Good practice for refining the types of fiber found in modern paper furnishes

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ABSTRACT: In most cases, paper is an evolved rather than a designed product. Many paper grades are made by modifying the properties of a different but allied product. This practice may not lead to manufacturing an optimized product but rather to a compromise in product properties. Over time, papermaking furnishes have also evolved as different sources of fiber have been identified and/or established. New fiber uses have created new demands for refining methods and equipment. This paper discusses the modern refining system, optimum refining of softwoods and hardwoods, new fillings and refiners, and how to best treat fibers.

KEYWORDS: Angiosperms, fibers, fibrillation, furnish, gymnosperms, hardwoods, paper making equipment, plants, refiners, refining, softwoods.

For centuries after the advent of papermaking, the raw materials tended to be long fibered. For this reason, most beating was designed to reduce fiber length as well as to develop the fibers. Traditionally, nonwood fibers, such as flax, hemp, and cotton, were major fiber sources. The techniques of beating this fiber are very different than for the comparatively short-fibered softwood pulps and, more recently, the even shorter-fibered hardwood pulps. Even cotton linters, the rag replacement, have shorter fibers than their predecessor.

The furnishes of the early 20th century were predominantly cotton-based, with some softwood and eventually birch. Even in the 1970s, although rag and cotton linters had been replaced by relatively shorter-fibered softwood pulps in many paper products, the proportion of long (nonwood and softwood) fibers was still between 60% and 90% in products like communication papers.

From 1970 to 1990, hardwood, especially eucalypt, was increasingly used as southern hemisphere forests became major sources of chemical pulp. Current fine paper furnishes can be produced from 100% hardwood, and most contain at least 70–90%, a complete reversal of the earlier scenario.

Fiber beating has been a batch process and, in a sense, an art form. The feel of the pulp and the beaterman's knife were often the primary subjective tools used to judge proper beating. A tendency to fibrillate or cut was governed by weight on the beater roll, the material used, and the sharpness of the bars. Early refiners paid little attention to the power or energy usage of the beater process; only the time of beating was considered.

The art of beating was to subject the fibrous material to the most load without "burn through" and to attempt to reduce fiber length, providing good formation while having enough fibrillation to create tensile and burst strength. The good beaterman could judge the state of the fiber in the beater and control his process qualitatively but not quantitatively.

As beaters were replaced by refiners and batching gave way to the continuous process, the ability to "feel" the stock disappeared and control became more difficult. Much of the beating experience could no longer be applied. Therefore, once the correct refining action and equipment were established for a product, the settings and mode of operation were kept constant, even though different and shorter fibers were evolving. The current trend is directed toward reducing fiber

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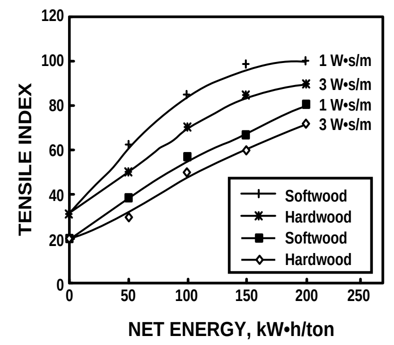
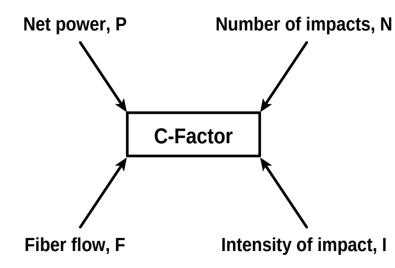
length, as softwood or long-fibered refiners and fillings are used for hardwood in older systems.

Over the last 20–30 years, equations have been derived for the refining process. These equations allow quantification of the refining process, the evaluation of optimum treatment for each species, and application to the production system. Because refining is arguably the most important papermaking step, incorrect practices at this stage are very difficult to rectify later in the process.

1. Effect of SEL for softwood and hardwood kraft pulps



2. Optimized refining of softwood and hardwood pulps



I. Operating characteristics

Characteristic	*Jordan*	*Wide-angle*	*Shallow-angle*
Motor power, kW	263	250	200
No-load power, kW	132	85	35
Rotational speed, rpm	419	360	740
Efficiency, %	50	66	82
Cutting edge length, km/s	30–80	23–44*	30–150

*Excluding special “Develomax” filling

Quantification of refining

In recent years, process and equipment parameters have been used to describe the refining process with an emphasis on energy usage. Knowing how this energy is used is essential to understanding the refining process.

The specific edge load (SEL) theory presented by Wultsch and Flucher is widely accepted *(1)*. Danforth *(2)* and Lieder *(3, 4)* later developed equations also relating to the severity and number of impacts. Because of its ease of application, the specific edge load theory is the most widely used *(5)*. In this theory, the power applied to the bar edges is considered to be most critical, having seven times the effect of bar width.

$$B_s = P_n/L_s \quad (1)$$

$$W_e = P_n/m \quad (2)$$

where

B_s = Specific edge load, W·s/m

P_n = Net power, kW

L_s = Cutting speed, m/s

W_e = Specific net energy, kW·h/ton

m = Dry fiber flow, tons/h.

Eqs. 1 and 2 are linked by Lieder’s term for a number of impacts:

$$N_i = L_s/m \quad (3)$$

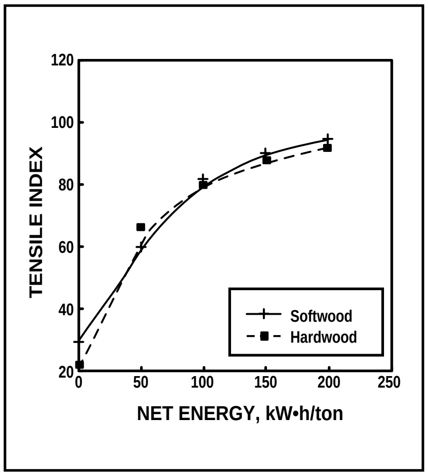
These formulae, although not exact mathematical expressions, are used to visualize the refining process.

A high SEL denotes a tendency to cut, whereas a low value gives fibrillation (**Fig. 1**). Using this theory, a clearer picture of how to treat different fibers emerges. A tough softwood fiber requires a high SEL, whereas the relatively weaker hardwood fibers require a much lower SEL. Evaluating Eqs. 1 and 2, the following refiner and stock parameters are of prime importance: refiner power (kW), no-load power (kW), type of refiner tackle (for L_s), rotation speed (for L_s), consistency of stock (for m), and volumetric flow.

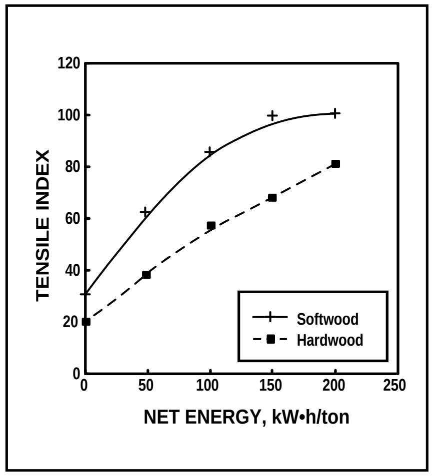
The number and length of bars in a refiner tackle, combined with the rotational speed of the motor, determine the ability of that tackle (or refiner) to cut or fibrillate in an efficient manner. New terms are currently being developed to predict the refining process. These terms focus on the severity of impact received by the fibrous mat. As its name implies, the specific edge load theory only takes into account the effect of the bar edge; it ignores the effect of bar and groove width. However, accounting for these parameters changes the number of available cutting edges and hence the specific edge load *(5)*.

Two terms, the specific surface load (SSL) *(6)* and C factor *(7)*, have been postulated to describe the severity-of-impact term. The former takes into account the area of contact. The following equation relates

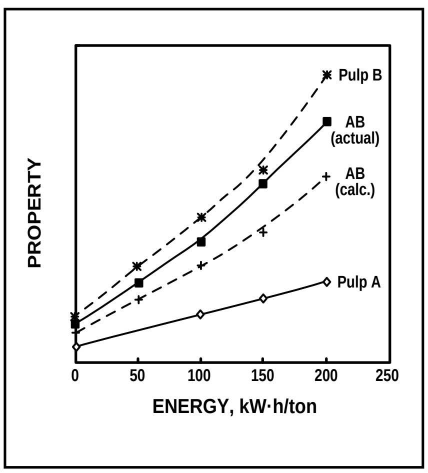
3. Comparison at equal refining intensity



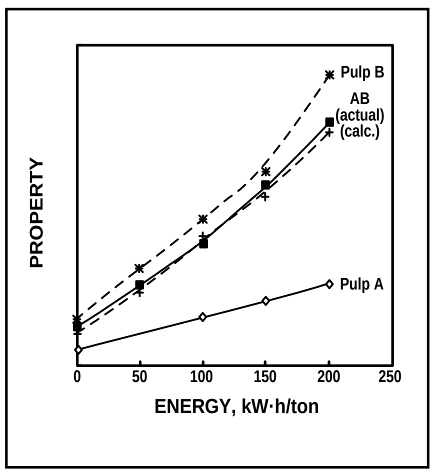
4. Uncorrected comparison



5. Corrected for protection



6. Results for 1-1-2 filling



SEL to the bar area and is expressed as W·s/m^2.

$$SSL = SEL/\text{Bar width factor} \qquad (4)$$

The C factor represents a refiner's capacity to impose impacts on pulp fibers. Equations have been derived to compute the factor from refiner variables, fiber length and coarseness, and consistency. Conical and disc refiners have different C factors. The C factor links the power input and pulp mass flow through a refiner to the average number and intensity of impacts imposed on the fibers (**Fig. 2**).

Because the SSL and C factor represent somewhat new and unproven theories, the specific edge load theory will be referred to in the following description of the refining process.

Application of theory to practice

In order to apply the specific edge load theory to the production of various grades of paper, consider the diverse requirements of several papers:

- Security papers require short, *cut* fibers to give good watermarking while needing longer, *fibrillated* fibers to give the strength and feel needed for such a high-quality paper.
- Coating papers need high strength from relatively highly refined, fibrillated fibers to give runnability in the coaters, but demands of dimensional stability require a moderate degree of fibrillation to reduce shrinking on contact with aqueous coating mixes.
- Glassines and tracings need the water holdout and translucency that come from highly fibrillated fibers but also require high tear strength given by stock with little refining and long fiber length.

The desired properties can be imparted by furnish selection and correct refining. The science of refining ensures that this is done with the right equipment under the right conditions. Only then will energy use be optimized and the best quality product be made.

Refiner and stock parameters

The refining parameters previously described can be combined in many ways in different refiners.

Main types of paper mill refiners

A refiner manufacturer's manual states, "It should be noted that, within certain limits, when a refiner is properly applied, there is not a great difference between conical and disc refiners regarding their ability to develop fibers. In other words, a fiber cannot read the label on the refiner and does not know if it is in a disc or a conical refiner. It is aware of only two things—how many times it is hit and how hard it is hit each time."

The refiner chosen must provide the proper treatment for the product being made. Only when this primary consideration has been taken into account should the other important considerations, such as reliability and efficiency, be considered. This section describes the major types of refiners.

II. Mixed vs. separate refining

Product	Average throughput, tons/h	Gross energy, kW·h/ton
A (Mixed)	7.8	175
A (Separate)	8.5	132
B (Mixed)	7.7	179
B (Separate)	8.2	131

III. Filling parameters

Filling geometry	CEL,* km/s	SEL at max. power, W·s/m
2-2-4	32	1.25
1.5-1.5-3	60	0.7
1-1-2	145	0.3

*Cutting edge length

Jordan or low-angle conical refiner

The Jordan refiner is found in many paper mills but has a number of drawbacks when compared to the shallow-angle conical and double-disc refiners:

- High no-load power, which translates to a low operating efficiency. The efficiency is less than 50% in many applications.
- Lack of flexibility. There are a limited number of fillings for these refiners.
- The fillings have few bars. As a result, refining intensity is high and not suitable for short-fibered pulps.

Wide-angle conical refiner

The most widely used version of this refiner is the Bematec Claflin, in which the cone angle has been increased to 60°. This refiner, found in many mills, is considered a robust design. A particular feature is the Develomax filling, which simulates the action of a basalt lava filling. This gives a very low SEL, once considered ideal for use on tracing and glassine-producing machines. This refiner is a good softwood refiner, but the coarse fillings and slower rotation speed preclude its use for hardwoods.

Sunds-Jyhla Conflo conical refiner

The Conflo refiner, a relatively new conical refiner design, is now well established in the marketplace. Its claimed advantages are low no-load power and a long refining zone. This unit's outer casing is also the shell, which decreases the time for filling changes compared to conventional conical refiners. The groove depth is relatively shallow, reducing the no-load energy requirement arising from pumping. The fillings for this refiner can have more bars, so the cutting edge length can be greater than for other conical refiners.

Comparative efficiencies

Typical operating parameters for different conical refiners of similar treatment capacity are shown in **Table I.** The Conflo uses a faster motor, which increases the cutting edge length. In spite of the higher rotational speed, the unit has a lower no-load power requirement and a much higher efficiency than conventional conical refiners. The Conflo refiner is therefore an energy-efficient replacement for older conical refiners and offers a range of fillings that are suitable for softwood and hardwood pulps.

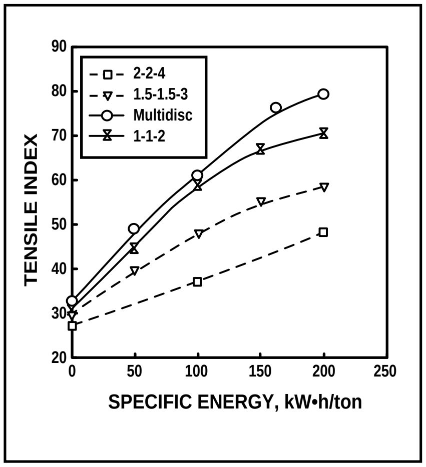
Double-disc refiner

The double-disc refiner offers a greater efficiency than standard conical refiners and greater potential for treatment because of its two internal zones. The unit also offers considerable operating flexibility because of the diversity of its plate design. Standard fillings offer (for a similar size) a range of bar lengths similar to the Conflo refiner. However, the disc refiner offers a large number of short bar impacts, whereas the Conflo unit offers a lesser number of long bar impacts.

The two zones of the double-disc refiner allow a higher energy input per refiner for a given SEL. This means that a number of Jordan refiners can theoretically be replaced by one double-disc unit. For example, to treat stock to an SEL of 1.0 W·s/m with a net energy input of 100 kW·h/ton (net) to achieve the properties for a printing paper on a 1.0-ton/h machine, four Jordan refiners, operating at 22 kW·h/ton (gross) would be required.

One 24-in.-diam. double-disc refiner operating at 175 kW·h/ton (gross) could supply the same net energy with improved properties, saving 45 kW·h/ton. Similarly, a Conflo refiner of equal size could supply the same net energy at 135 kW·h/ton (gross), saving 55 kW·h/ton.

7. The effect of various filling designs on the development of hardwood fibers



Monoflo and duoflo operation

Having two zones, a double-disc refiner can be internally configured for series or parallel operation; this is known as monoflo or duoflo operation. In monoflo mode, stock flows sequentially through each zone; in duoflo, stock flows through each zone simultaneously. In duoflo mode, the refiner has twice the capacity of monoflo operation.

By blocking or unblocking the passages through the rotor, a double-disc refiner can be changed from duoflo to monoflo mode. This can be necessary where fiber usage changes (e.g., with increased hardwood or reduced softwood content) to allow modification of the flow characteristics of each refiner. With duoflo operation, it is easier to maintain equal gaps in the two zones.

Stock parameters

Important stock parameters include pH, consistency, fiber morphology, and chemical composition. Most modern papermaking furnishes are mixtures of fiber species, minerals, and other additives. Each fiber type requires a different type of refining treatment.

Nonwood fibers

The most common nonwood fiber is cotton, which is normally used in linters. Other types are hemp, esparto, jute, and flax. The fibers are characterized by their length and a tendency to form tight clumps when treated in high-speed refiners. For this reason, it is common to reduce the fiber length in a beater before refining. The normal practice is then to refine with coarse tackle using low-speed conical refiners.

Suggested fillings are:

- Jordan-type refiner with 0.375-in.-wide bars and grooves or coarser
- Claflin filling (Reference F1)
- Sunds-Jyhla filling Type BB
- Double-disc (linters only) 4-4-5 (sixteenths).

Refining consistency should be as low as possible without causing plate clash.

Softwood fibers

Softwood fibers are relatively long compared to hardwoods and are tougher, requiring a moderately harsh treatment. In SEL terms, an intensity of 2.0 W·s/m is considered optimum, with an operating range of 1.5–3.0 W·s/m. In this case, optimum refining is considered to be that which gives the best property balance. To give a well formed sheet, the softwood should be cut as well as fibrillated for strength. Suggested conditions are:

- Fairly coarse-barred filling with shallow angle
- Medium specific energy input (about 100 kW·h/ton) to give strength and retain tear
- Refine at about 4% consistency. This reduces fiber length and develops this tougher fiber.

Possible fillings for this fiber might be:

- Jordan-type refiner with 0.188-in.-wide bars and grooves or coarser
- Claflin-type refiner (Reference F9)
- Sunds-Jyhla filling Type AA or AB
- Double-disc (linters only) 3-3-4 or 2-2-4 (sixteenths).

Hardwood fibers

Hardwood fibers (e.g., eucalypt, birch, and mixed hardwoods) have traditionally been used as filler pulps with little refining treatment. The modern papermaker, however, treats hardwoods in order to develop their maximum potential. In order to do this, the refining process must be gentle. Birch generally has the highest strength and mixed hardwood has the lowest, depending on the fiber species used. All hardwoods require the following conditions:

- Low intensity or specific edge load, with a range of 0.5–1.0 W·s/m, for a good property balance
- Fairly high specific energy inputs of up to 150 kW·h/ton, to develop strength and, in the case of eucalypt fibers, tear and reduced vessel picking
- Higher consistencies (5–6%), to avoid fiber length reduction and increase fiber-to-fiber friction.

Suggested refiner fillings are:

- Claflin refiner—Develomax-type filling or F3
- Sunds-Jyhla filling Type FF or preferably EE
- Double-disc refiner 1.5-1.5-3 (sixteenths).

Secondary fiber

The increasing use of secondary fiber poses another problem, because this fiber consists of a mixture of fibers. Both chemical and mechanical and nonwood and wood fibers, which have already been refined, are present. It is normal to use these materials without further refining treatment, but there is a trend toward further refining as methods of "upcycling" are sought. The first inclination is to give a very gentle treatment, as though one were dealing with a hardwood. The problem with this approach is that the previously refined fiber is now over-refined to the point where properties begin to degrade, and strength is reduced. The best practice is to treat the fiber at a low to medium intensity (0.7–1.5 W·s/m), depending on the type of waste. A good-quality office recovered paper can cope with more treatment than newsprint or old corrugated containers.

Because furnishes are mixtures of these fibers requiring very different treatments, they should have separate treatment for each type of fiber whenever possible. However, especially for smaller machines, the fiber flows would be too low to have separate lines; mixed refining is the only option.

Refining of pulp blends

The refining methods for a mixture of softwood and hardwood may be described as follows:

- **Mixed refining.** All components are treated equally in the same refiner.
- **Split mixed refining.** There are two or more refiners in line. The first refiner is set up to treat the softwood component and the second and subsequent refiners treat the hardwood component.
- **Sequential refining.** The softwood component is refined separately, the hardwood is added, and the mixture is refined to the desired specification.
- **Separate refining.** Components are refined individually using the optimum treatment.

The mixed and separate systems are the most common. Given the different refining characteristics needed by the two types of fiber, as more short fiber is used, a change in refining methods is necessary. Furthermore, refining softwood and hardwood fibers as a mixture does not provide the best development for either fiber.

Figure 3 shows refining curves for a bleached softwood and a hardwood kraft at the correct refining intensity, where strength properties are nearly equal. Compare this with **Fig. 4,** in which both pulps have been treated in the same way.

Mixed furnish refining

When a furnish is refined as a mixture, the larger softwood fibers tend to protect the thinner hardwood fibers and receive most of the treatment. This is true in practice *(8, 9)*, where unrefined hardwood fibers were found in a blend with softwood that had been refined to 30°SR in mixture.

The linear blending theory states that the properties (P_{AB}) of a furnish consisting of components A and B can be predicted from the arithmetic mean of the two components:

$$P_{AB} = \%P_A \times \%P_B \qquad (5)$$

When calculating the properties of a furnish from its component properties using the linear blending theory, the calculated results differ greatly from the actual results obtained when refining in mixture (**Fig. 5**). However, if the results are calculated as though the softwood component has received more energy than the hardwood component, the calculated results are much closer to actual values (**Fig. 6**).

For mixed furnishes, good compromise fillings are:

- Claflin refiner F9 or F3
- Sunds-Jyhla filling Type AA, AF, or FF
- Double-disc refiner 2-2-4.

Separate furnish refining

To develop the maximum potential from a furnish, the components must be treated individually. The benefits of separate refining can be seen in **Table II.** This shows the change in energy requirement when a mill system was changed from mixed to separate refining of softwood and hardwood to give optimum treatment to each fiber type. The change to separate refining enabled increased throughput and reduced refining energy by about 25%.

System design

When designing a system to treat modern furnish with a high hardwood content, care must be taken to incorporate optimum treatment and energy efficiency by using the correct fillings and refiner.

Refiner fillings

Softwood refining. Fillings used for optimum treatment of softwood kraft are readily available for both conical and double-disc refiners. As softwood content decreases, there is a trend toward using finer fillings to maximize the strength potential.

Hardwood refining. For all current-production refiners, available fine fillings allow moderately efficient refining of hardwood pulps. New fillings are continually being developed by refiner manufacturers. A new type of filling on trial at Pira International is described in the literature *(10)*.

When considering most hardwood kraft pulps, gentle treatment is required. In conventional refiners, good results are achieved with refining intensities of less than 1.0 W·s/m (commonly operating between 0.7 and 0.9 W·s/m). However, research work at much lower intensities, such as those achievable with the Beloit Multidisc, shows that an optimum intensity, providing the best balance of properties, is less than 0.5 W·s/m.

The refining development of softwood and hardwood kraft pulp strength properties shows marked differences. With increasing amounts of hardwood used, as well as ever-increasing speed and demands of converting processes, strength is at a premium. As previously shown, using a very low SEL (0.2 W·s/m) on eucalypt kraft provided strength equal to a softwood kraft at the optimum intensity (2.0 W·s/m). The only refiner currently able to achieve an SEL of 0.2 W·s/m in an efficient manner is the Beloit Multidisc unit.

In the work described here, a specially machined filling was tested at Pira International using a 12-in.-diam. double-disc Beloit refiner. The filling used was a 1-1-2 (sixteenths); the relevant parameters of the fillings used for comparison are shown in **Table III.** Initial observations were that the new type of filling caused no throughput problems and there was no groove plugging. Results from these trials are shown in **Fig. 7.** Changing from the best current practice (1.5-1.5-3) to the new fillings could, for a hardwood kraft, offer energy savings of at least 50 kW·h/ton (gross) for a refiner operating at 120 kW·h/ton. Also, the similarity in development between this filling and the Multidisc should be noted. These fillings are currently in use at a South African mill on 42-in.-diam. double-disc refiners.

Types of refiners

Softwood. Any refiner can be used, with the correct filling, to treat a softwood kraft, but the most efficient refiner for this purpose is probably the shallow-angle conical refiner, because of its low no-load power requirement. There have been no recent refiner developments for refining softwoods. For all types of softwood, the range of fillings currently supplied provides the correct treatment.

Hardwood. New refiner designs, such as the Multidisc *(11)* and medium-consistency (14–25%) refiner *(12),* offer opportunities for very low specific edge load refining. This can further the development of hardwood properties to a point where softwood and hardwood pulps can give nearly identical properties. The Multidisc refiner is being applied to the postrefining of mechanical pulps and the treatment of hardwoods. The SEL is too low for softwood refining.

The medium-consistency refiner is being used to treat waste furnishes for upgrading. An interesting point is that each fiber species performs best at a different consistency. Using well designed systems, many papermakers are making good-quality paper (e.g., copier, printing, and writing paper) from 100% hardwood, especially eucalypt. The trend for modern fine papermaking is to develop short fibers rather than to cut long fibers and then develop them.

Conclusions

The following conclusions can be drawn:

- The modern refining system features refiners that are designed to fibrillate rather than to cut as increasingly higher proportions of hardwood fiber are used.
- When refining softwood, the optimum treatment occurs when an SEL of 2.0 W·s/m is used to an energy level of 80–120 kW·h/ton. Refiners that are currently available have a range of fillings that enable this best-practice refining.
- When refining hardwood, the optimum treatment, in terms of strength, occurs at an SEL of 0.2 W·s/m over an energy range of 100–150 kW·h/ton. The increasing use of hardwood can yield a well formed, strong sheet if the correct refining is used.
- Refiner systems should be designed to separately refine each component where production rate permits, thereby gaining the maximum potential for each fiber.
- New fillings and refiners will make it possible to achieve equal strength for hardwoods and softwoods.
- Finally, *how* a fiber is treated is more important than *what* is used to treat it. TJ

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