
Tear (mNm^2/g)	11.6_a	8.67_b	7.00_c	5.67_d	4.11_e
Bulk (cc/g)	3.54_a	2.97_b	2.47_c	2.56_d	2.16_e
Zero Span (km)	12.1_a	11.9_a	12.5_a	11.8_a	12.1_a
Scattering Coef. (cm^2/g)	41.9_a	41.8_a	42.8_b	44.0_c	44.7_d
T.E.A. Index (mJ/g)	210_a	401_b	402_b	205_a	222_a
Stretch (%)	1.20_a	1.61_b	1.45_c	1.07_a	1.01_a
Tensile Index (Nm/g)	29.0_a	39.9_b	44.9_c	32.0_d	36.6_e
Burst Index (kPa m^2/g)	2.14_a	2.37_b	2.63_c	1.91_d	1.79_e
Brightness	52.1_a	51.2_b	51.9_a	51.4_b	49.4_c
Opacity % (ISO)	92.5_a	93.2_b	93.5_b	94.0_c	96.2_d
Fracture Toughness (Jm/kg)	12.5_a	-	11.4_b	-	6.85_c
Fibre Properties					
Fibre Length (NA mm)	0.84_a	0.76_b	0.63_c	0.53_d	0.4_e
Fibre Length (LWA mm)	2.11_a	1.87_b	1.50_c	1.14_d	0.76_e
Fibre Length (WWA mm)	2.81_a	2.56_b	2.11_c	1.61_d	1.04_e
Flexibility ($1/Nm^2 \times 10^{10}$)	6.2_a	-	20_b	-	-
Curl Index (LF)	0.055_{ab}	0.052a	0.054a	0.059_b	0.067_c
Kink Index (LF)	0.48_a	0.48_a	0.5_a	0.54_b	0.55_b
Coarseness(mg/m)	0.292_a	0.306_b	0.273_c	0.244_d	0.254_d
Pulp Properties					
Screen Rejects (%)	0.20	0.01	0.04	0.01	0.03
Screened CSF (ml)	489_a	396_b	252_c	223_d	117_e
Sommerville Shives (%)	0.17	0.08	-	0.04	0
Sulphonation (mg/kg)	2367	-	-	-	-
Bauer McNett Fractions (g)					
R14	2.99	-	0.42	-	0
R28	3.32	-	3.62	-	0.22
R48	1.89	-	3.16	-	3.39
R100	0.64	-	1.38	-	3.28
R200	0.30	-	0.55	-	1.03
P200	0.87	-	0.88	-	2.08

Table A.2: Complete experimental results for kraft pulps

	Kraft Pulps		
	Base	High100	High200
Refining Variables			
Low Consistency Refining			
Incremental Energy (kWh/t)	0	100	203
Intensity of Impacts (J 10^{-6})		13	13
No. Impacts (1/fibre)	0	17	35
Handsheet Test Results			
Breaking Length (km)	7.1_a	10.0_b	12.0_c
Tear (mNm^2/g)	22.2_a	15.3_b	11.5_c
Bulk (cc/g)	1.74_a	1.48_b	1.39_c
Zero Span (km)	21.8_a	21.1_a	21.1_a
Scattering Coef.(cm^2/g)	25.1_a	18.9_b	16.2_c
T.E.A. Index (mJ/g)	725_a	1630_b	2260_c
Stretch (%)	1.64_a	2.61_b	3.03_c
Tensile Index (Nm/g)	69.5_a	98.0_b	118_c
Burst Index (kPa m^2/g)	5.8_a	8.9_b	10.3_c
Brightness	29.3_a	25.8_b	24.5_c
Opacity % (ISO)	95.3_a	93.2_b	90.5_c
Fracture Toughness (Jm/kg)	21.8_a	-	36.4_b
Fibre Properties			
Fibre Length (NA mm)	1.93_a	1.64_b	1.41_c
Fibre Length (LWA mm)	2.95_a	2.76_b	2.63_c
Fibre Length (WWA mm)	3.37_a	3.24_b	3.18_c
Flexibility ($1/Nm^2 \times 10^{10}$)	16_a	-	32_b
Curl Index (LF)	0.057_a	0.118_b	0.111_c
Kink Index (LF)	0.37_a	1.00_b	0.94_b
Coarseness(mg/m)	0.183_a	0.202_b	0.205_b
Pulp Properties			
Screened CSF (ml)	707_a	643_b	478_c
Bauer McNett Fractions (g)			
R14	7.17	-	6.14
R28	1.44	-	1.56
R48	0.94	-	0.83
R100	0.27	-	0.44
R200	0.05	-	0.11
P200	0.13	-	0.93

Table A.3: Key properties of CMP

CMP Pulp Type	Base CMP	Low90	Low180	High90	High190
Incremental Energy (kWh/t)	0	90	180	90	160
Breaking Length (km)	3.0_a	4.1_b	4.6_c	3.3_d	3.7_e
Tear Index (mNm^2/g)	11.6_a	8.7_b	7.0_c	5.7_d	4.1_e
Bulk (cm^3/g)	3.54_a	2.97_b	2.47_c	2.56_d	2.16_e
LWA Fibre Length (mm)	2.11_a	1.87_b	1.50_c	1.14_d	0.76_e
Bauer McNett R14 (g)	2.99	-	0.42	-	0
Bauer McNett Fines R200 + P200 (g)	1.07	-	1.43	-	3.11
Curl Index	0.055_{ab}	0.052_a	0.054_a	0.059_b	0.067_c
Kink Index	0.48_a	0.48_a	0.50_a	0.54_b	0.55_b
Flexibility ($1/Nm^2 \times 10^{10}$)	6.2_a	-	20_b	-	-
No. Impacts ($fibre^{-1}$)	0	50	110	20	40
Intensity of Impact ($J \times 10^{-6}$)	0	4.1	4.1	8.4	8.8

CMP fibre flexibility changes in a similar manner to that for low-intensity low consistency refined TMP. Median value increases from 6.2×10^{10} to 20×10^{10} $1/Nm^2$ as shown in Figure A.2. As with TMP, the increase in flexibility seems to come from the loss of stiffer and coarser summerwood fibres. Increased flexibility can be a major contributor to densification [Mohlin 1979, Biasca 1989, Paavilainen 1993, Karnis 1994].

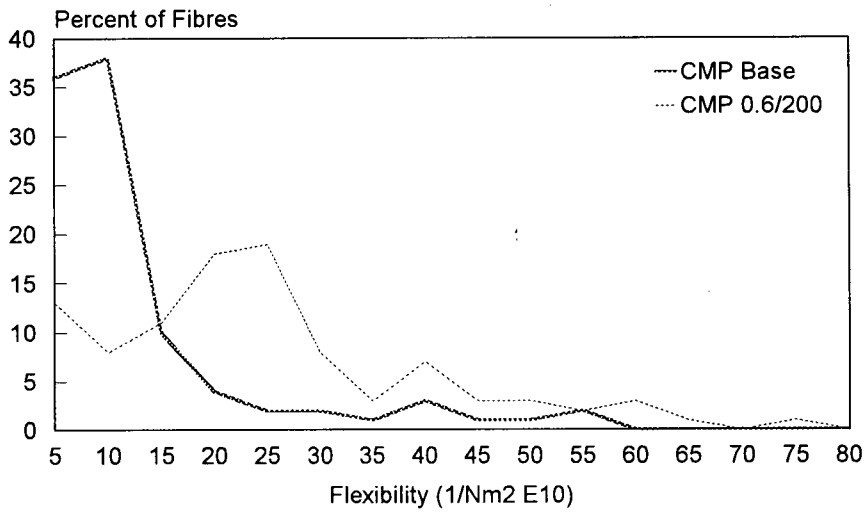


Figure A.2: CMP wet fibre flexibility distribution

Tear Index decreases by 39% for Low180 and 64% for High190. The reduction in average fibre length and loss of long fibre are primarily responsible for the large reduction in tear.

For High190, bulk decreases by 39%, which is a slight increase over the 30% of Low180. This further increase in density is due to loss of long fibre and creation of fines. This is helped by the increase in flexibility and somewhat counter-balanced by the small increase in curl and kink with high-intensity refining.

Although the tensile strength of CMP increased with low-intensity LC refining, tear index fell due to loss of long fibre and a corresponding decrease in average fibre length. Perhaps CMP requires a lower intensity than 0.6 Ws/m to maximize its potential.

A.2 KRAFT

Kraft pulp was processed with an H-factor of 1350 at a maximum temperature of 170°C, liquor-to-wood ratio of 4.5:1 and an effective alkali of 16%. This resulted in a 49% yield and Kappa number of 28.9 representing a typical kraft cook. The kraft pulp was screened on an 8 cut screen. In this thesis kraft pulp is used as a reference point for the inter-pulp type comparison in section A.4. It is refined with a refining intensity of 3.0 Ws/m and energy levels as shown in Table A.5, containing the complete results of kraft testing. Table A.4 is a summary of kraft results.

Table A.3: Key properties of kraft pulps

Pulp Type	Base Kraft	High100	High200
Incremental Energy (kWh/t)	0	100	200
Breaking Length (km)	7.1_a	10.0_b	12.1_c
Tear Index (mNm^2/g)	22.2_a	15.3_b	11.5_c
Bulk (cm^3/g)	1.74_a	1.48_b	1.39_c
LWA Fibre Length (mm)	2.95_a	2.76_b	2.63_c
Bauer McNett R14 (g)	7.17	-	6.14
Bauer McNett Fines R200 + P200 (g)	0.18	-	1.04
Curl Index	0.057_a	0.118_b	0.111_c
Kink Index	0.37_a	1.00_b	0.94_b
Flexibility ($1/Nm^2 \times 10^{10}$)	16_a	-	32_b
No. Impacts ($fibre^{-1}$)	0	15	35
Intensity of Impact ($Jx10^{-6}$)	0	13.4	13.4

With refining, the breaking length of High200 increases by 70%. Average fibre length decreases by 11% due primarily to increased fines. Essentially 10% of the pulp or one gram in total is converted from R14 fraction to fines fractions, R200 +P200 as shown in Table A.4. As already discussed the micrographs for kraft show that there has been a dramatic disruption of fibres during refining. Fibre exteriors have changed from smooth surfaces to torn and abraded pieces.

In addition to visible changes to the appearance of kraft fibres, the fibres have also become more flexible, increasing the contact area between them. Median flexibility for kraft doubles from 16×10^{10} $1/Nm^2$ for base kraft to 32×10^{10} $1/Nm^2$ for High200 as shown in Figure A.3. Of all the pulps tested, kraft showed the greatest change in measured flexibility.

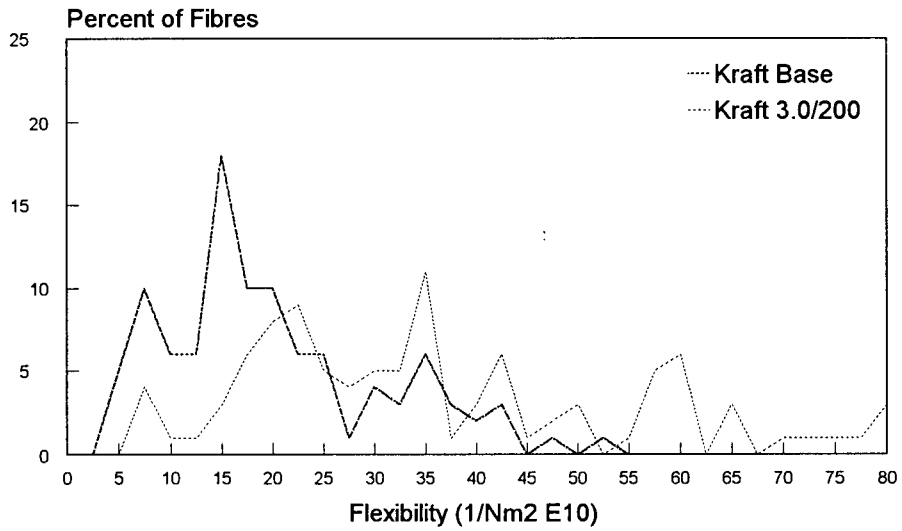


Figure A.3: Kraft wet fibre flexibility distribution

Kink index for High100 shows a very large increase. Increased kink is the major morphological change with kraft refining, as unrefined kraft fibres are very straight. LC refining introduces kinks to about the level of mechanical pulps before refining.

Tear index decreases by 48% for High200 as expected by the reduction in average fibre length. The correlation of tear and average fibre length is consistent with observations for the mechanical pulp studied in this work. For postrefined kraft there is no change in zero span and therefore no contribution from this factor in tear development or loss. For kraft pulp the significant increase in relative bonded area works to lower tear strength by concentrating tearing force at the point of rupture [Institute of Paper Chemistry Staff, 1944].

Bulk decreases by 20% for High200. The doubling of fibre flexibility is considered a major contributor to increased density [Paavilainen 1993]. The increase in fines with refining also contributes to increased density. Hartman and Higgins [1983] found that increased external abrasion increased density. Therefore roughening of the fibre surfaces, as observed in this work, may be important in density development.

In summary, the tensile strength of kraft pulp increases with LC refining due to higher bondable area from increased flexibility and creation of fines. There is a loss of tear strength due to the small decrease in average fibre length. These changes are as expected.

APPENDIX B

The Escher Wyss Refiner - A Tool for Pulp Evaluation

The following paper was completed early in the work done for this thesis. It is a simplified overview of the potential usage of the Escher Wyss refiner. This paper placed second in the annual Canadian Pulp and Paper Association (Pacific Coast Branch) paper competition held in Parksville, B.C. April 1992.

The Escher Wyss Refiner:

A Tool for Pulp Evaluation

John D. Hoffmann - Pulp and Paper Research Institute of Canada, Vancouver

Lorrie V. Welch - Pulp and Paper Centre, U.B.C.

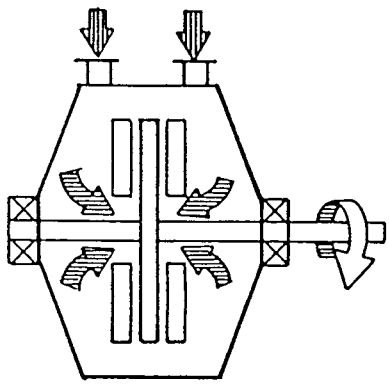
ABSTRACT

Pulp refining is an important step in papermaking. However it is not well understood. Variations in the operating parameters, the refiner, its plates, or the furnish can significantly influence the refining action thus changing the drainage and strength characteristics of the pulp. The Escher Wyss laboratory refiner at Paprican can simulate mill conditions. The effect of refining variables such as intensity and energy can be investigated with a small sample of pulp.

This paper reviews the Paprican experience with the Escher Wyss refiner. Refining theory and the potential application of the equipment for pulp evaluation are discussed.

INTRODUCTION

Generally pulp refining, as opposed to chip refining, involves mechanically treating paper stock before the papermachine to improve the quality of the resultant sheet. In Canada pulp refining is usually performed in parallel plate disc refiners, although conical units are also used. Many refiners contain a double surfaced rotor which floats between 2 stationary discs as shown in Figure 1.

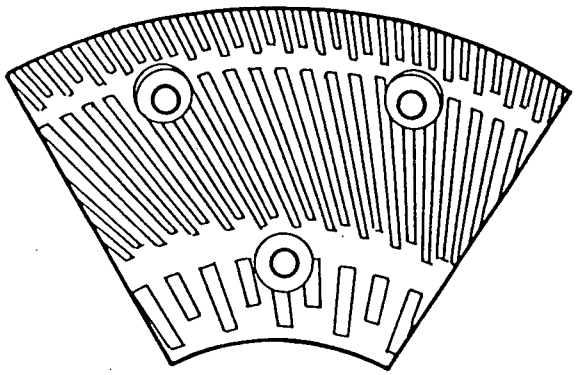


Source: N. Webster, Sprout-Bauer Andritz

Figure 1 - Schematic of twin-flow refiner

Each surface has a varying bar and groove pattern as shown in Figure 2. The height, width and arrangement of the bars can vary significantly and play an important role in the refining results. The design of the bars and grooves should be chosen to fit the pulp stock and the

specific operating conditions. In the case where a significant amount of refining is required, recirculation or refiners in series are used to increase the residence time in the units and further the effects of refining.



INTERMEDIATE CUTTING
AND DEVELOPMENT

Source: N. Webster, Sprout-Bauer Andritz

Figure 2 - Typical plate pattern

Once the refining equipment has been installed and a plate pattern has been selected, the variables are limited to motor load, specific energy, throughput and variations in the stock (e.g. furnish mix, temperature, pulping method and yield, incoming freeness, etc.). Usually feedback on the performance of the refiners is provided by manual freeness tests and the runnability of the stock on the papermachine.

Although all the factors stated above influence the final product, one of the most significant contributions is the species or wood type used. Figure 3 illustrates the variability introduced through this factor alone. For example, western red cedar has long, thin-walled fibres. Douglas fir has long, thick fibres. In comparison, birch has shorter fibres and a medium coarseness.

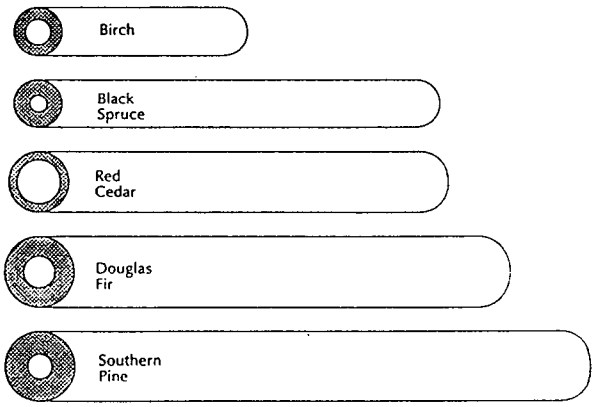


Figure 3 - Typical fibre dimensions

(Fibre lengths are shown shorter and wider than actual size for illustrative purposes.)

The pulping process (chemical or mechanical) and degree of treatment plays an important role in fibre development and the type of refining required. Accordingly, the refining conditions must be chosen to optimize each species component of the stock.

PROCESS IMPROVEMENTS

As with any part of the manufacturing process, the refining operation must be continually optimized. The papermaker needs to minimize furnish costs through the reduction of chemical pulp usage while maintaining the required sheet properties. Optimum refining of all components can help to achieve this end. Dynamic fluctuations in stock furnish, energy costs and end product requirements also demand different operating conditions.

On-line trials are one option. However, full scale trials are limited by production demands, availability of equipment and expense. Lab scale refining, for the most part, is limited to machines which do not impart the same effect as the mill scale refiner. To bridge the gap between mill refining and laboratory analysis, the Escher Wyss refiner was developed. Like commercial units, the rotor and stator have a bar and groove pattern. The refiner is operated to a target intensity and specific energy and thus can analyze variations in the plate pattern, throughput or other factors. Being a pilot plant refiner, the amount of pulp used in the Escher Wyss is much smaller than that required for on-line work. This makes it more convenient and less expensive to use then full scale equipment. As it is a separate unit, a variety of tests can be run without the concern of affecting downstream equipment.

REFINING THEORY

Different refining actions are required on the various stock components used to make paper. For example, the papermaker may need to cut or chop the groundwood component and flexibilize the kraft stock. Careful selection of the refiner, its plate pattern and operation will lead to the required result.

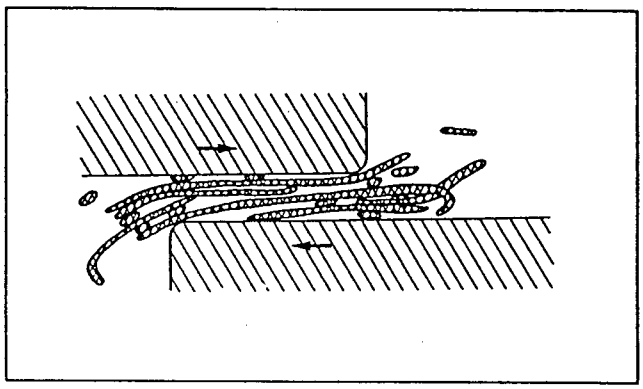
To understand a refining system, it is helpful to think about the number, N, and intensity, I, of impacts that fibres receive as they pass through the equipment. Specific energy, E, is the product of the number and intensity of impacts as shown:

$$E = NI \qquad (1)$$

According to the above equation, two parameters are needed to define the refining action. That is, once the specific

energy and the intensity of impacts is known, the refining action is defined. The number and intensity of impacts determine the refining action. For example, a few impacts of high intensity lead to a cutting action. A large number of impacts at a low intensity tends to increase the flexibility and fibrillize the outer surface of the fibres rather than cut them into pieces.

One calculation commonly used to determine the intensity of impacts is the Specific Edge Load (SEL). This calculation is based on the concept that the energy of refining is primarily transferred to the fibres as the edges of the rotor bars and stator bars cross one another and hit the fibres between them.



Source: D H Page, Ninth Fundamental Research Symposium, vol. 1, 1989

Figure 4 - Action of Refiner Bars

To calculate SEL, first determine the cutting edge length, L, from the bar pattern of the refiner plates as follows:

$$L = \frac{RPM\ Z_r Z_s Y}{60} \qquad (2)$$

Here Z_r and Z_s represent the number of bars on the rotor and stator respectively and Y is the effective length of the bars. The specific edge load is then calculated as shown.

$$SEL = \frac{P_{net}}{L} \qquad (3)$$

Constant SEL and constant specific energy conditions have successfully been used to compare the actions of various conical and disc refiners.[1,2] Generally speaking, a lower SEL leads to more homogeneous and less intense treatment of the fibres. From the above equations it can be seen that a lower SEL can be achieved by decreasing the net power, increasing the RPM, or increasing the number or length of refining bars.

In providing numerical comparisons, the SEL theory offers a good starting point for analyzing the performance of a refiner. For example, typical mill scale refining is done at a

SEL of 3 Ws/m. A number greater than this indicates a low number of high-intensity impacts per fibre which represents a cutting or chopping action. A SEL lower than 3.0 Ws/m is representative of a larger number of impacts at a lower intensity. This promotes flexibilizing and fibrillation. Thus the exact value of the specific edge load can be used as an indication of the refining results.

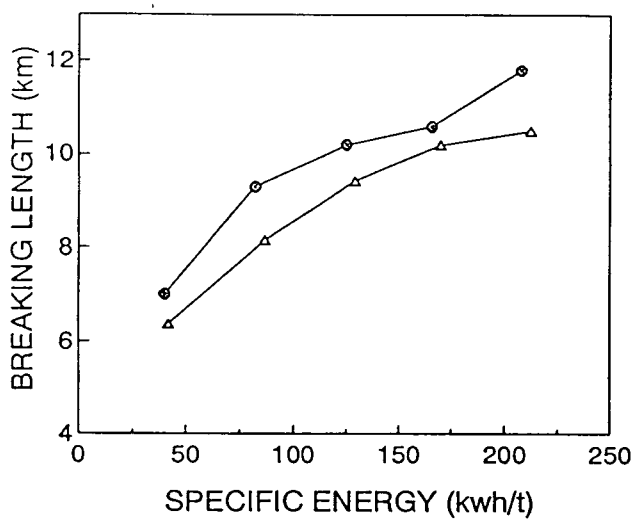
In the last few years a number of other equations have been developed which build on this theory and take into account additional refining variables.[3,4]

EXPERIENCE WITH THE ESCHER WYSS REFINER

The Escher Wyss is becoming a common laboratory tool for studying the effects of refining. It is very common in Europe. To illustrate its use, the recent conference entitled Current and Future Technologies of Refining[5] cited the Escher Wyss a total of 7 times in 12 experimental papers. It is just beginning to be used in North America where there are currently 3 units. The only Escher Wyss in Canada is located in the Vancouver lab of the Pulp and Paper Research Institute. This refiner has been in place since August 1987. To date 65 runs have been performed.

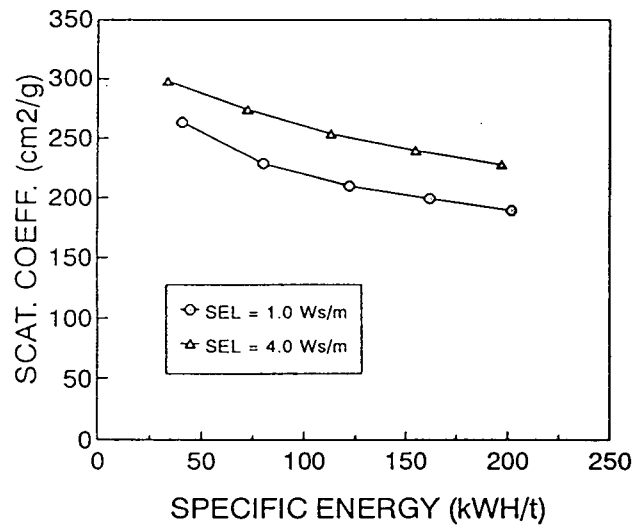
As the Escher Wyss is operated to a target SEL and specific energy, the results from its operation can be used to determine the optimum conditions for the mill refiner with the particular furnish under investigation. This information can then be used to improve the performance of the mill refiner.

Although the primary emphasis of the Escher Wyss work has been analyzing trends in sheet properties due to varying refining conditions of chemical pulps, recent work has also included refining mechanical pulp and a comparison of mill to pilot plant work based on the number and intensity of impacts.[6] A numerical correlation between the Escher Wyss and the PFI has just been completed. Typical developmental curves for Escher Wyss work are shown below.



Fully Bleached Softwood

Figure 5 - Strength Development



Eastern Canada

Figure 6 - Scattering Coeff. Development

APPLICATION

How does this help the local mills? Clearly the Escher Wyss is another tool to analyze the effects of changing refiner conditions. By closely simulating the action of mill scale refiners, it allows one to understand how the mill operation will be affected through on-line changes. Variations in stock components, operating conditions and to some extent, plate design, can be analyzed conveniently and inexpensively with a small pulp sample without jeopardizing downstream production. This information can then be used to evaluate the necessity and effects of mill scale trials. Having a tool which can closely parallel mill conditions can be a great benefit to the industry.

NOMENCLATURE

E	specific energy (kWH/t)
I	intensity of impacts (J/impact or kWH/impact)
L	cutting edge length (m/s)
N	number of impacts (impacts/fibre or impacts/t)
P_{net}	net power (kW)
RPM	rotations per minute (min^{-1})
SEL	specific edge load (Ws/m)
Y	effective length of the bars (m)
Z_r	number of bars on the rotor
Z_s	number of stator bars

ACKNOWLEDGEMENTS

We wish to thank R. Seth and R.J. Kerekes for their helpful input.

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APPENDIX C

Calibration of the Fibre Flexibility Tester

Before the pulp fibre flexibility tests were done, I calibrated the fibre flexibility tester with carbon fibres and obtained an acceptable match between calculated and experimental flexibility values for carbon fibres. Previously the unit was calibrated with nylon fibres although there is a wide range given in literature for the elastic modulus of nylon and it is believed that the elastic modulus is changed when nylon fibres are wet, as required for flexibility testing [Soszynski 1987]. Indeed in measuring the flexibility of soaking wet and just wet nylon fibres, I found the latter to be statistically stiffer at a confidence level of 99.9%. The results for carbon fibres are as shown.

Stiffness: Measured 6.81 E-11 Nm^2

with a standard deviation of 1.54 E-11 Nm^2

Calculated 9.86 E-11 Nm^2

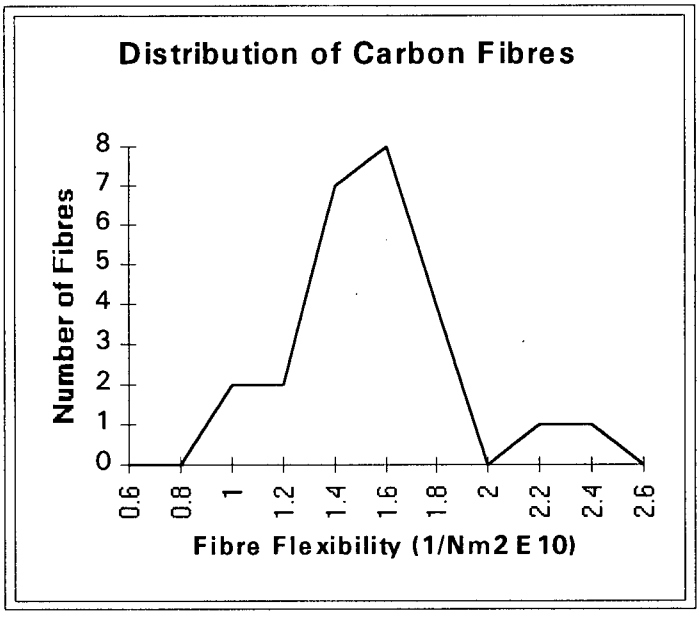

Figure C.1: Distribution of carbon fibre flexibility

APPENDIX D

FTFA Validation for Mechanical Pulp

I was the first to work with mechanical pulp on the prototype Flow Through Fibre Analyzer. I found there was considerable difficulty in running R14 samples due both to the flow cell outlet configuration and position of the data capture line in the program. When a long fibre was caught and traced, it often spanned the area from the capture line to the upper edge of the monitor. If a fibre touched the outer edges of the monitor area, this was interpreted as an error by the software and therefore not included in the fibre data base. My work showed that there were indeed fibres of this length and that by lowering the capture line the entire fibre population was recorded. This in turn corrected what, until this time, had been seen as a difference between the FTFA and the FS-200 with the FS-200 recording a longer fibre length for the R14 fraction. After this change, the mean fibre length values as calculated by the two measuring units were within 0.01 mm of each other.

As a point of interest, the banding effect seen on the long fibre fractions of TMP and CTMP was first noticed during my FTFA work.

APPENDIX E

STATISTICAL METHODS

The statistical work for my thesis follows, to a large extent, the standard procedures found in the Canadian Pulp and Paper Association statistics manual which was originally put together by the Operations Research Committee in 1969 [Canadian Pulp and Paper Association, 3d ed. 1986]. Tests for statistically significant differences were performed by the t-test at a significance level of 95% probability with the assumption of a normal distribution unless stated otherwise in the text. Proportion testing for the microscopic analysis follows that in Walpole and Myers [1978]. The Duncan multiple-range test is outlined by Walpole [1982].

Fracture toughness is calculated as the y-intercept of the work of fracture (Jm/kg) plotted against ligament length (mm) [Seth et al. 1993]. The statistical analysis for this calculation follows the technique outlined by Devore [1991] for estimating the fit of a linear regression.

Section 5.3.1 includes linear regression analysis using paper properties as the dependent variable and fibre properties as independent variables. The computations were completed in an EXCEL spreadsheet using the least squares linear regression technique with a minimum confidence level of 90% and a correlation coefficient of 80% as a minimum standard for concluding there that is a linear relationship. It is understood that both of these factors are conservative in establishing a linear relationship.