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Chapter 4

Refining of chemical pulp

4.1 Targets of refining

Refining or beating of chemical pulps is the mechanical treatment and modification of fibers so that they can be formed into paper or board of the desired properties. It is one of the most important unit operations when preparing papermaking fibers for high-quality papers or paperboards.

The term "beating" dates back to the early days of papermaking when beating was effected by manually beating pulp with a stick, but has remained in use to this day to describe the mechanical treatment of wet fibers. The term was generally used earlier when the equipment commonly used in the process was Hollander beaters, but various refiners have now replaced beaters and the term "refining" is widely used. In fact, both terms are synonymously used, but here the term "refining" is used to describe the work accomplished with refiners on the fibers.

The main target of refining is to improve the bonding ability of fibers so that they form strong and smooth paper sheet with good printing properties. Sometimes the purpose is to shorten too long fibers for a good sheet formation or to develop other pulp properties such as absorbency, porosity, or optical properties specifically for a given paper grade.

4.2 Principles of refining

The most commonly used refining or beating method is to treat fibers in the presence of water with metallic bars. The plates or fillings are grooved so that the bars that treat fibers and the grooves between bars allow fiber transportation through the refining machine. Figure 1 demonstrates all refining stages. At first, fiber flocs are collected on the leading edges of the bars. During this fiber pick-up stage, the consistency is typically 3%–5% (sometimes, in special applications, 2%–6%) and the fiber flocs comprise mainly water.

When the leading edge of the rotor bar approaches the leading edge of the stator bar, the fiber floc is compressed and receives a strong hit. As a result, most of the water is compressed out of the floc. Simultaneously, short fibers with low flocculation ability are probably peeled off (escape the floc together with water) and flow into the grooves between the bars. Only those fibers remaining in the floc are compressed between two metallic bar edges and receive refining.

Figure 1. *Refining mechanism.*

After this, both leading edges slide along the fiber floc and press it against the flat bar surface. In low-consistency refining, the average gap clearance is 100 μm. It corresponds to the thickness of 2–5 swollen fibers or 10–20 collapsed fibers. Most refining is performed during this edge-to-surface stage when bar edges give mechanical treatment and friction between fibers gives fiber-to-fiber treatment inside the floc. This stage continues until the leading edges reach the tailing edges of the opposite bars. After the edge-to-surface stage, the fiber bundle (floc) is still pressed between the flat bar surfaces until the tailing edge of the rotor bar has passed the tailing edge of the stator bar. The above described refining stages exert one refining impact on the fiber bundle, and the length of the refining impact depends on the width and intersecting angle of bars[1].

When the rotor bars move across the stator bars, there are quite strong vortex flows in the grooves between bars, and this phenomenon gets fibers stapled on bar edges during the fiber pick-up stage as shown in Fig. 2[2]. If grooves are too narrow, fibers or fiber flocs cannot rotate in the groove and do not get stapled on bar edges, and those fibers staying in the grooves pass the refiner without receiving any refining impacts.

Figure 2. *Vortex flows and fibers stapling on bar edges.*

The refining results to a great extent depends on the stapling of fibers on the bar edges and on the behavior of the fibers in the floc during refining impacts. Long-fibered softwood pulps easily get stapled on the bar edges and build strong flocs that do not easily break in refining. Decreased gap clearance hastens refining degree change and increases fiber cutting. On the contrary, it is more difficult to get short-fibered hardwood pulps stapled on the bar edges, and they build weak flocs that easily break in refining. Decreased gap clearance means slower refining, and bars easily establish contact.

4.3 The effect of refining on fiber characteristics

Refining affects fibers in many ways, with the most important effects[3] being as follows:

- Cutting and shortening of fibers
- Fines production and complete removal of parts from fiber walls, creating debris in suspension
- External fibrillation, the partial removal of the fiber wall, leaving it still attached to the fiber
- Internal changes in the wall structure, variously described as delamination, internal fibrillation, or swelling
- Curling the fiber or straightening the fiber
- Creating nodes, kinks, slip planes, microcompressions in the cell wall, or removing those from cell wall
- Dissolving or leaching out colloidal material into the external liquor
- Redistribution of hemicelluloses from the interior of the fiber to the exterior
- Abrasion of the surface at the molecular level to produce a more gelatinous surface.

As a result of the above effects, fibers after refining are collapsed (flattened) and made more flexible, and their bonding surface area is increased. The measurable fiber and sheet properties, when refining chemical pulps, can be seen as follows:

- Drainage resistance (water removal resistance) increases.
- Tensile strength, tensile stiffness, burst strength, internal bonding strength, and fracture toughness increases.
- Tear strength of softwood fibers might slightly improve at first, but then decreases, whereas that of hardwood fibers at first significantly increases but then decreases after prolonged refining.
- Air permeability, bulk, absorbency, opacity, and light scattering decreases.
- Brightness slightly decreases.

The main effects are visible in Fig. 3, which shows unrefined pulp and refined pulp after applying in total 340 kWh/bdmt net refining energy. The multipass refining, 85 kWh/bdmt in each pass, was performed at 4.2% consistency. In this chapter, bdmt is equal to moisture-free metric ton.

***Figure 3.** Unrefined and refined bleached softwood kraft pulp fibers.*

***Figure 4.** Factors affecting refining result.*

4.4 Theories of refining

Refining results depend on many factors as indicated in Fig. 4. Fiber-based factors such as wood species/origin and pulp manufacturing affect the obtainable refining results and establish requirements for refining. As fiber-based factors are established before pulp arrives in paper mills, the refining system must be able to provide suitable refining for various fibers.

Several refining theories have been developed in order to determine the most suitable refining system and control and to determine refining conditions. The use of refining theories, which mathematically describe the refining action, goes back more than a century, pioneered as long ago as 1887 by Jagenberg. He introduced such terms as "edge length per second" and "beating area," both of which are still used as a basis for further investigations[4]. Since that time, a number of different theories have been developed and Ebeling has presented an excellent review of those theories[5]. However, in this chapter, we do not go into detail of deep fundamental aspects of the refining process; therefore, only four theories are included. One important feature of these theories is that they work independently from the size of mill-scale refiners and can be used both for conical-type and disc-type refiners.

Because high-consistency refiners run at much higher rotation speed with much larger gap clearance and because there is steam instead of water, the following theories are only used in low-consistency refining.

The common feature of low-consistency refining theories is that the total or gross applied refiner power is divided into two components. The net refining power, which is the fiber-treating component, is the total absorbed refiner power minus no load power or idling power. The no load power is measured with water flowing through the running refiner, and the gap clearance is as narrow as possible without fillings or plates touching each other or any substantial increase in power. Total power, of course, depends on the actual running situation. Often the refining resistance of fibers determines the maximum loadability, but the ultimate limit is set by the torque moment of the refiner. This torque-based maximum total power increases linearly as the rotation speed of the refiner increases.

The no load power increases exponentially as the function of rotation speed or rotor diameter. The effect of the rotation speed is approximately to the 2.8 power (exponent) and the effect of the rotor diameter is approximately to the 4.2 power. The following table shows no load power for two medium angle conical and for two double-disc refiners. Smaller refiners Conflo JC-01 and double-disc DD 20 in. are comparable as are bigger refiners JC-04 and DD 42 in.

Table 1. No load power of various refiners.

Smaller refiners JC-01 and DD 20 in.			**Bigger refiners JC-04 and DD 42 in.**		
Speed	No load power, kW		Speed	No load power, kW	
rpm	JC-01	DD 20 in.	rpm	JC-04	DD 42 in.
1 500	150	–	750	610	–
1 200	82	130	720	550	–
1 000	50	73	600	340	390
900	40	50	514	220	250
750	27	35	500	200	230
720	24	32	400	115	120

Figure 5 shows power curves for a relatively small-sized conical, JC-01, refiner. The area between maximum total power line and no load power curve shows maximum available net power at various rotation speeds. For example at 1 000 rpm this refiner has typically a 250 kW motor, which at full load gives 200 kW net power because the no load power is 50 kW.

Figure 5. *Effect of the rotation speed on refiner power.*

4.4.1 Specific edge load theory (Wultsch and Flucher, Brecht and Siewert)

One of the best known and most widely used refining theory is the "specific edge load theory." In 1958, Wultsch and Flucher introduced the term "refining intensity" as the quotient of effective refiner load and edge length per second[6]. Then Brecht and Siewert defined the "refiningintensity" term as specific edge load in 1966[7]. This theory can be considered as a two-parameter characterization of pulp refining. It comprises two factors which are used to describe how much the fibers are treated and how intensively they are hit. The amount of the refining is described by evaluating the specific refining energy, SRE, in net [kWh/t] and the nature of refining is evaluated by the specific edge load, SEL, which describes the intensity of the refining impacts in [J/m or Ws/m].

$$SRE = \frac{Pt - Pn = Pe}{F \times C} \quad (1)$$

$$SEL = \frac{Pt - Pn = Pe}{Zr \times Zst \times l \times n = L \times n = Ls} \quad (2)$$

where SRE is specific refining energy [kWh/bdmt],
SEL specific edge load [J/m],
Pt total absorbed refining power (refiner load) [kW],
Pn no load power (idling power) [kW],
Pe effective refining power (net power) [kW],
F flow [L/min],
C consistency [%],
Zr, Zst number of rotor and stator bars
l common contact length of opposite bars [km]
L cutting edge length [km/rev],
n rotation speed [1/s] and
Ls cutting speed of bars [km/s].

Figure 6. *Cutting edge length calculation.*

Independently of the type of the refiner in question, cutting edge length of bars, CEL or L, is calculated in a way similar to that illustrated in Fig. 6. Typically, bars are slightly inclined in conical and disc refiners so there are no parallel bar crossings.

From its derivation, the specific edge load is a measure of the energy expended per unit length of bar crossings. It only tells the amount of net energy transferred by a one meter long bar edge crossing to the fibers; it does not tell how the fibers have received this net energy input.

The SEL theory fails to consider many important factors having influence on the obtainable refining result. For example, it does not pay any attention to such factors as net energy input during one-pass, refining consistency, width of bars, fibers stapling on bar edges, condition of fillings, and gap clearance. It only considers the length of the bar edges and assumes that the refining result is independent of the above mentioned factors. This theory is very commonly used worldwide because it is easy to use, it only comprises simple calculations, and all factors are readily available. Experienced papermakers know approximately what kind of fillings and specific edge load should be used when refining certain pulp at a given consistency.

4.4.2 The specific surface load theory (Lumiainen)

Lumiainen further developed the idea from specific edge load theory assuming that the energy is transferred to the fiber bundles, during short edge-to-edge contact phase as well as during the edge-to-surface phase. Accordingly, in 1990 he presented his definition of refining intensity as specific surface load[1].

During the following year, his theory developed into its final form. The amount of refining (net energy) is the result of the number and energy content (specific edge load) of refining impacts; the nature of refining (previously specific edge load) is the result of intensity (specific surface load) and length of refining impacts. By combining four previous factors, the amount of the refining or specific refining energy, SRE, becomes the result of three factors and is obtained by multiplying the number, the intensity, and the length of refining impacts[8],[9].

$SRE = IN \times SSL \times IL$ (3)

where SRE is specific refining energy [kJ/kg],

IN number of refining impacts [km/kg],

SSL specific surface load [J/m2] and

IL bar width factor [m].

The last two factors describe the nature of refining by considering both the real intensity, SSL, and the length, IL, of the refining impact. The number of refining impacts having a given intensity and length determines the refining energy.

The number of refining impacts, IN, is obtained by dividing cutting speed (number of generated impacts) by fiber mass flow, M. The impact number figure (km/kg) only tells number of generated refining impacts when a given fiber mass flow has passed through the refining system. It does not tell at all how many fibers have received refining impacts.

$IN = \frac{Ls}{M}$ (4)

where IN is number of refining impacts [km/kg]

Ls cutting speed of bars [km/s] and

M fiber mass flow [kg/s].

The new specific surface load, SSL, value is obtained by dividing the old specific edge load, SEL, by the bar width factor, IL.

$SSL = \frac{SEL}{IL}$ (5)

The length of the refining impact across the bars depends on the width and the angular setting of the bars (Fig. 7).

$IL = \frac{Wr + Wst}{2} \times \frac{1}{\cos(\alpha/2)}$ (6)

where Wr is width of rotor bars [m],

Wst width of stator bars [m] and

α average intersecting angle [°].

The new specific surface load theory, SSL theory, has partly replaced the old specific edge load theory. The specific surface load theory seems to work quite well when bars are so narrow that fiber flocs when receiving a refining impact cover the whole width of bar surface. However, it must be remembered that the nature of refining depends both on the specific surface load and on the width of the bars. If bars are much narrower than the fiber floc is, they heavily cut fibers.

Figure 7. *Definition of the impact length.*

The specific edge load theory works quite well with coarse fillings when bars are wider than the length of the fiber flocs. The specific surface load theory still has many weak points as specific edge load theory, but these two theories offer very practical tools when selecting fillings and other refining parameters for various applications.

4.4.3 Frequency and intensity (Danforth)

At the end of the 1960s, Danforth developed two independent expressions for describing refining and, according to this theory, refining is expressed as a function of following two factors, namely number, N, and severity, S, of refining impacts between the bar edges[10]. Here the equations are presented in their original form without units.

$$S = \frac{(HPa - HPn)At}{D(RPM)LrLsC}K2 \quad (7)$$

$$N = \frac{LrLs(RPM)C}{XR}K1 \quad (8)$$

where S is relative severity of impacts,

N relative number of impacts,
HPa total horsepower applied,
HPn no load horsepower,
HPa–HPn net horsepower,
At total area of refining zone,
Lr total length rotor edges,
Ls total length stator edges,
D effective diameter,
RPM rotor RPM,
C stock consistency,
X average bar contact length,
R throughput rate and
K1, K2 appropriate constants.

This theory includes most factors that affect the refining result, but there are constants that are not easily available; therefore, theory is not so commonly used.

4.4.4 C-factor (Kerekes)

The starting point of this theory is the same as in many other refining theories: The effective refining energy may be directly related to the number of impacts and the intensity or energy content of each impact as shown below.

$$E = N \times I \quad (9)$$

Then the author developed the "C-factor," which represents the capacity of the refiner to impose impacts upon pulp fibers passing through. The C-factor links the power input, P, and pulp mass flow rate, F, through a refiner to the average number, N, and intensity, I, of impacts imposed on fibers. N and I are derived from the resulting relationships[11].

$$N(Number\ of\ impacts) = \frac{C-factor}{F(Pulp\ mass\ flow)} \quad (10)$$

$$I(\mathrm{Intensityorenergyofimpact}) = \frac{P(Net\ power)}{C-factor} \quad (11)$$

The C-factor itself is a function of filling geometry, rotation speed, consistency, fiber length, and coarseness.

For a disc refiner in a simplified case (small gap size, similar bar pattern on rotor, and stator), the C-factor is given as follows:

$$C = 8\pi^2 GD\rho Cf \ln^3 \omega(1 + 2\tan\varphi)(R_2^3 - R_1^3)/3w(l + D) \quad (12)$$

For a conical refiner in a simplified case, the C-factor is given as follows:

$$C = 8\pi^2 GD\rho Cf \ln^3 \omega(1 + 2\tan\varphi)[LR_1^2 + L^2 R_1 \sin\theta + (L^3/3)\sin^2\theta]/w(l + D) \quad (13)$$

Because the above C-factor equations do not consider the width of the bars at all, there is another C-factor equation for a simplified disc refiner case as follows:

$$C = 8\pi^2 \rho CflDG\omega \cos^2\varphi(\cos\varphi + 2\sin\varphi)(R_2^3 + R_1^3)/3w(l + D)(G + W)^3 \quad (14)$$

Because the whole presentation comprises 31 various equations with simplification of equations and substitution of terms, we present here only those terms occurring in the final equations.

Nomenclature:

N is number of impacts/mass pulp [kg-1],
F pulp mass flow through refiner [kg/s],
I energy/impact [J],
P net power applied to refiner [W],
G width of grooves [m],
D depth of grooves [m],
ρ density of water [kg/m3],
Cf pulp consistency, fraction,
l length of fiber [m],
n number of rotor and stator bars on circle $2\pi r$ in refiner,
ω rotational velocity of refiner [revolutions/s],
φ bar angle from radius [degree],
R_1 inner radius of refining zone [m],
R_2 outer radius of refining zone [m],
w coarseness of fiber [kg/m],
θ angle of conical refiner [degree],
L length of refining zone [m] and
W width of bar surface [m].

C-factor analysis is perhaps the most rigorous and comprehensive of these theories developed to date and, in essence, builds on other well known refining theories, e.g., specific edge load and specific surface load. It is quite suitable when comparing refiners with given conditions, but fillings wear, for example, can affect the C-factor. Because these factors are not always so easily determined and relatively complicated calculations are required, this theory is not very much used by papermakers.

4.4.5 Floc refining hypothesis (Hietanen, Ebeling)

The floc refining hypothesis confirms the commonly accepted fact that fibers are not refined individually but in flocs. References to fiber flocs have appeared in literature since the 1920s. The consistency range in low-consistency refining is 2%–6% and, at this consistency, fibers are not free to move independently. Instead they form flocs, and flocs are formed and broken up continuously under the shear forces that exist in the grooves and in the refining zone. The thickness of individual flocs (1–5 mm) is high in comparison to the size of gap (usually 50–150 µm).

The probability that floc of this size will be driven into the gap is thus low. Similarly, the volume flow through the rotor and stator grooves is much larger than the flow through the "gap volume." This leads to a heterogeneous refining result: Some fibers do not get any refining at all, but some fibers get very harsh treatment. Thus, much energy is probably consumed in transporting fiber flocs through the refiner and in maintaining turbulence in fiber slurry[12].

Based on the concept above, a small laboratory size disc refiner with a dispersing unit in the middle was built. Dispersed fibers were then individually refined with very fine plate pattern and narrow gap. The results were promising, but at this time no industrial size refiner has been developed based on this hypothesis.

4.5 Refiners

4.5.1 Hollander beater

The first refining machine was a Hollander beater. This batchwise operating machine comprises a large open vessel, a rotating bar equipped drum, and 2–3 bar equipped counter bed plates (Fig. 8). Batchwise operating Hollander beaters are energy intensive, but they produce a gentle, quite uniform fiber treatment. An advantage is that both the refining energy and refining intensity can be independently controlled. Batchwise operation, high energy consumption, and quite large floor area requirement in comparison to their capacity encouraged development of continuously operating refining machinery. Today Hollander beaters are only used in small mills and often in special applications, for example, cutting long cotton/rag fibers before refining with refiners.

Continuously operating refiners can be divided into two groups, namely conical- type and disc-type refiners.

Figure 8. *Hollander beater.*

4.5.2 Conical refiners

In the group of the conical refiners, the first machine was a Jordan-type shallow angle conical refiner with a thoroughgoing shaft (Fig. 9). Cone angle of these refiners is approximately 10° and, as fillings often are quite coarse, these refiners are considered to give fiber cutting refining result. However, when fillings (plug and shell) with narrow bars are used, these refiners do excellent fiber development and are suitable for all kinds of fibers. Due to the difficult change of fillings and long low-capacity machine, the number of these machines in use is decreasing.

Figure 9. *Cross section of Jordan-type conical refiner.*

The next conical-type refiner is a Claflin-type wide angle refiner (Fig. 10). Basically the construction is close to a Jordan-type refiner, with the only differences being shorter fillings with a wider 30° cone angle.

Figure 10. *Cross section of Claflin-type conical refiner.*

The newest member in the conical refiner group is the medium angle Conflo®-type refiner with a 20° cone angle (Fig. 11). Fillings are longer than in the Claflin-type refiner but much shorter than in the Jordan-type refiner. The basic construction also differs from the other refiners because the shaft is not a thoroughgoing type. The cantilevered design allows an easy access to fillings. This modern medium angle conical refiner with a wide variety of different fillings is today a very popular low-consistency refiner in use worldwide.

Figure 11. *Valmet Conflo® refiner.*

The Conflo refiner series comprises six different sizes. The connected maximum power range is from 110 kW to 3 500 kW, and the gap clearance adjustment is electromechanical. Typical data for refining of chemical pulps in paper mills are:

	Softwood pulps	**Hardwood pulps**
- Bar width of segments	3.5–5.5 mm	2.0–3.0 mm
- Refining intensity, SEL	0.9–6.0 J/m	0.3–1.5 J/m
- Refining intensity, SSL	250–1 000 J/m2	150–500 J/m2
- Refining consistency	3.5–4.5 %	4.0–6.0 %

4.5.3 Disc refiners

The disc refiner group comprises three types, namely, single-disc, double-disc, and multi-disc type refiners. Single-disc refiners are almost entirely used only in high-consistency refining because their efficiency in low-consistency refining does not meet today's requirements. Multi-disc refiners are intended for very low-intensity refining with extremely fine plate pattern and are most suitable for the post-refining of mechanical pulps. The following figures show modern machinery for low-consistency refining of chemical pulps in paper mills.

As an example of several double-disc type refiners on the market, figures for Voith Sulzer and Andritz AG Twin Flo E double-disc refiners are presented. These refiners (Fig. 12) are available in five different sizes, each capable of accommodating at least two disc sizes, ranging from 18 in. (467 mm) to 58 in. (1 473 mm) disc diameter. Plate adjustment at a power range of 200 kW to 3 000 kW is accomplished by an electromechanical positioning device. Typical data when refining chemical pulps in paper mills are:

	Softwood pulps	**Hardwood pulps**
- Bar width of segments	3.0–> mm	2.0 mm
- Refining intensity, SEL	1.5–4.0 J/m	<1.0 J/m
- Refining intensity, SSL	500–> J/m2	<500 J/m2
- Refining consistency	3.5–4.5 %	4.0–6.0 %

The Beloit double disc refiners (Fig. 13) also are well known refiners in paper mills. The Beloit Double Disc Series DD 4000, as Voith Sulzer Double Disc refiners, are of cantilevered design with a hinged door for plate change and electromechanical plate adjustment. These refiners are available in five base sizes, each capable of accommodating two disc sizes, 16 in. (406 mm) to 46 in. (1 168 mm) diameter. The power range is from 260 kW to 1 900 kW. Typical data for refining chemical pulps in paper mills are:

Figure 12. *Voith Sulzer Double Disc.*

	Softwood pulps	**Hardwood pulps**
- Bar width of segments	3.5–4.8 mm	2.4–3.5 mm
- Refining intensity, SEL	1.7–4.5 J/m	0.5–1.5 J/m
- Refining intensity, SSL	370–720 J/m2	180–360 J/m
- Refining consistency	3.5–4.5 %	4.0–5.5 %

Figure 13. *Beloit Double Disc.*

With every refiner type, the actual power, capacity, segment type, refining intensity, and consistency figures depend on the physical dimensions and refining resistance of fibers and on the targeted refining result. In general, long unbleached softwood sulfate pulp fibers are strongest and have the highest refining resistance, whereas short bleached hardwood sulfite pulp fibers are the weakest with the lowest refining resistance. Accordingly, long and strong softwood pulps also require more energy and coarser fillings than short and weak hardwood fibers[9].

4.6 Refining systems

The selection of the refining system starts from the end products, available pulps, and planned capacity range. End product and pulp blend establish requirements for desired refining results for each pulp in the blend. Thereafter, refining consistency, bar pattern of fillings/plates to give required nature for the refining, net energy requirement, and number of recommended refining stages (number of refiners in series) will be determined. After this the size, rotation speed, and power of refiners is selected to meet capacity, net energy, and refining intensity requirements for various end products. Because the refining behavior of pulps depends on so many factors, the dimensioning of the refining system must be based on the known pulps. If pulps are not well known, they must be analyzed. Wood species, fiber length, fiber coarseness, bleaching method, brightness, viscosity, and laboratory beating results are good indicators. Sometimes, refining trials with mill scale machinery are required.

Most often, there are separate refining lines for different pulps (called a separate refining system as shown in Fig. 14), but sometimes different pulps are mixed together before refining (as in a mixed refining system as shown in Fig. 15). In both cases, the number of refiners in a series depends on targeted refining results and the capacity variations. The higher the required refining energy input (the greater the Freeness or Schopper-Riegler changes) is or the greater the capacity variation is, the higher will be the number of the refining stages. For example, slightly refined fibers for toilet tissue require only one stage, but heavily refined fibers for greaseproof papers require 5–6 stages.

Both separate and mixed refining systems are widely used usually so that new big paper machines use separate refining and older smaller paper machines use mixed refining systems. Regardless of the main refining system, there are many good reasons to have a trimming refiner after the blending chest to homogenize the fiber mixture by cutting too long fibers for a better sheet formation and to recondition fibers from the broke line. Figures 14 and 15 show typical refining systems for fine paper machines[13].

Figure 14. *Separate refining system.*

Figure 15. *Mixed refining system.*

Both separate and mixed refining systems have their advantages. For some pulp blends, separate refining produces better strength at lower energy consumption than a mixed refining, but for some pulp blends, mixed refining is a better alternative. For this reason, a combined system with separate refining for different pulps (fibers) followed by mixed refining, offers a good alternative because the benefits from both separate and mixed systems can be utilized[13]. Figure 16 shows one possibility for a new refining system for a fine paper machine.

Figure 16. *Future refining system.*

Figure 17. *Refining system for a multi-layer board machine.*

In the case of a multi-layer board refining system, the process is much more complicated because the number of pulps is much higher and different layers set their own requirements on the refining result. Figure 17 shows a modern refining system for a multi-layer liquid packing board machine.

4.7 Low-consistency, medium-consistency, and high-consistency refining

Table 2 provides some of the main differences between various refining consistencies. The data contains typical figures when refining softwood kraft pulp fibers. As the consistency increases, the running speed (peripheral velocity at outlet) increases as well.

Table 2. Various refining consistencies.

	LC-refining	MC-refining	HC-refining
Consistency	2%–6%	10%–20%	30%–35%
Peripheral velocity	15–25 m/s	40–50 m/s	90–110 m/s

Different refining consistencies produce different fiber development; therefore, the selected refining consistency depends on the targeted refining result.

MC-refining is sometimes more suitable for recycled fibers and various rejects in pulping processes. In the MC-refining system, consistency is approximately 15%. Fibers are pumped at approximately 4% consistency to a thickener and, by means of a screw feeder, are fed at 10%–20% consistency to a single-disc refiner. The results indicate that refining at 10%–12% consistency gives internal fibrillation and swells the fibers, whereas refining at 15%–20% consistency gives curl and microcompressions. As the consistency increases, the internal fibrillation of fibers decreases. The refining results in medium-consistency refining are between results in low- and high-consistency refining.

High-consistency refining (HC-refining) at 30%–35% consistency is typically used when the end product must have high tensile energy absorption at high porosity (at low air resistance). Typical end products include sack kraft paper because sacks to be filled with powder (e.g., cement) must be strong enough while simultaneously allowing air removal through the paper layers. As high-consistency refining creates curled/kinky fibers with low bonding ability, the high-consistency stage must be followed by 2–3 low-consistency refining stages for straightening fibers and for increasing bonding ability.

Figure 18 illustrates that high-consistency refining has practically no effect on other fiber properties but on the fiber length, which seems to be shortened due to curling. After a relatively low-energy high-consistency refining, bulk and strength properties are slightly reduced, because collapsed but curly fibers have less bonding possibilities than straight unrefined never dried fibers. Low-consistency refining after high-consistency refining straightens fibers, decreases bulk, increases beating degree, tensile strength, tensile energy absorption, and air resistance.

Figure 19 shows a typical refining system for sack kraft paper. The high-consistency refining is followed by 2–3 low-consistency refining stages, and the energy input depends on the pulp and on the end product. Bleached pulp for paper bags paper requires less energy than unbleached pulp for sack kraft paper.

Figure 18. *Refining system for sack kraft paper.*

Figure 19. *Effect of HC+LC refining on fibers.*

4.8 Operation of refiners

The following operational statements are valid in low-consistency refining as the refining in paper mills is almost entirely performed below 6% consistency, when normal centrifugal pumps can feed the refiners.

4.8.1 Effect of refining conditions

There are a number of variables that affect the refining result as already explained in Fig. 4. Some of those variables such as all fiber-based variables are predetermined and cannot be influenced in refining. Process conditions such as consistency, pH, temperature, and pressure can to some extent be controlled. So-called "equipment parameters" (passive process variables) such as type of refiners, fillings (pattern, material, and condition), rotational speed, and rotation direction of refiners can be affected when selecting a refining system and the equipment for it. During maintenance stops, fillings and rotation direction can be changed. Flow depends on the requirement set by the paper machine and cannot be freely controlled. Basically only the gap clearance (refiner load) can actively be controlled to give required net refining energy. In case there is a circulation line back to the pump suction, the flow rate through the refiners can be controlled.

4.8.1.1 Effect of consistency

Consistency should not be considered as an independent variable because the bar pattern of fillings/plates has an effect on it. In general, coarser pattern with wider grooves requires higher consistency than finer pattern with narrower grooves. Typically, consistency in low-consistency refining is approximately 3.0%–5.0%; 3.5%–4.5% when refining softwood, 4.5%–5.0% when refining hardwood, and 3.0%–3.5% in trimming refining.

Lower than 3.0% consistency when refining long softwood fibers strongly increases cutting tendency. Short hardwood fibers behave on the contrary because decreased refining consistency increases fiber floc breakage and more fibers are peeled off from the bar edges into the grooves and avoid refining action.

Basically bar pattern should be suitable for the fiber, but sometimes bar pattern is not most suitable because pulps vary. If the fillings cannot be changed, the only possibility is to adjust the consistency to suit.

An increased refining consistency with any fibers means slower vortex flow in grooves and increases fiber flocculation tendency, therefore requiring a coarser pattern than lower refining consistency. The following figure (Fig. 20) shows the approximate effect of the consistency on the refining intensity when unrefined pulps are refined with correct fillings. Data indicate the maximum safe intensity without risk for metallic contact (bars clash).

Figure 20. *Refining intensity vs. consistency.*

4.8.1.2 Effect of refining or beating degree

Another important factor is the beating degree of pulp when entering the refiner. Beating degree can be measured in many ways. The most commonly used measurements are freeness (CSF) and Schopper-Riegler (°SR). Here curves in figures include both freeness and Schopper-Riegler. In refining, freeness decreases and Schopper-Riegler increases. As the refining reduces the refining resistance of the fibers, the refining intensity must be reduced in the prolonged refining (Fig. 21). The curves indicate refining intensity for pulps entering the refiner.

Figure 21. *Refining intensity vs. freeness and Schopper-Riegler.*

4.8.1.3 Effect of energy input

The amount of refining is described by means of the net energy input or the amount of net energy transferred to fibers. It is a practical way for evaluating one of the refining conditions inside the refiner. However, the total energy consumption for obtaining correct refining conditions should also be considered because it determines the energy costs. There also are limitations on how much net energy can be transferred to fibers in one pass. Depending on the refining resistance of fibers and on the desired refining result, the energy transferred varies from 25 to 200 net kWh/bdmt in one pass. If more energy is required, there must be several refiners in series.

	Net energy input in one pass
Type of pulp	**kWh/bdmt**
-Softwood sulfate	60–200
- Softwood sulfite	40–60
- Hardwood sulfate	40–80
- Hardwood sulfite	25–40

Most common refining theories do not consider energy input in each refining stage; they only consider the total amount of net energy. However, the higher the energy input in one pass is, the lower the strength development will be. When refining reinforcement kraft pulp, it is important to develop necessary tensile strength, and simultaneously maintain fiber length and the tearing strength as high as possible. Because a relatively low percentage of reinforcement fibers form a strong net inside the paper web, those fibers must be refined to have maximum reinforcement ability. The following figures indicate that at the same total energy 75 kWh/bdmt in one pass produces much better reinforcement properties than 150 kWh/bdmt in one pass[14].

This refining trial series was performed with an industrial scale Conflo JC-01 refiner at a research plant. The pulp was an ECF bleached Scandinavian pine kraft pulp, especially produced for reinforcement purposes. The refining conditions in both series were equal except that, in the first refining series, net energy input was approximately 75 kWh/bdmt in each pass and, in the second refining series, it was increased to approximately 150 kWh/bdmt by reducing the flow from 950 L/min to 475 L/min. Refining was performed at 4.0% consistency with LM (long fiber medium) type fillings (4.5 mm wide bars). The refiner speed was 1 000 rpm, and the refining intensity was 3.9 J/m (830 J/m2).

The curves (Figs. 22 – 26) show the development of some pulp properties. The higher energy input in one pass shows a quicker freeness drop or Schopper-Riegler increase than the lower energy input (Fig. 22).

Figure 22. *Freeness and Schopper-Riegler vs. net refining energy.*

The lower energy input in a single pass requires less net refining energy for a given tensile strength than the higher energy input (Fig. 23). The same applies to the total refining energy.

Figure 23. *Tensile vs. refining energy.*

Figure 24. *Tensile vs. beating degree.*

Figure 25. *Tear vs. tensile.*

The lower energy input in each stage also produces a higher tensile strength at a given beating degree than the higher energy input does (Fig. 24).

Combination of tear and tensile strengths favors lower energy input in a single stage (Fig. 25).

The higher the energy input in each stage, the heavier the fiber shortening in the refining (Fig.

26).

The conclusion drawn from this trial series is that serial refining produces more homogeneous refining results (less unrefined and less over refined fibers) and better strength properties than single-pass refining. Lower refining energy in each stage and less variations in the residence time of fibers inside the refining zone are in favor of serial refining[15]. In practice in the 1980s and 1990s, typical refiner applications comprise refiners in a serial system. The above trial series confirms mill experiences.

Figure 26. *L.W.A. fiber length vs. tensile.*

4.8.1.4 Effect of refining intensity

The optimum refining intensity for chemical pulps, as for any pulps, depends on the refining resistance, the physical dimensions, and the flocculation ability of fibers. Optimum intensity figures must be determined on a case-by-case basis by considering the properties of the fibers and the desired refining results. When refining long softwood fibers, too low intensity cannot treat fibers effectively. On the other hand, too high intensity strongly shortens long softwood fibers and increases their dewatering resistance. As the following comparisons indicate, there are great differences between different pulps.

The following figures show the effect of refining intensity when refining a low coarseness, 0.166 mg/m, Canadian ECF bleached softwood kraft pulp. In this trial series, the net energy input in each pass was approximately 75 kWh/bdmt. At the lowest flow, namely 500 L/min at 3.8% consistency, the refiner was loaded to give 87 kW net power and 2.0 J/m (423 J/m2) refining intensity. Then flow was increased to 950 L/min at 3.9% consistency and the refiner load was increased to give 174 kW net power and 4.0 J/m (845 J/m2) refining intensity. The JC-01 refiner had LM fillings and was running 1 000 rpm.

The curves (Figs. 27 – 29) show the development of some pulp properties. At first, the beating degree development against net energy is very similar with both intensities but, in prolonged refining, the higher intensity shows slightly quicker freeness drop or Schopper-Riegler increase than the lower intensity (Fig. 27).

Figure 27. *Freeness and Schopper-Riegler vs. net refining energy.*

The higher refining intensity requires slightly less total refining energy for a given tensile strength than the lower refining intensity does (Fig. 28), but cuts slightly more fiber (Fig. 29).

Figure 28. *Tensile vs. total refining energy.*

The conclusion from this trial series is that this softwood kraft pulp is not very sensitive to the refining intensity. However, it must be noted that the flow was reduced together with the refining intensity as the refining energy in each pass was kept constant. Decreased refining intensity with a given fillings type, naturally, decreases the net power of the refiner, which leads either to bigger refiners or to a higher number of refiners for a given capacity and net energy input. The effect of the refining intensity on the refiner power curves is demonstrated in Fig. 30 when a JC-01 refiner is provided with LM fillings and is running 1 000 rpm.

Figure 29. *L.W.A. fiber length vs. tensile strength.*

In order to demonstrate the differences between ECF bleached softwood kraft pulps, following figures show effect of the refining intensity when refining a slightly higher coarseness, 0.235 mg/m, Chilean ECF bleached softwood kraft pulp. In this trial series, the net energy input in each pass was approximately 95 kWh/bdmt. At the lowest flow, 375 L/min at 4.1% consistency, the refiner was loaded to give 87 kW net power and 2.0 J/m (423 J/m2) refining intensity. Then the flow was increased to 720 L/min at 3.9% consistency and the refiner load was increased to give 174 kW net power and 4.0 J/m (845 J/m2) refining intensity. The JC-01 refiner had LM fillings and was running 1 000 rpm. Refining conditions were similar to those in previous Canadian softwood kraft pulp trials, except there was slightly higher net energy input applied in each pass and therefore lower flow.

Figure 30. *JC-01 refiner with LM fillings at 1 000 rpm.*

The beating degree development against net energy shows a great difference between various intensities (Fig. 31). The lower intensity is not really able to develop fiber.

Figure 31. *Freeness and Schopper-Riegler vs. net refining energy.*

Figure 32. *Tensile vs. total refining energy.*

When considering tensile strength development against the total refining energy, the higher refining intensity clearly decreases the energy requirement (Fig. 32). The lower refining intensity is not able to develop tensile strength properly.

When refining short hardwood fibers, low refining intensity is able to develop fibers, but the lower the intensity is, the higher is the share of the no load power: too low an intensity increases total refining energy requirement. Too high an intensity destroys hardwood fiber flocs on bar edges, and "peeled off" fibers go back to grooves without receiving any refining treatment. If fiber floc is not broken, increased intensity increases fiber cutting.

The following figures show the effect of the refining intensity when refining a Portuguese chlorine bleached eucalyptus kraft pulp. In this trial series, the net energy input in each pass was approximately 50 kWh/bdmt. At the lowest flow, 605 L/min at 4.3%consistency, the refiner was loaded to give 85 kW net power and 0.4 J/m (195 J/m2) refining intensity. Then the flow was increased to 1 515 L/min at 4.3% consistency and the refiner load was increased to give 213 kW net power and 1.0 J/m (490 J/m2) refining intensity. The JC-01 refiner had SF (short fiber fine) fillings with 2.0 mm wide bars and was running 1 000 rpm.

Figure 33. *Freeness and Schopper-Riegler vs. net refining energy.*

Figure 34. *Tensile vs. total refining energy.*

The curves (Figs. 33 – 36) show the development of some pulp properties. The lower refining intensity shows a quicker freeness drop or Schopper-Riegler increase than the higher refining intensity (Fig. 33).

Figure 35. *Tear vs. tensile.*

The lower refining intensity requires less total refining energy for a given tensile strength than the higher refining intensity (Fig. 34).

Combination of tear and tensile strengths favors lower refining intensity (Fig. 35).

The lower the refining intensity is, the longer are the fibers in a given tensile strength (Fig. 36).

Figure 36. *L.W.A. fiber length vs. tensile.*

The conclusion from this trial series is that eucalyptus kraft pulp, in general, is better refined at quite a low refining intensity. However, it must again be noted that the decreased refining intensity with a given fillings type naturally, decreases the net power of the refiner, and this leads either to bigger refiners or to a higher number of refiners for a given capacity and net energy input.

The effect of the refining intensity on the refining power curves is demonstrated in Fig. 37. Here a JC-01 refiner is provided with SF fillings and is running 1 000 rpm.

Figure 37. *JC-01 refiner with SF fillings at 1 000 rpm.*

Sufficient refining intensity and width of bars also depend on the type of refiner. Disc-type refiners operate with narrower bars and at lower refining intensity than conical-type refiners[2],[13]. As guidelines, the following bar width and intensity figures are practical for Conflo refiners.

	Bar width	**Edge load**	**Surface load**
Type of pulp	**mm**	**J/m**	**J/m2**
- Softwood sulfate	4.0–5.5	2.0–6.0	500–1000
- Softwood sulfite	3.5–4.5	0.9–1.5	250–400
- Hardwood sulfate	2.0–3.0	0.4–1.5	200–500
- Hardwood sulfite	2.0–2.5	0.3–0.8	150–300

4.8.1.5 pH

pH has an effect on the water penetration into fibers. Recommended pH is close to neutral, because too low pH prevents water penetration inside fibers and too high pH makes fibers slippery (soapy). In case the pH is below 5 in the refining, the fibers do not get properly wetted and fiber cutting and fines generation tend to increase. On the other hand, pH over 10 makes it more difficult to keep fibers or fiber flocs on the bar edges. In practice conditions in the paper mill determine the pH in refining because white water is used in slushing of pulp and pH is only controlled when necessary.

4.8.2 Refiner fillings or plates

For small-sized refiners the rotor or stator is one solid piece but, for bigger-sized refiners, every rotor or stator surface is formed from several segments. In both cases, the barred refining surface area (bar pattern) is divided into segments and, therefore, refiner fillings or plates are sometimes called segments. In this chapter, we use fillings (plug and shell) for conical refiners and plates for disc refiners.

Most typical metallic low-consistency refiner fillings or plates are manufactured by casting, typically from martensitic stainless steel, and they have barred refining surface area. The basic design parameters are width of bars and grooves, height of bars, and angle of bars from the radial direction. Because straight bars (rotor and stator bars are parallel) are both noisy and tend to cut fibers, intersecting angle is used, approximately 20° for short fibers and 35° for long fibers. Those angles allow refiners to run both in pumping and opposite to pumping direction. Dams between bars are very seldom used when refining chemical pulps but are typically used when refining reject pulps in pulp mills.

Because the fibers have different physical dimensions and different refining resistance, the bar patterns are different. Typical dimensions vary as follows:

	Softwood fillings	**Hardwood fillings**
Conflo refiners		
- Width of bars	3.5–5.5 mm	2.0–3.0 mm

- Width of grooves	4.5–7.0 mm	2.5–3.5 mm
- Depth of grooves	10.0 mm	7.0 mm
Disc refiners		
- Width of bars	3.0–5.0 mm	1.5–3.0 mm
- Width of grooves	3.0–5.0 mm	1.5–3.0 mm
- Depth of grooves	7.0 mm	5.0 mm

The selection of bar pattern must be based on the fiber type, the targets in refining, and the refining conditions. Long and strong softwood fibers require wider bars and wider grooves than do shorter and weaker hardwood fibers.

There are various material compositions available, and the heat treatment before final finishing determines the final characteristics of segments or plates. Other than stainless steel, high chrome iron, NiHard, and ceramic materials are sometimes used in low-consistency refining. It is important that – in addition to having a good resistance to breakage, corrosion and wear – the bar edges must keep their shape, and not get too rounded, and the flat bar surface must not get polished and slippery. Deformation of bars results in increased energy consumption and decreased fiber development.

4.8.3 Control of refining

The refiner is controlled by adjusting the gap between rotor and stator fillings. The signal for automatic or manual control may come from the main motor load, the amount of the refining energy, the temperature rise of the stock, the drainage characteristics of the stock, the vacuum from a flat box or couch roll, or from the air permeability of the paper web.

Manual power control, either by turning gap control device by hand or by pushing a button that activates a gap control device, is the simplest way to adjust the refiner load. The advantage of this simple method is that flow or consistency variations automatically change the refiner load to the correct direction, although not accurately in proportion. If the gap clearance is kept constant, decreased flow or consistency decreases the thickness of fiber flocs between bars thus also decreasing the refiner load.

The simplest automatic control is power control, which keeps the refiner motor load on the set value. In case flow and consistency variations occur, the net refining energy varies directly with the stock mass flow variations. This type of refiner control can be more harmful than beneficial.

The most common control system maintains net energy (net kWh/bdmt) by controlling fiber consistency before refining and fiber flow prior to blending chest. Consistency and flow determine fiber mass flow expressed as bdmt/hour. When that is multiplied by net kWh/bdmt, the result is the required net kW for the refiner. Total refiner load is then obtained so that no load power in kW is added to the net power in kW. The basic set value is the net kWh/bdmt and that must be determined onsite, case-by-case, so that required fiber development is obtained. After setting the net kWh/bdmt figure, the control system automatically follows flow and consistency values and controls refiner load so that correct net energy is obtained.

Sometimes freeness, temperature rise, couch vacuum, or air permeability of the paper is used to determine refiner control. In those cases, the control operation is such that the measurements are converted to a new set value for specific refining energy control.

The accuracy of any control system depends on the accuracy of the performed signal measurement. It is important to avoid too quick refiner load changes. For example, when using the freeness signal, the average value of the five most recent measurements is better to use for control because individual measurements can vary too much.

Figure 38 shows a typical refining line including instrumentation, with three refiners in series. Depending on the type of refiner and on the capacity variations, there might be a circulating line after the last refiner back to pump suction. The purpose of this circulation line is to ensure sufficient fiber flow through the refiner in all conditions. Typically, circulation is required if flow range varies more than 1:2 through disc refiners and more than 1:3 through conical refiners.

Figure 38. *Typical refining line.*

4.9 Development of fiber and pulp properties in refining

The following curves show a typical fiber development in low-consistency refining. The curves show Scandinavian pine and birch, whereas the eucalyptus is from Portugal. All pulps were refined with JC-01 refiner in serial refining applying quite typical mill conditions. Medium coarse long fiber type fillings (LM with 4.5 mm wide bars) were used for the pine and medium coarse short fiber type fillings (SM with 2.5 mm wide bars) for the birch and eucalyptus. Refiner was running 1 000 rpm and, all pulps were dried ECF bleached market pulps.

The first curves (Fig. 39) show refining degree development as a function of net energy input. Additionally, the legend in these curves shows type of fillings, specific edge load, specific surface load, and refining consistency.

Figure 39. *Freeness or Schopper-Riegler vs. net energy.*

Tensile strength development as the function of net energy input is quite similar with all pulps, being only slightly faster with hardwood pulps than with pine (Fig. 40). The legend in this and in all later curves only shows type of pulp.

Figure 41 indicates that hardwood pulps for a given tensile strength must be refined to lower freeness or higher Schopper-Riegler than softwood pulps. Eucalyptus is the most demanding in this respect.

Figure 40. *Tensile vs. net energy.*

Figure 41. *Tensile vs. freeness or Schopper-Riegler.*

All curves in Figs. 42 – 54 show development of various fiber properties as a function of net energy input and, because the curves are self explanatory, there is no need to go into further discussions here.

Figure 42. *Burst vs. net energy.*

Figure 43. *Tear vs. net energy.*

Figure 44. *L.W.A. fiber length vs. net energy.*

Figure 45. *Bulk vs. net energy.*

Figure 46. *Tensile stiffness vs. net energy.*

Figure 47. *Internal bonding vs. net energy.*

Figure 48. *Air permeability vs. net energy.*

Figure 49. *Absorbency vs. net energy.*

Figure 50. *Opacity vs. net energy.*

Figure 51. *Light scattering vs. net energy.*

Figure 52. *Brightness vs. net energy.*

Figure 53. *WRV vs. net energy.*

Figure 54. *Fracture toughness vs. net energy.*

4.10 Evaluation of the refining system performance

The first criteria must be the obtained fiber development so that the critical pairs of properties are evaluated, e.g., tensile strength vs. beating degree and tear strength vs. tensile strength. In other words, the undesirable reduction of one property must be evaluated according to the desired increase of another property[16]. After this, the running and investment costs must be evaluated and compared to the benefits obtained from the fiber development.

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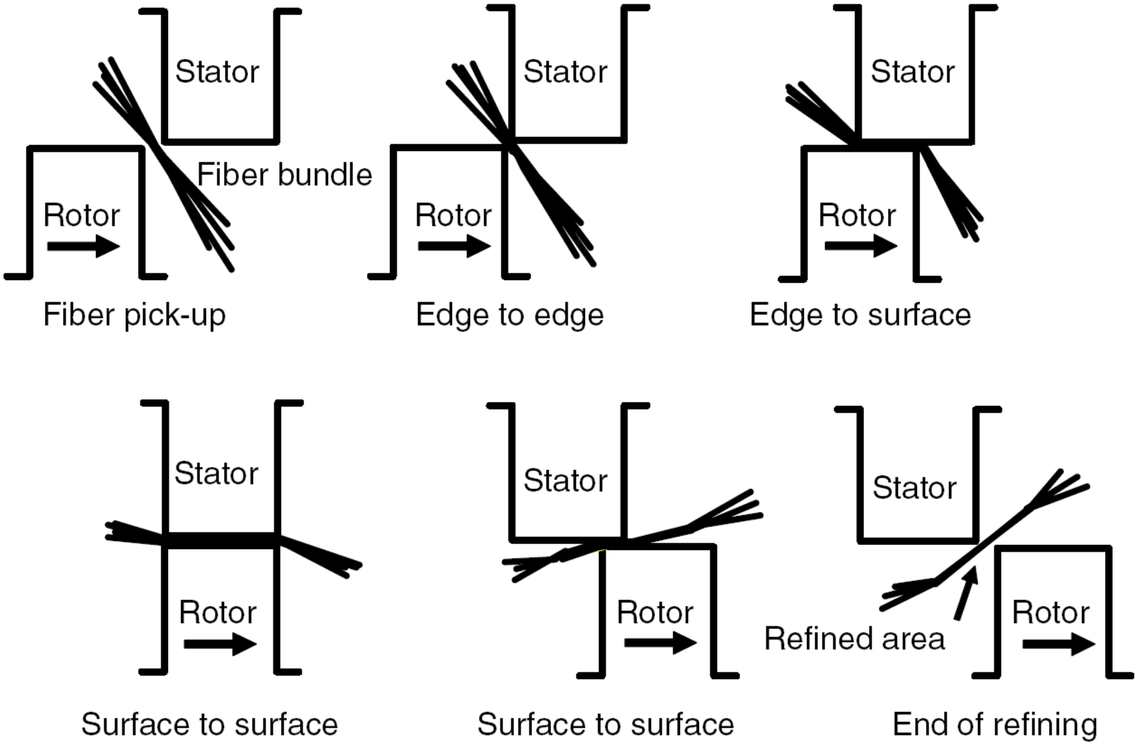


Figure 1. Refining mechanism.

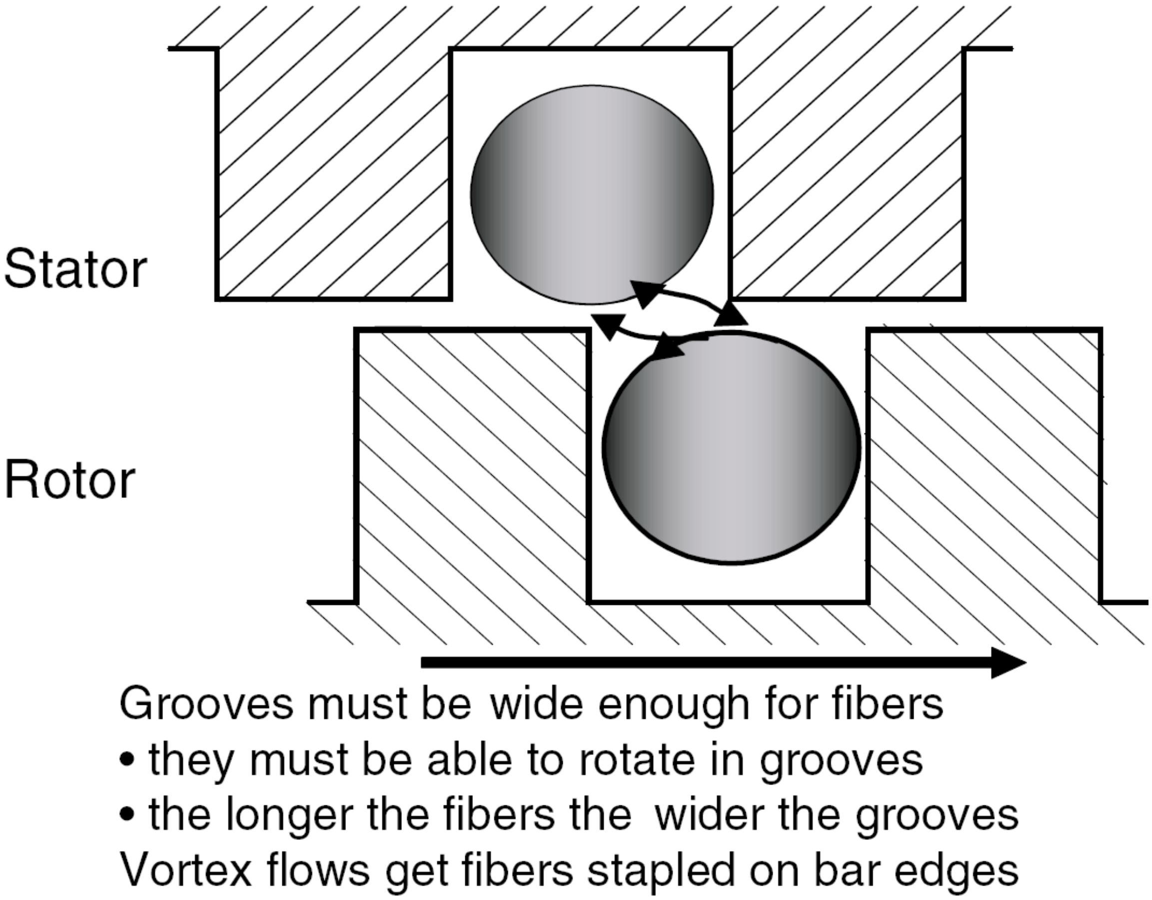
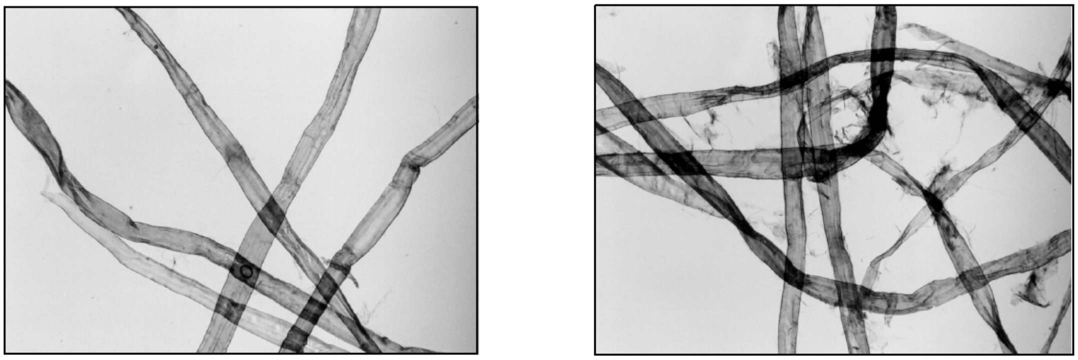


Figure 2. Vortex flows and fibers stapling on bar edges.

LC Refining of Cylinder Dried ECF Pine Kraft Pulp



Unrefined

Refined with JC-01 at 4.2% consistency
- Specific refining energy 4 x 85 kWh/bdmt

• Freeness, mL/°SR	750/13.5	510/24.7
• Fiber length, mm	2.12	2.07
• Tensile index, Nm/g	22.1	76.0
• Tear index, mNm^2/g	12.2	11.4
• Air permeability, Bendtsen mL	3000	850
• Tensile stiffness index, MNm/kg	3.49	7.30
• Bulk, cm^3/g	1.64	1.38

Figure 3. Unrefined and refined bleached softwood kraft pulp fibers.

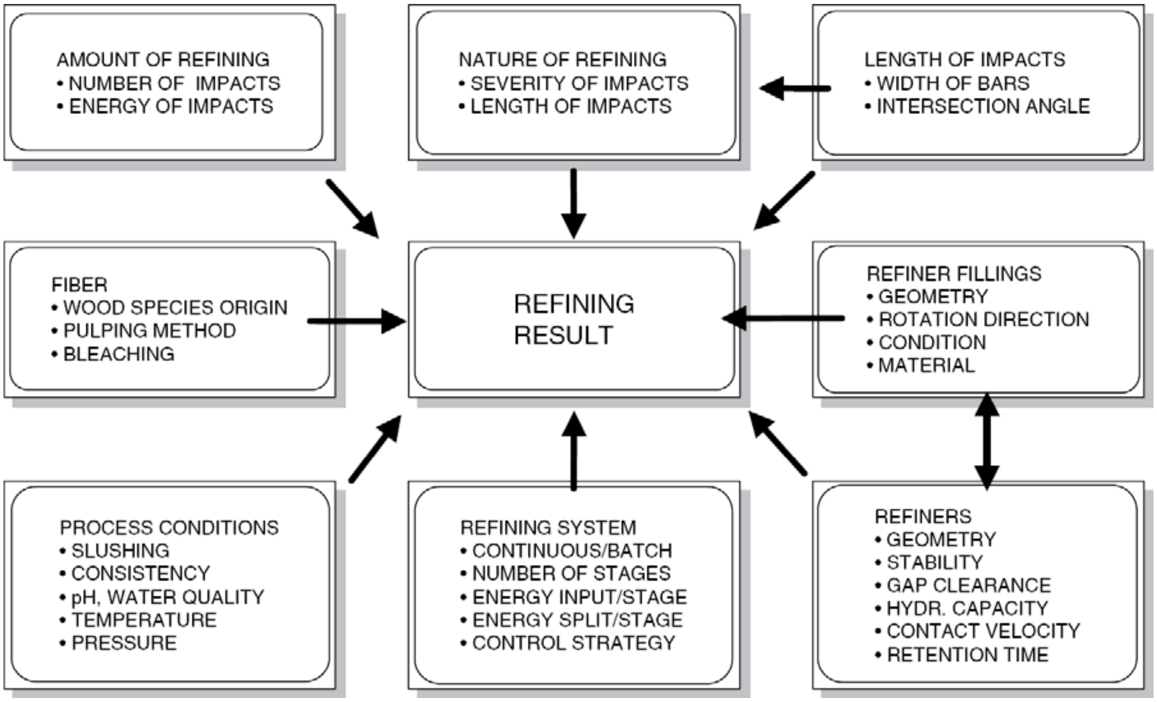


Figure 4. Factors affecting refining result.

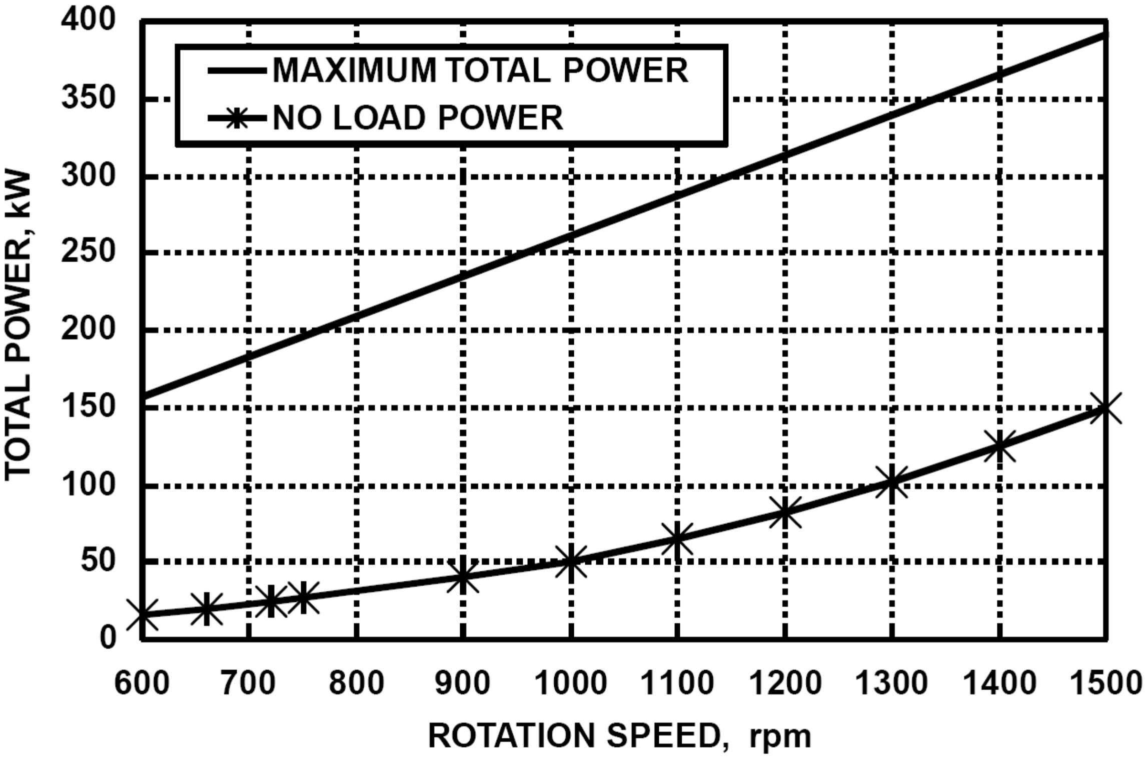
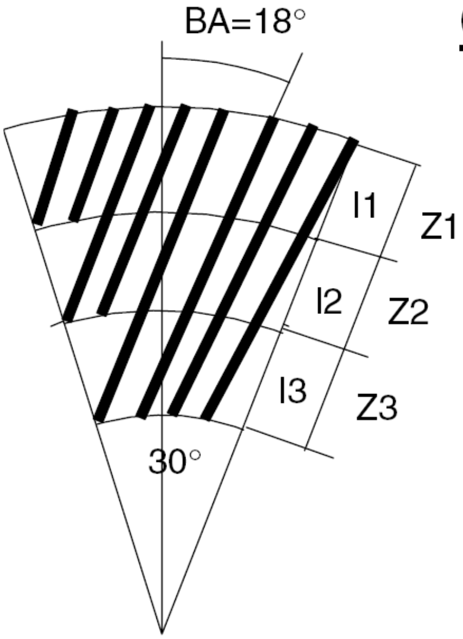


Figure 5. Effect of the rotation speed on refiner power.



CEL = Zr * Zst * l

Both rotor and stator are made of 12
segments (360/30), Each segment has
* 4(four) 315 mm long bars
* 2(two) 210 mm long bars
* 2(two) 105 mm long bars

l1=l2=l3=100 mm,
real bar length = l1....l3 /cosBA

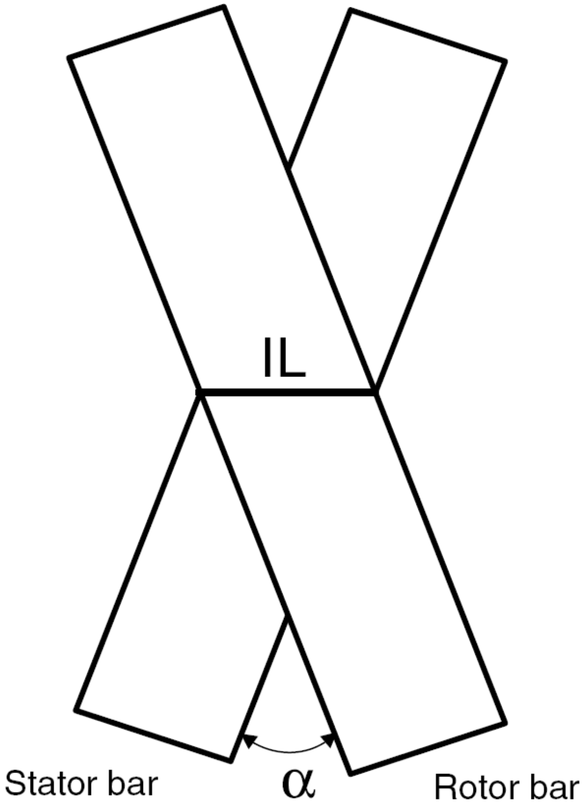
One full turn means
* Zone1 = 96r+96st bars, á 105 mm long
* Zone2 = 72r+72st bars, á 105 mm long
* Zone3 = 48r+48st bars, á 105 mm long

Cutting edge length calculation
* Zone1 96 * 96 * 0.105 m = 967.7 m/rev
* Zone2 72 * 72 * 0.105 m = 544.3 m/rev
* Zone3 48 * 48 * 0.105 m = 241.9 m/rev

Total (Zone1....Zone3) = 1753.9 m/rev

CEL = 1.754 km/rev for a single disc or conical refiner
= 3.508 km/rev for a double disc refiner

Figure 6. Cutting edge length calculation.



$$IL = \frac{Wr + Wst}{2} * \frac{1}{\cos \alpha/2}$$

IL = Impact length

Wr = Width of rotor bar

Wst = Width of stator bar

α = Intersecting angle

Figure 7. Definition of the impact length.

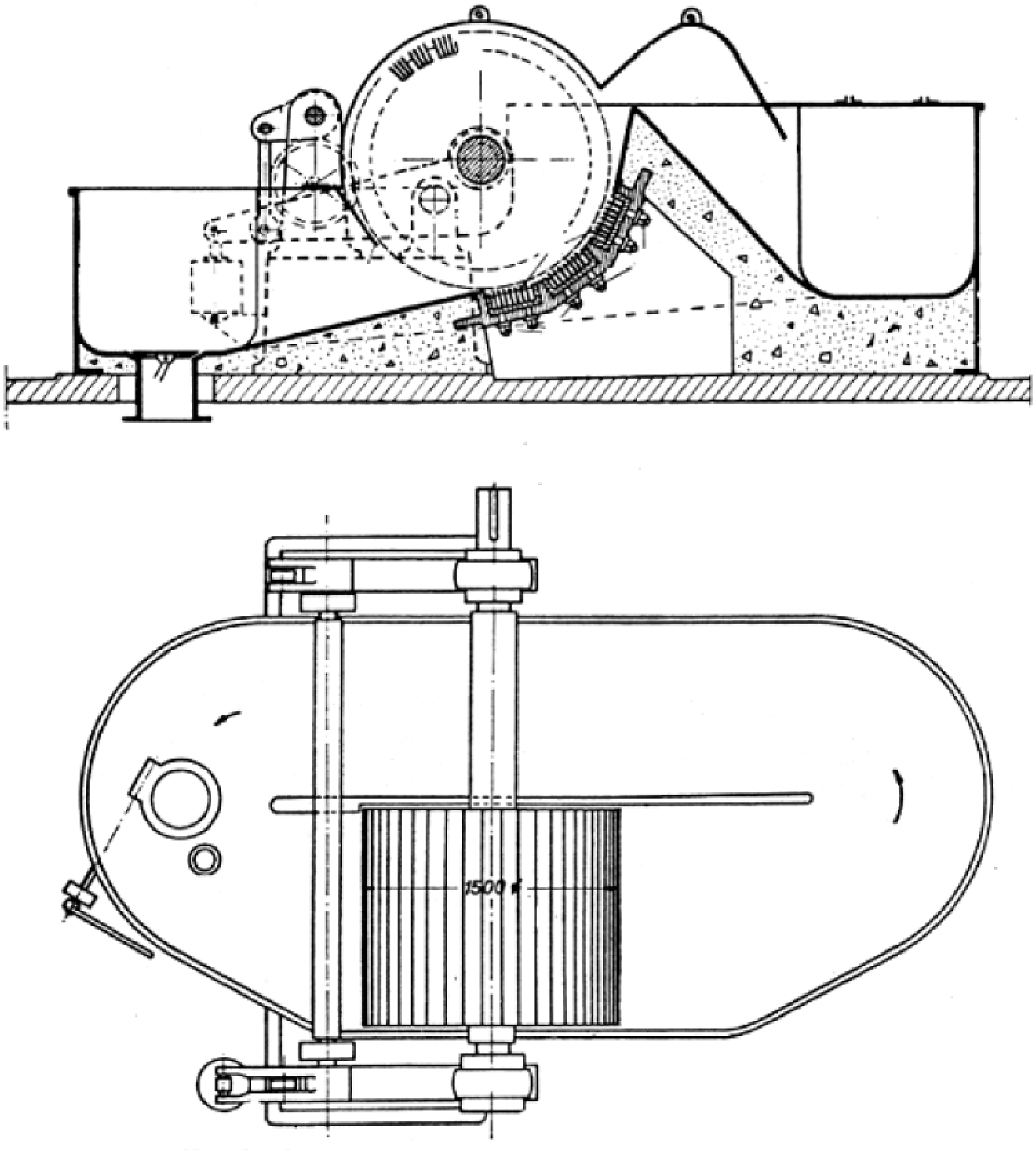


Figure 8. Hollander beater.

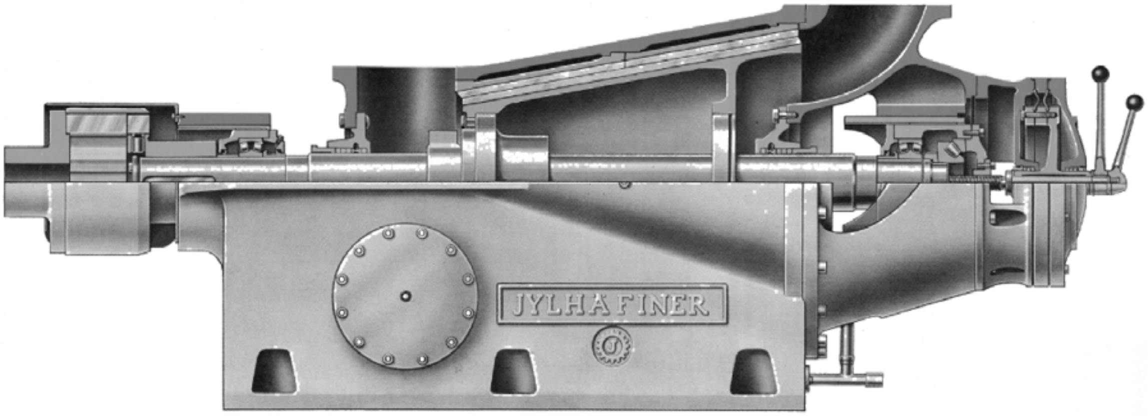


Figure 9. Cross section of Jordan-type conical refiner.

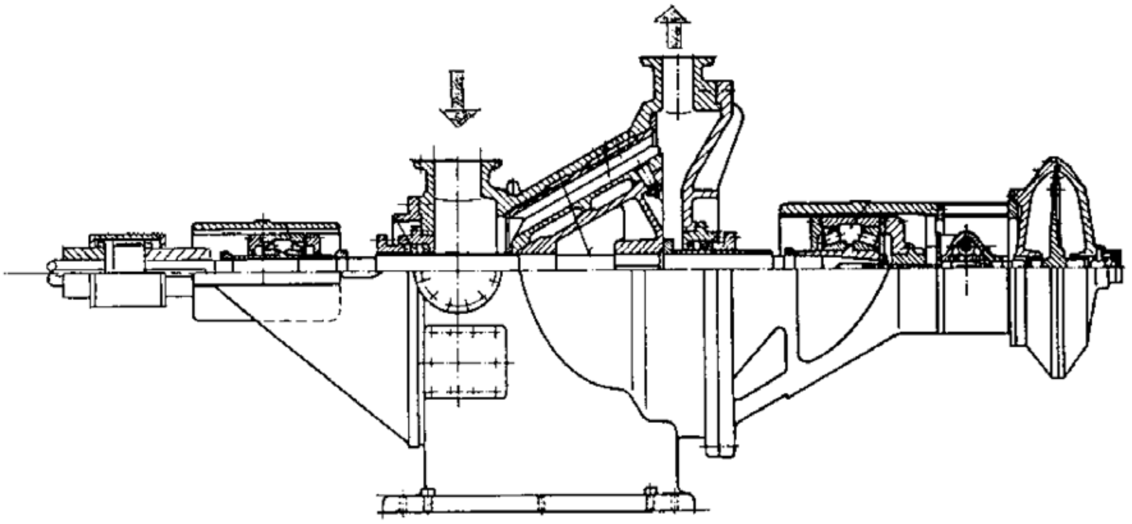
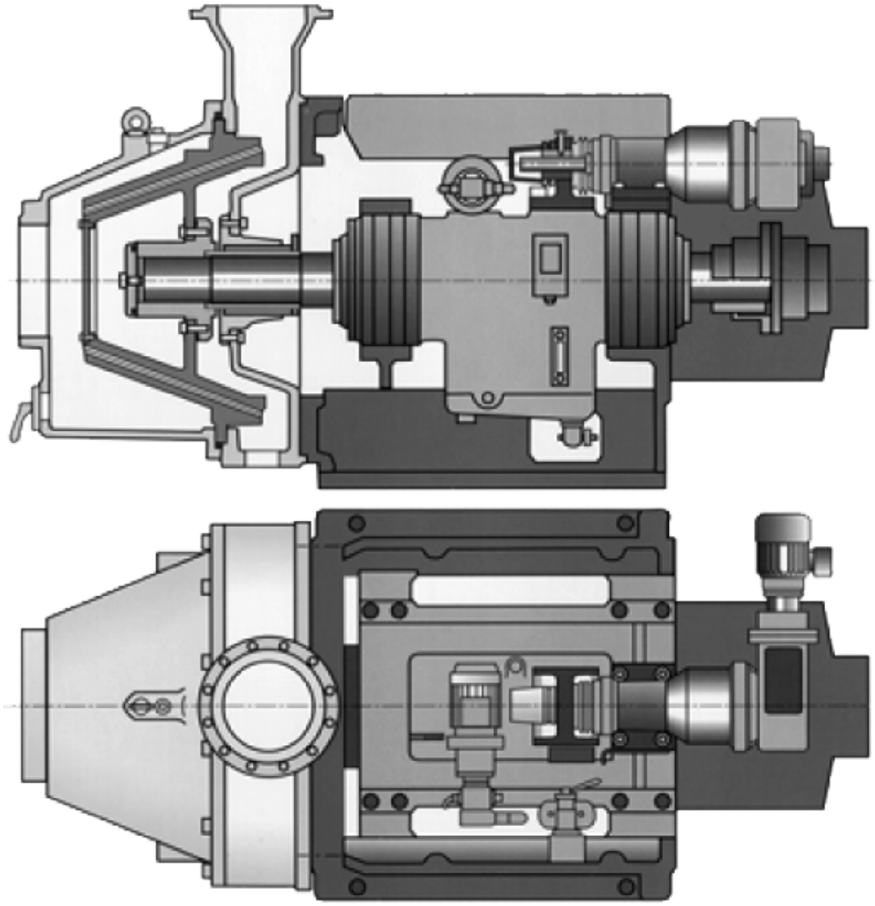


Figure 10. Cross section of Claflin-type conical refiner.



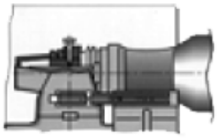


Figure 11. Valmet Conflo® refiner.

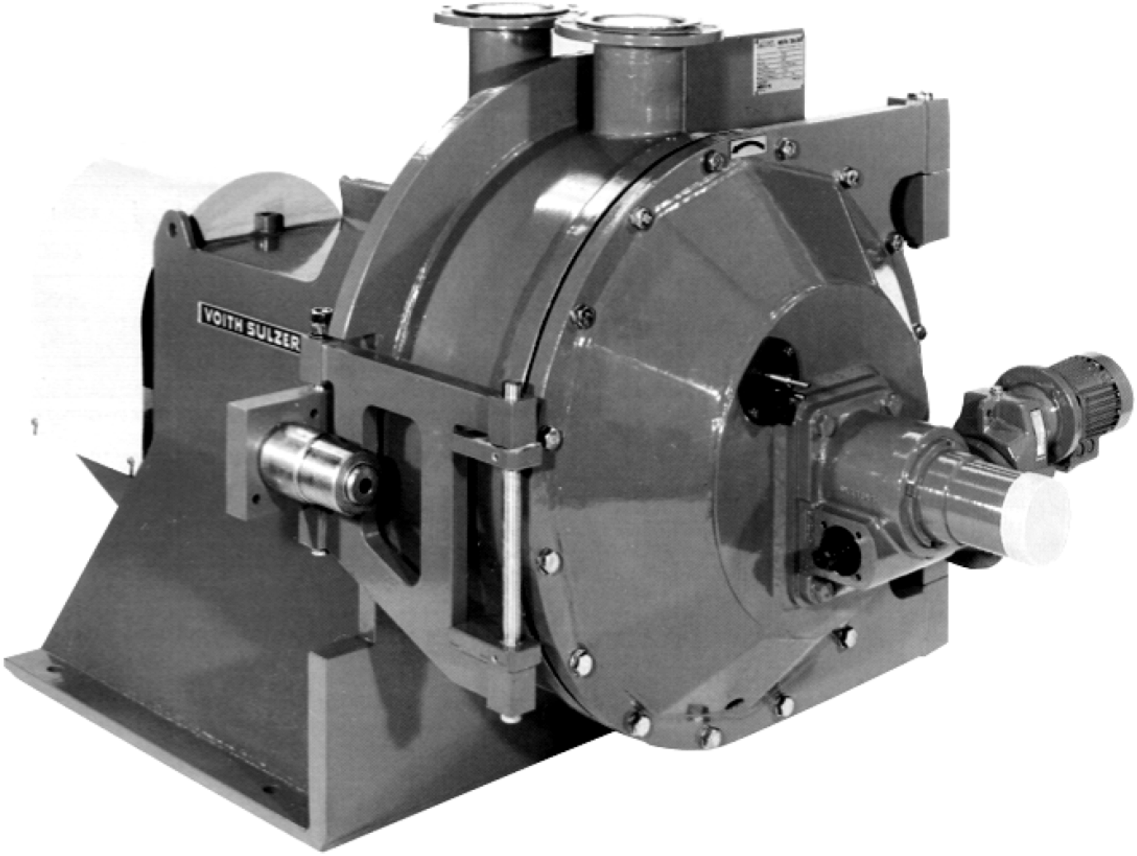


Figure 12. Voith Sulzer Double Disc.

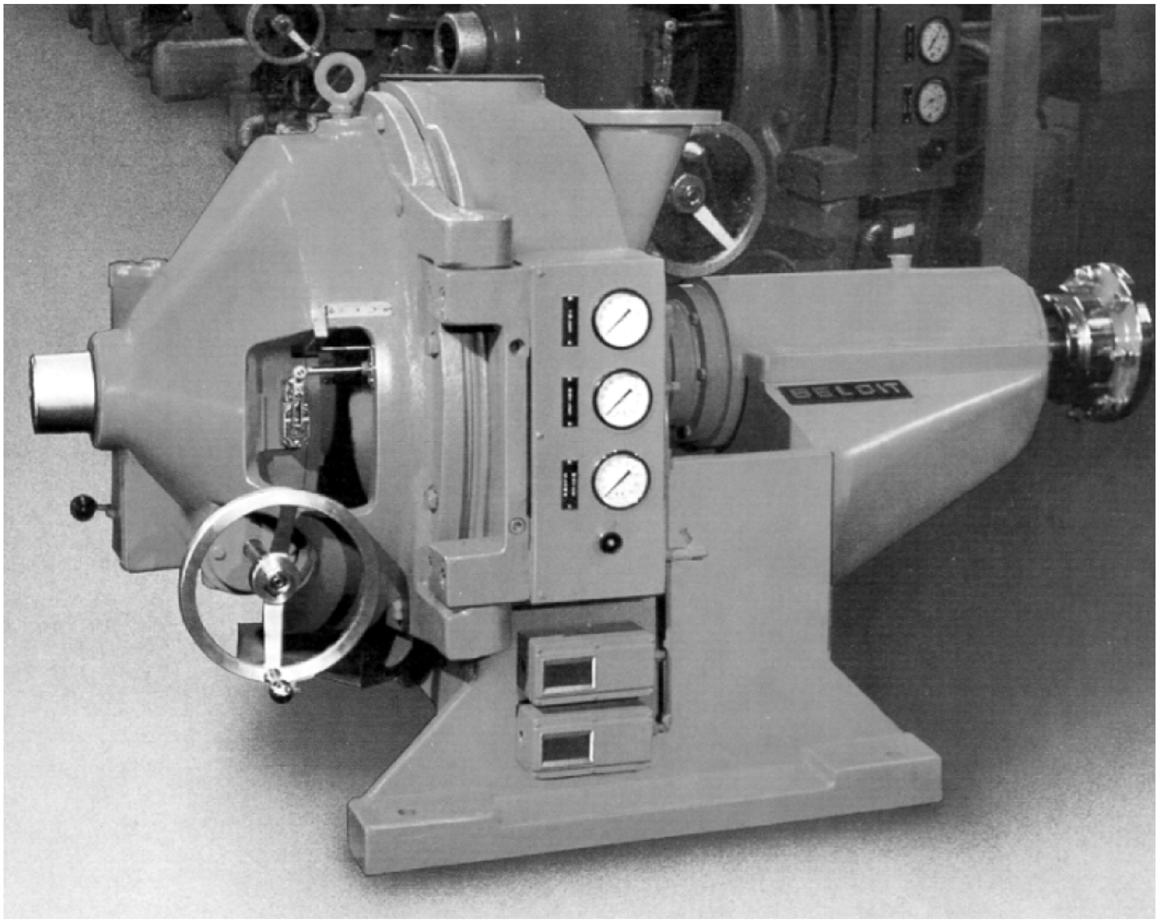


Figure 13. Beloit Double Disc.

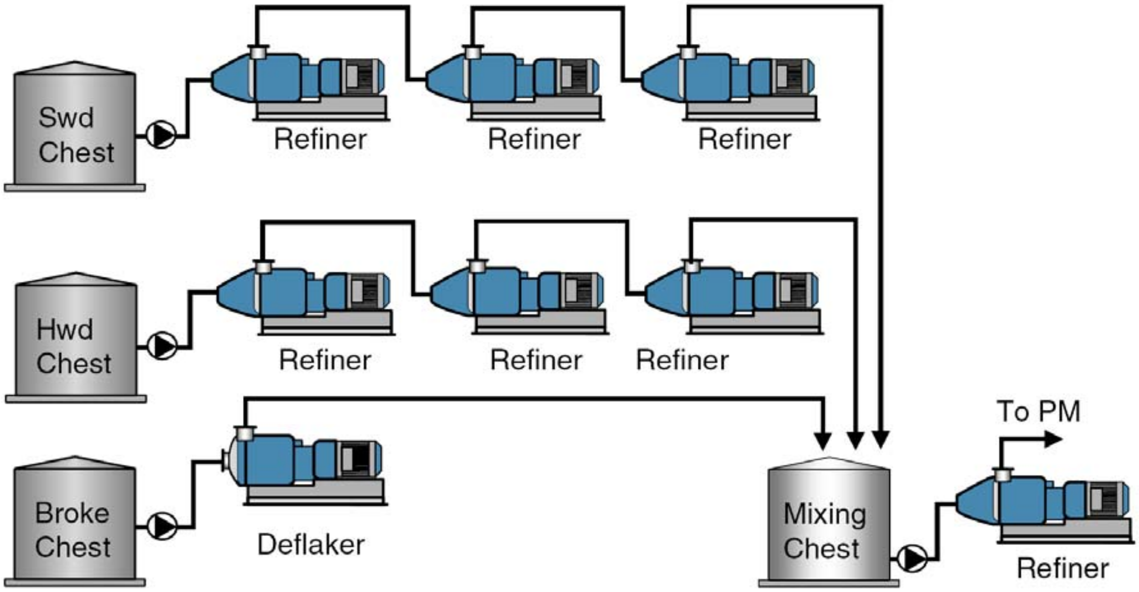


Figure 14. Separate refining system.

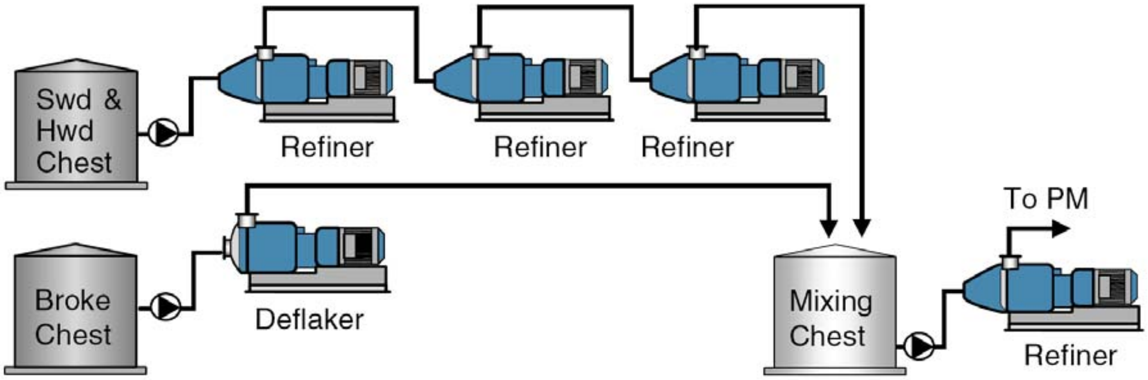


Figure 15. Mixed refining system.

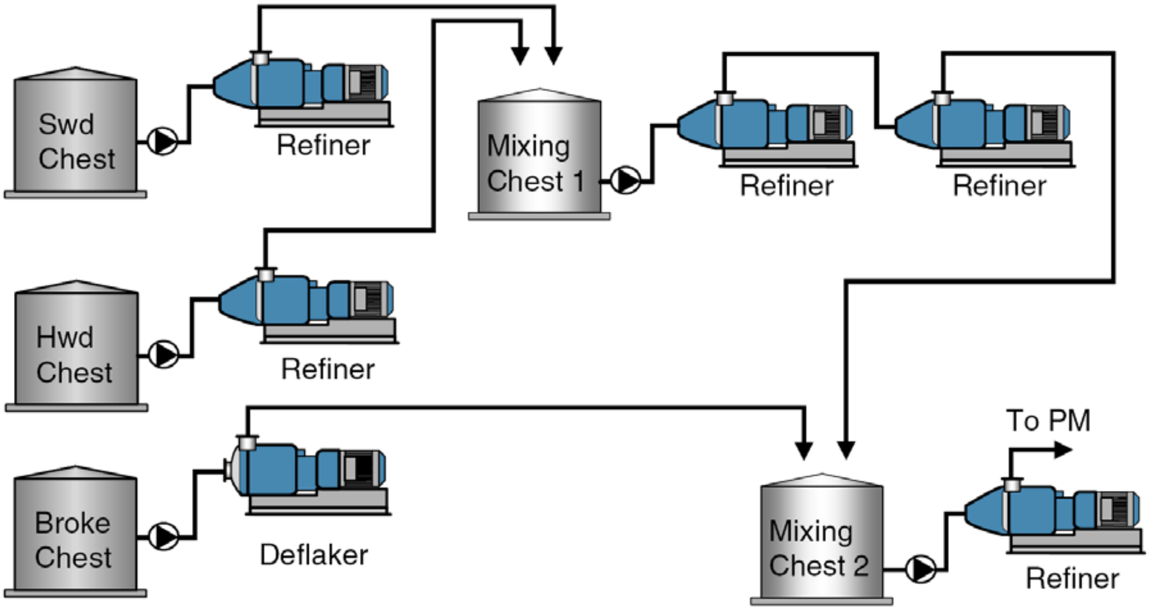
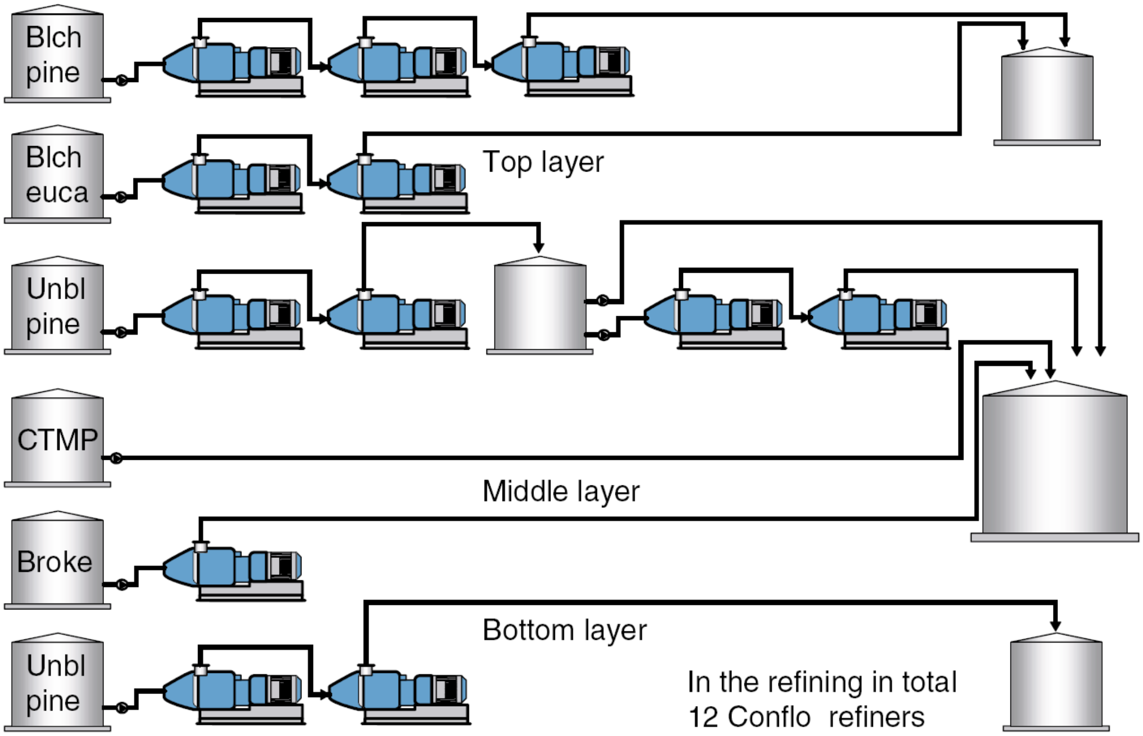
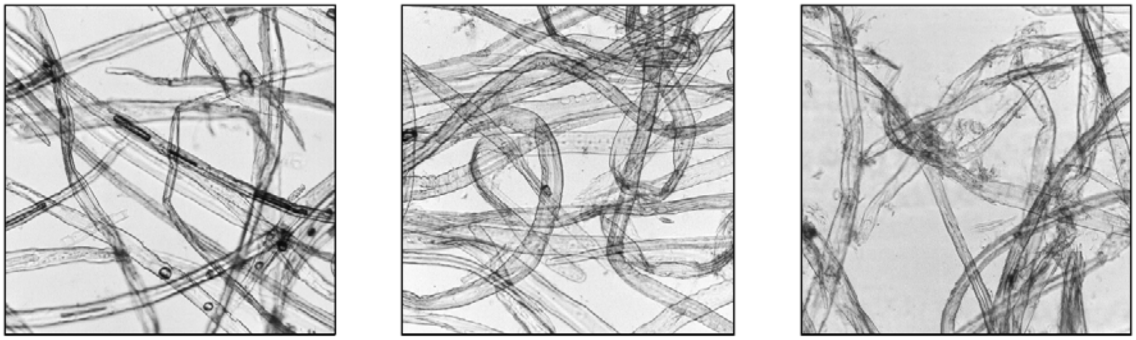


Figure 16. Future refining system.



In the refining in total
12 Conflo refiners

Figure 17. Refining system for a multi-layer board machine.



Unrefined

After HC-refining
220 kWh/bdmt

After LC-refining
110 kWh/bdmt

	Unrefined	After HC	After LC
Freeness, mL/°SR	705/15.7	700/15.8	550/21.6
Bulk, cm³/g	2.23	1.93	1.68
Fiber length, mm	2.30	2.11	2.25
Tensile index, Nm/g	46.0	44.0	84.0
Tear index, mNm²/g	19.3	18.8	12.2
TEA, J/g	0.9	1.0	2.0
Gurley, s	0.3	0.3	3.0

Figure 18. Effect of HC+LC refining on fibers.

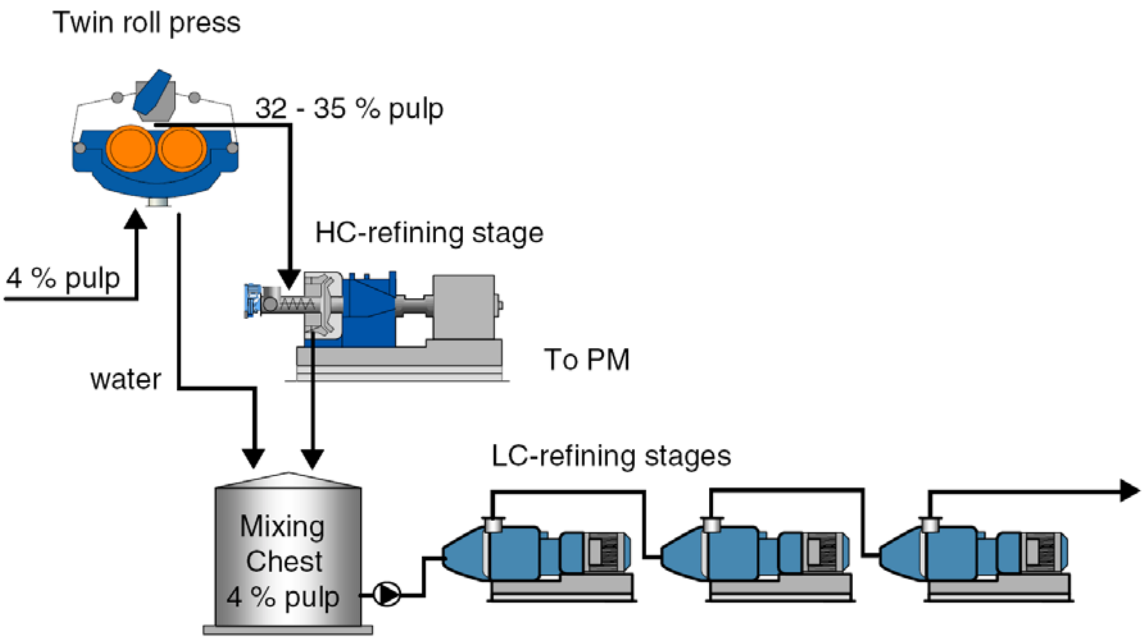


Figure 19. Refining system for sack kraft paper.

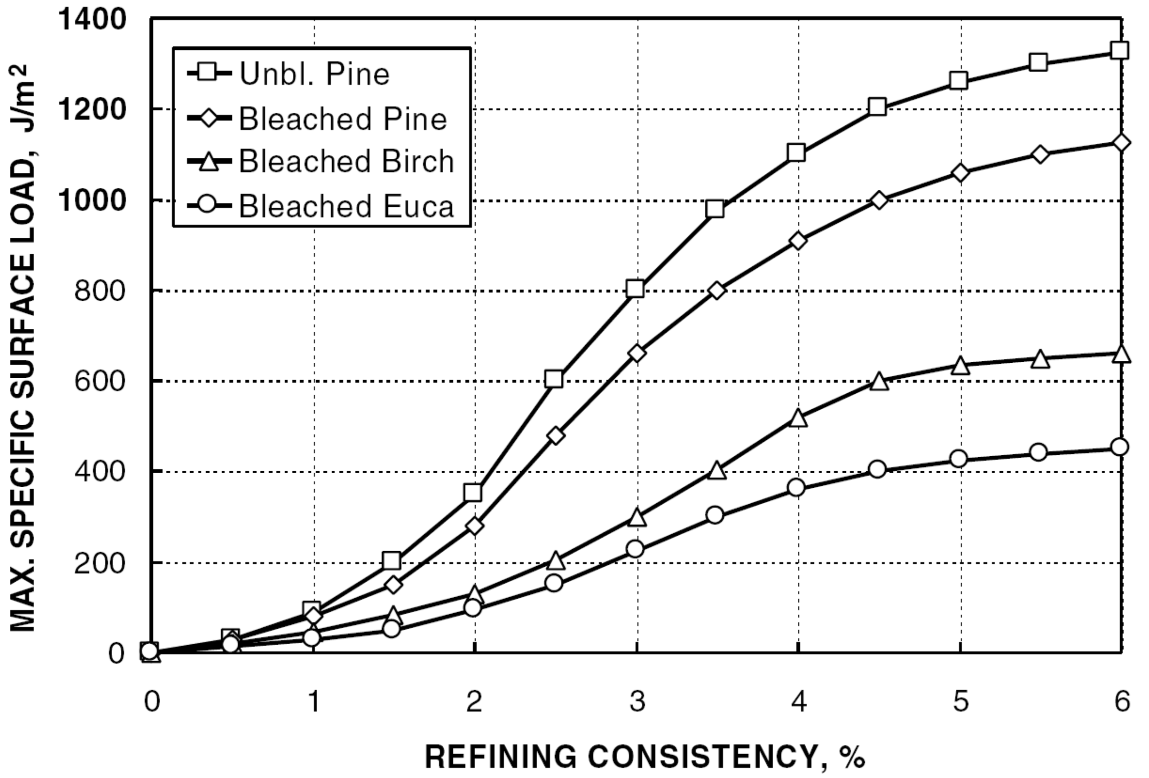


Figure 20. Refining intensity vs. consistency.

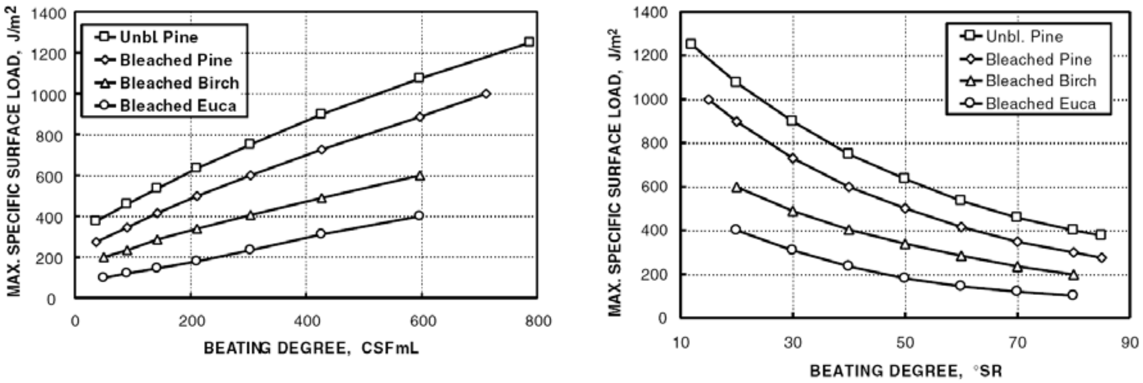


Figure 21. Refining intensity vs. freeness and Schopper-Riegler.

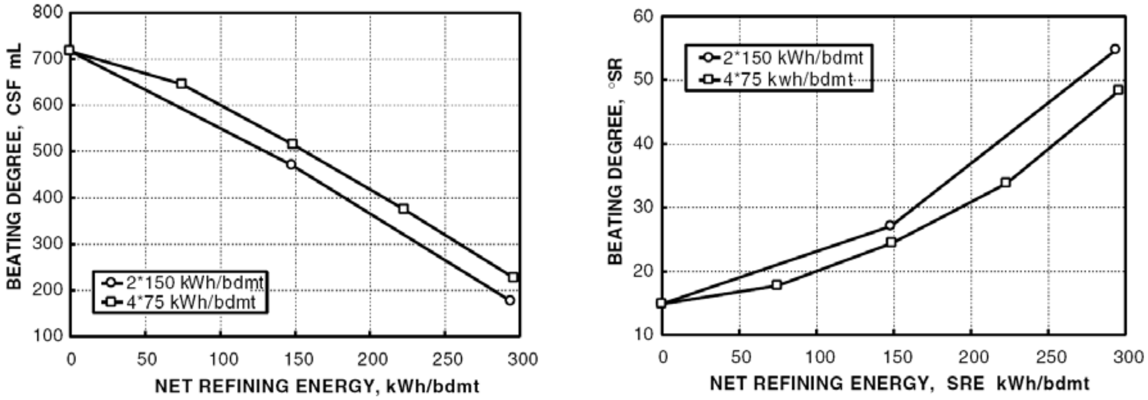


Figure 22. Freeness and Schopper-Riegler vs. net refining energy.

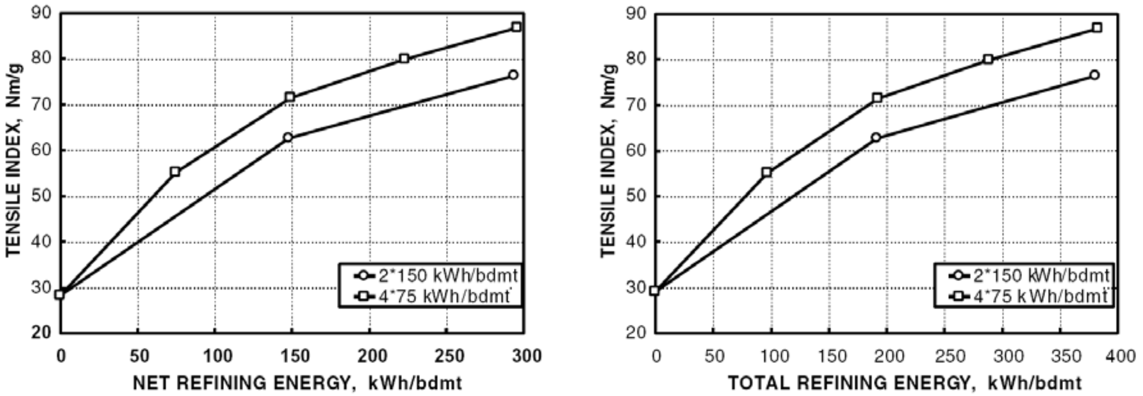


Figure 23. Tensile vs. refining energy.

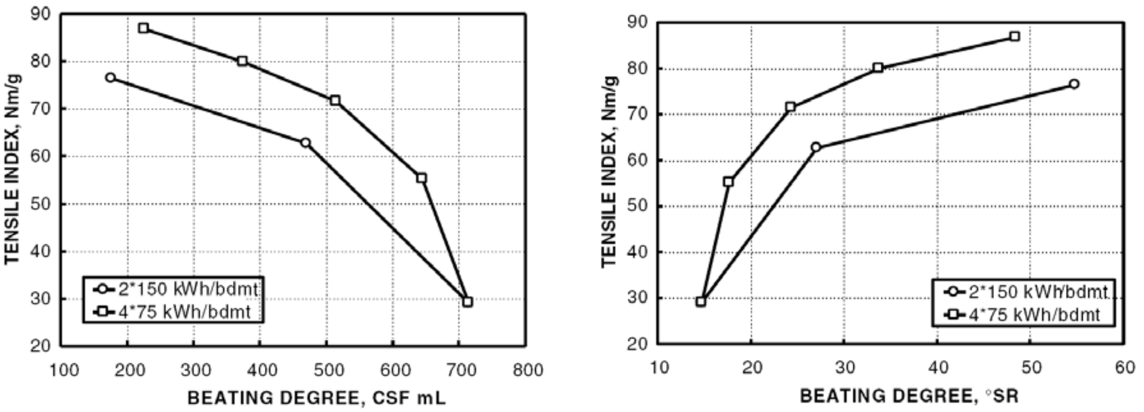
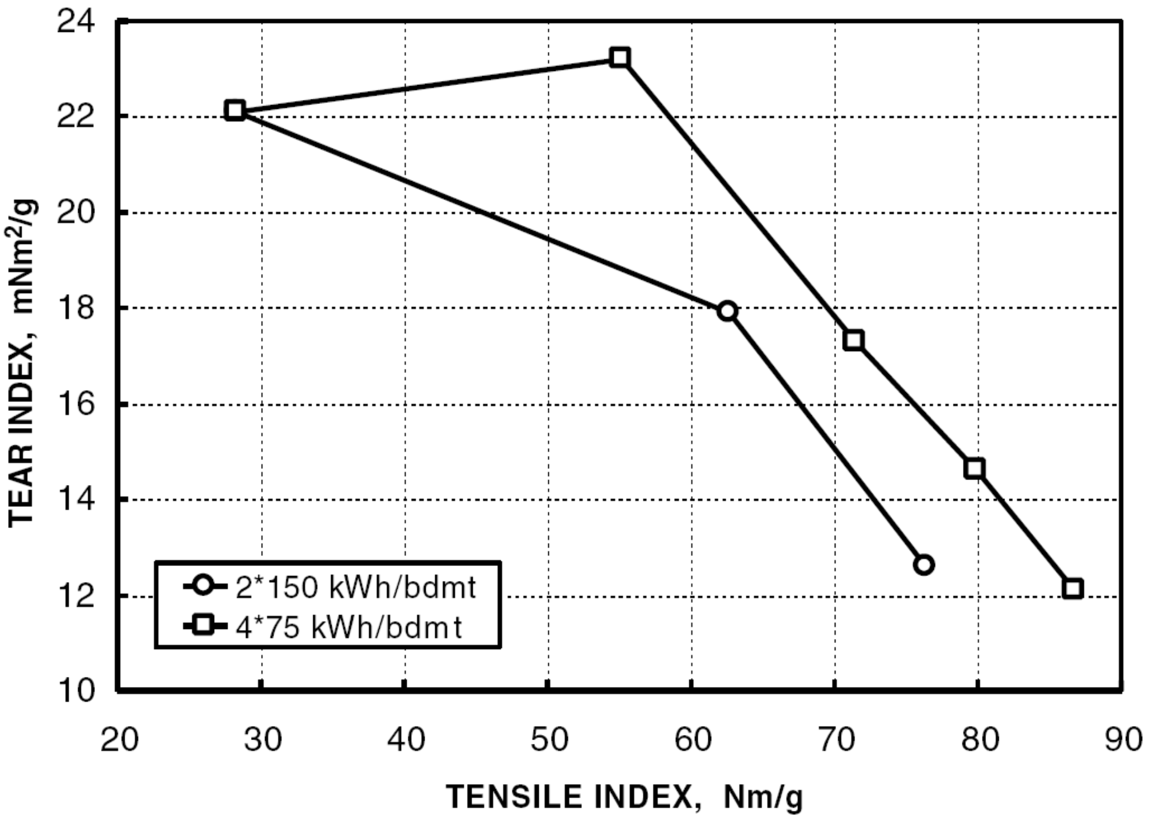
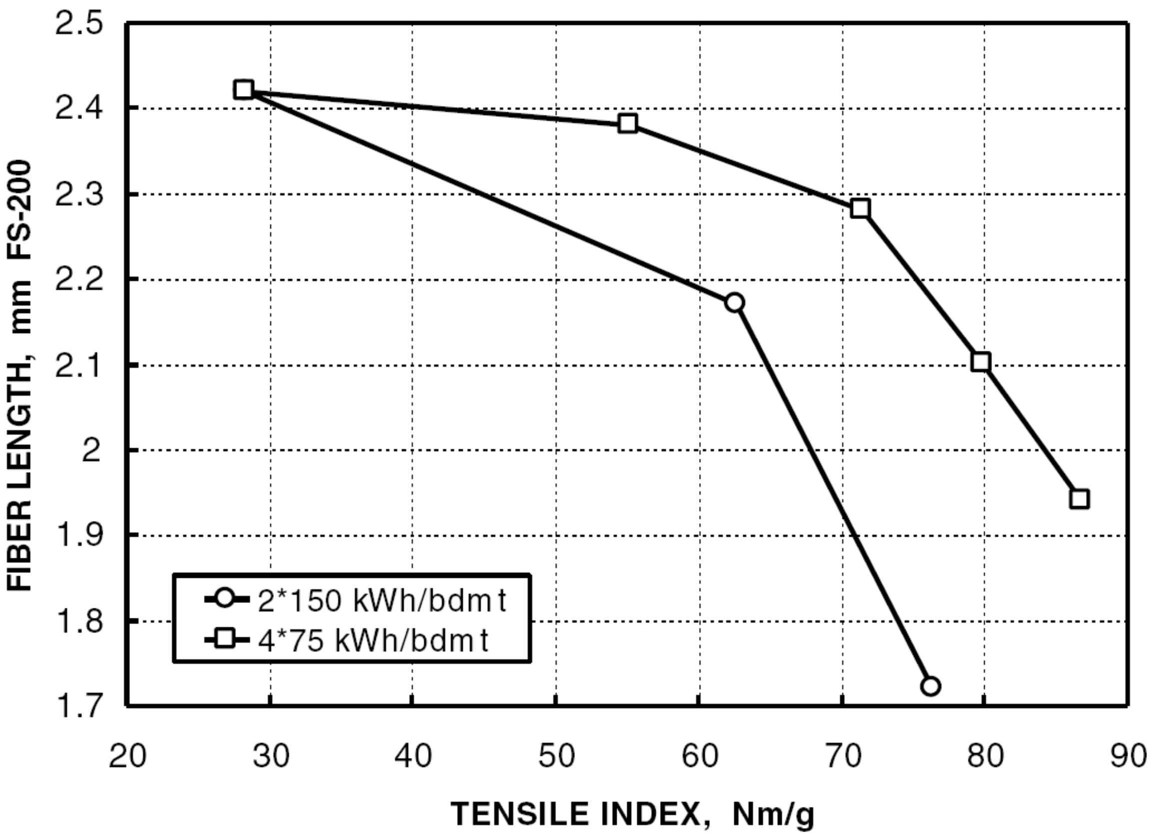


Figure 24. Tensile vs. beating degree.



C4FIG25. Tear vs tensile.

Figure 25. Tear vs. tensile.



CFIG26. Fiber lengthvs tensile.

Figure 26. L.W.A. fiber length vs. tensile.

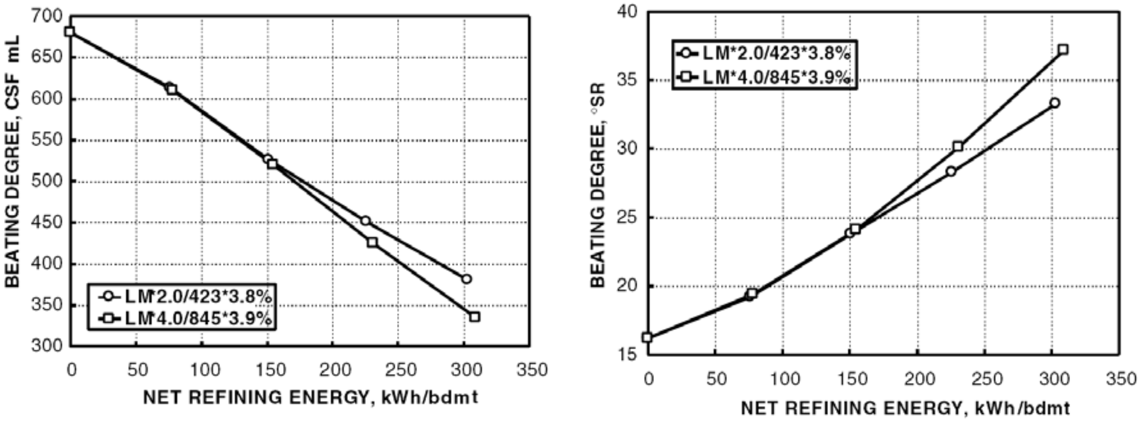


Figure 27. Freeness and Schopper-Riegler vs. net refining energy.

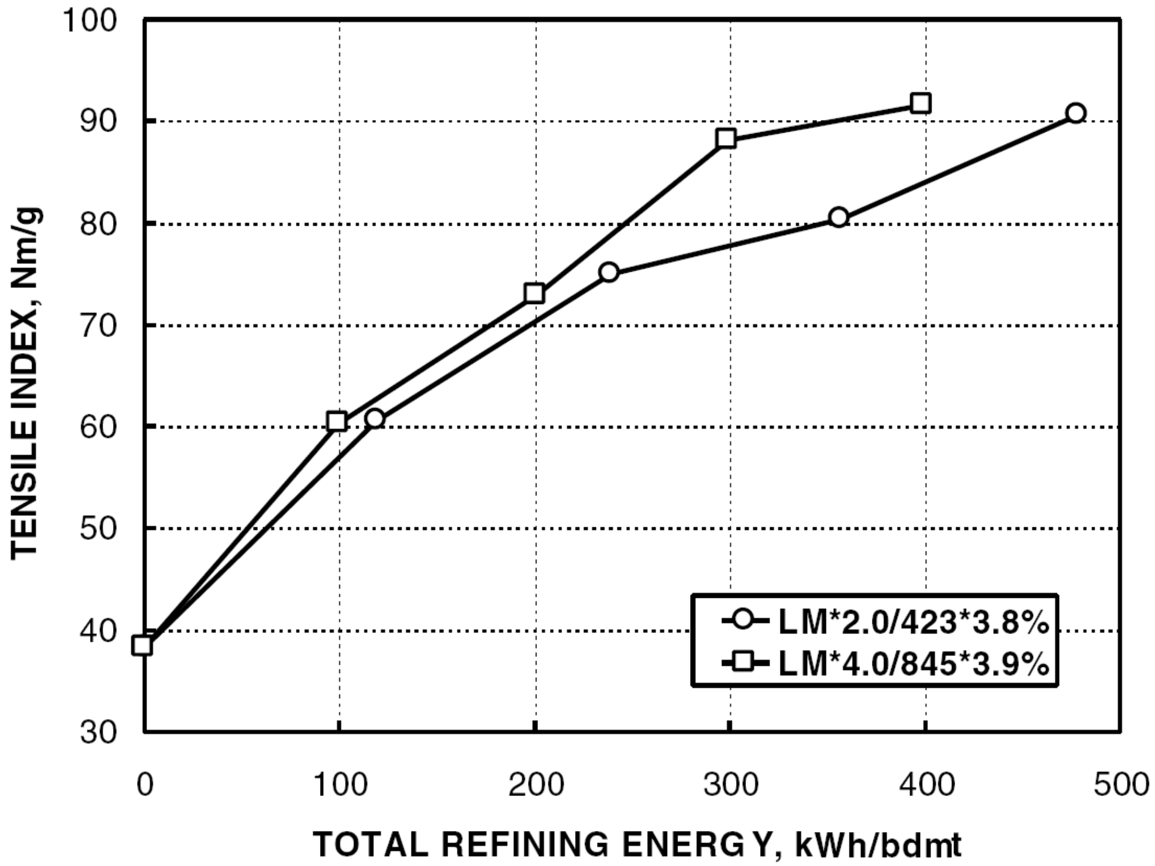


Figure 28. Tensile vs. total refining energy.

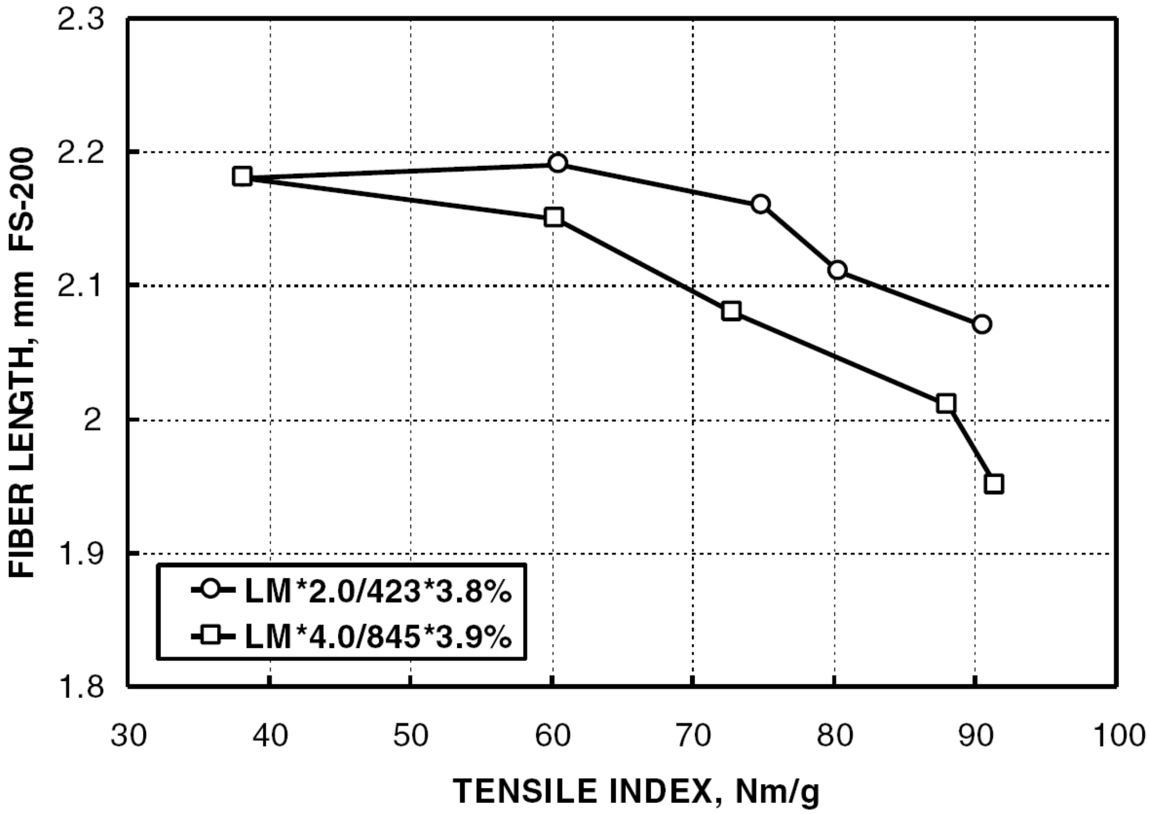


Figure 29. L.W.A. fiber length vs. tensile strength.

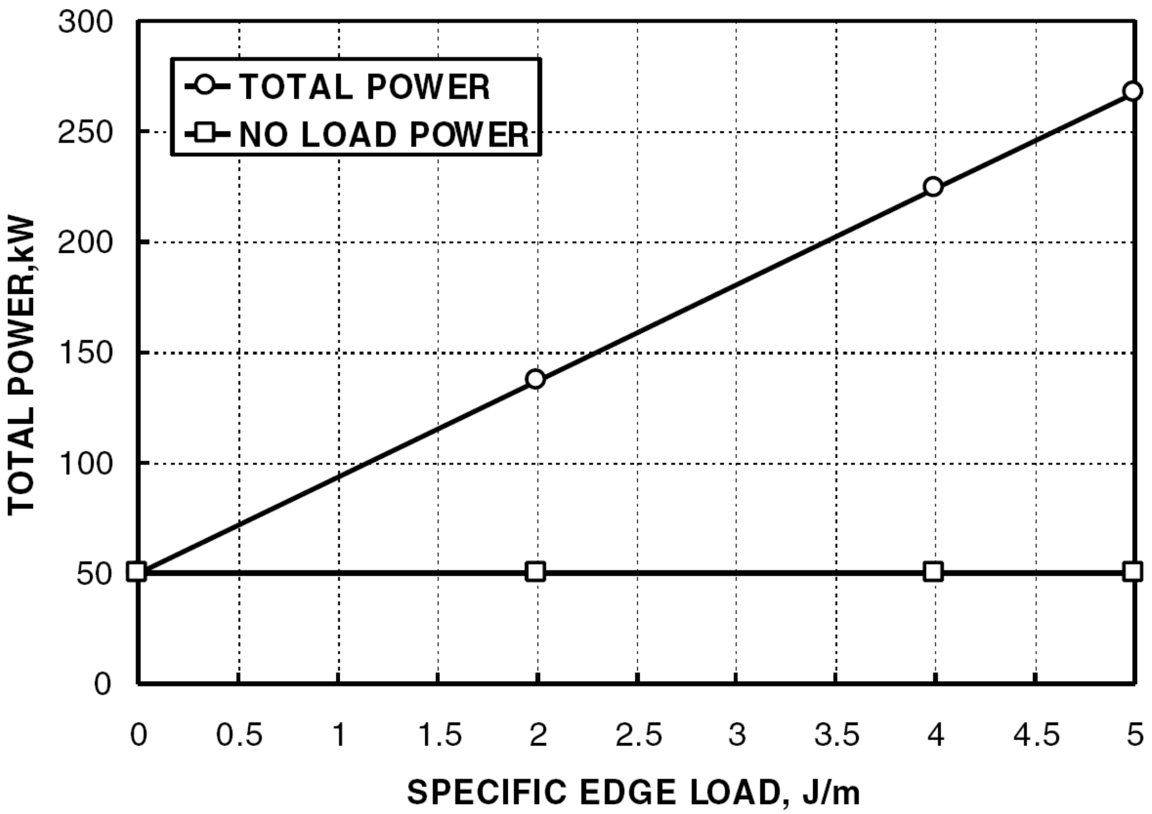


Figure 30. JC-01 refiner with LM fillings at 1 000 rpm.

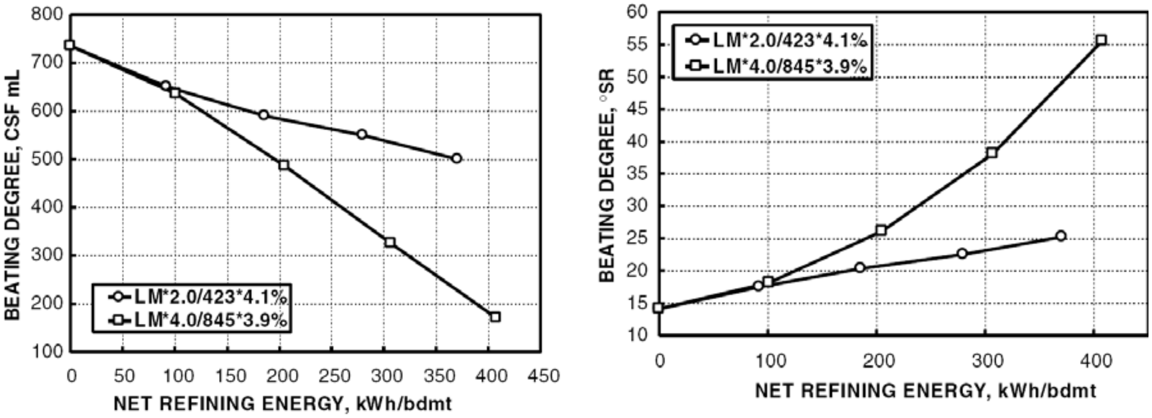


Figure 31. Freeness and Schopper-Riegler vs. net refining energy.

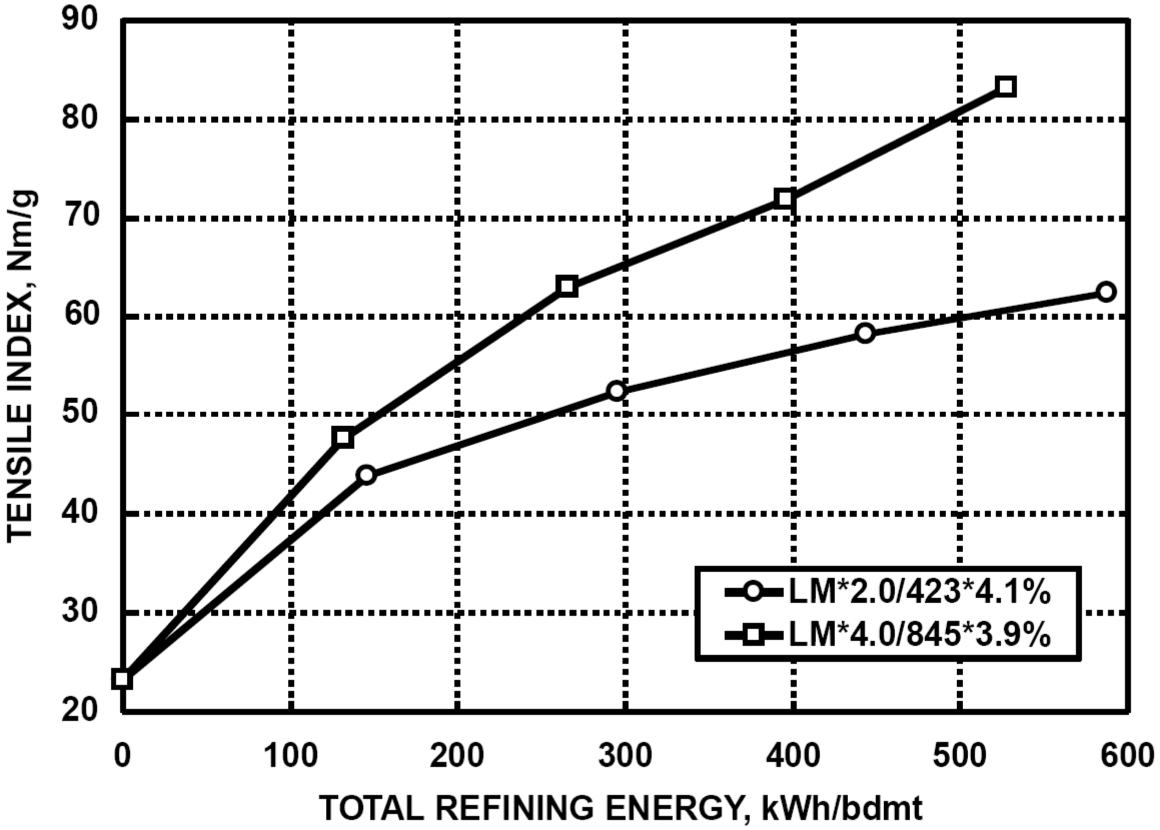


Figure 32. Tensile vs. total refining energy.

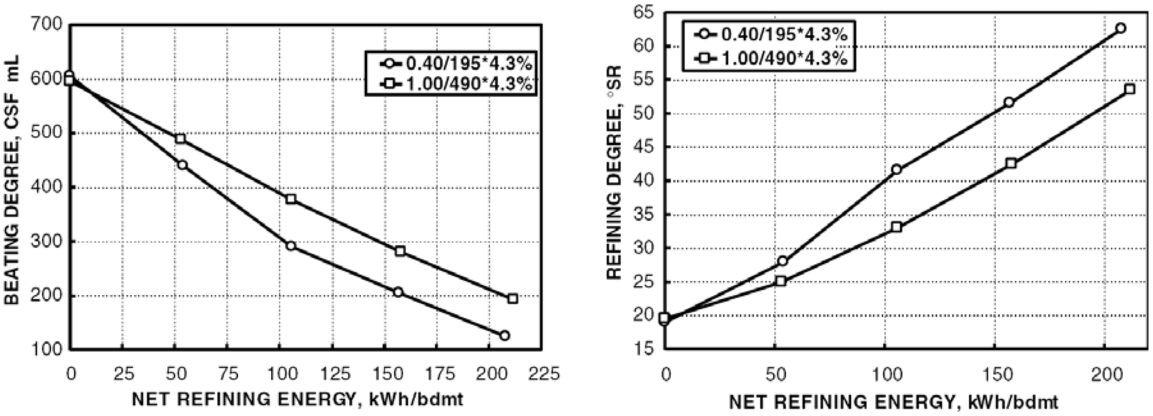


Figure 33. Freeness and Schopper-Riegler vs. net refining energy.

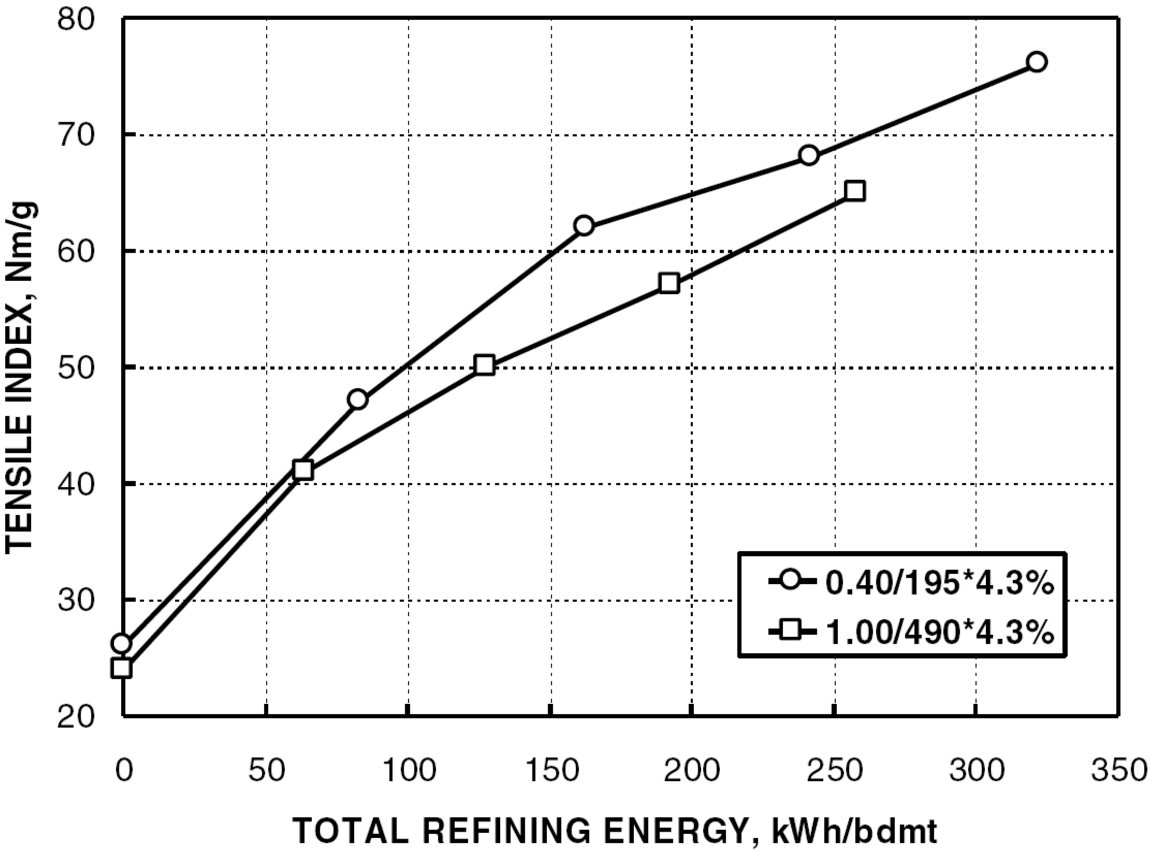


Figure 34. Tensile vs. total refining energy.

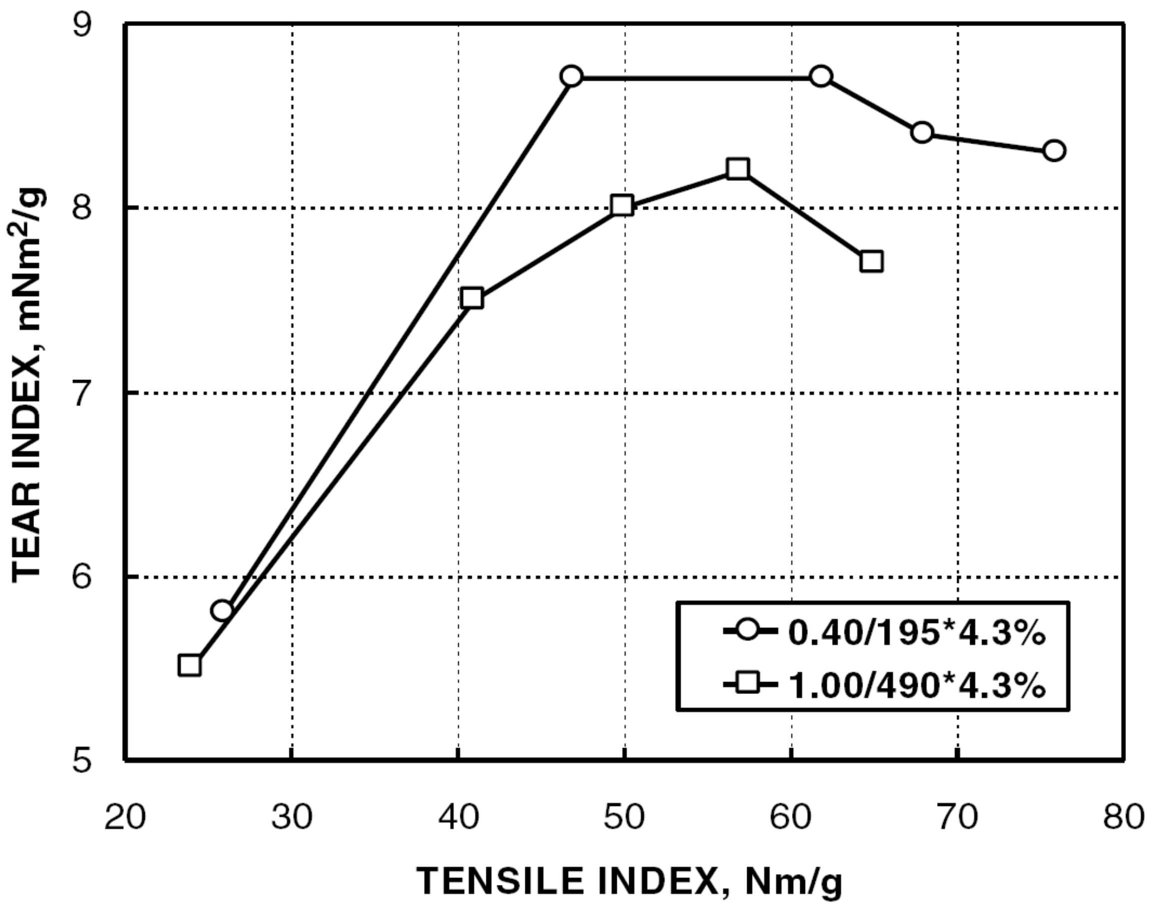


Figure 35. Tear vs. tensile.

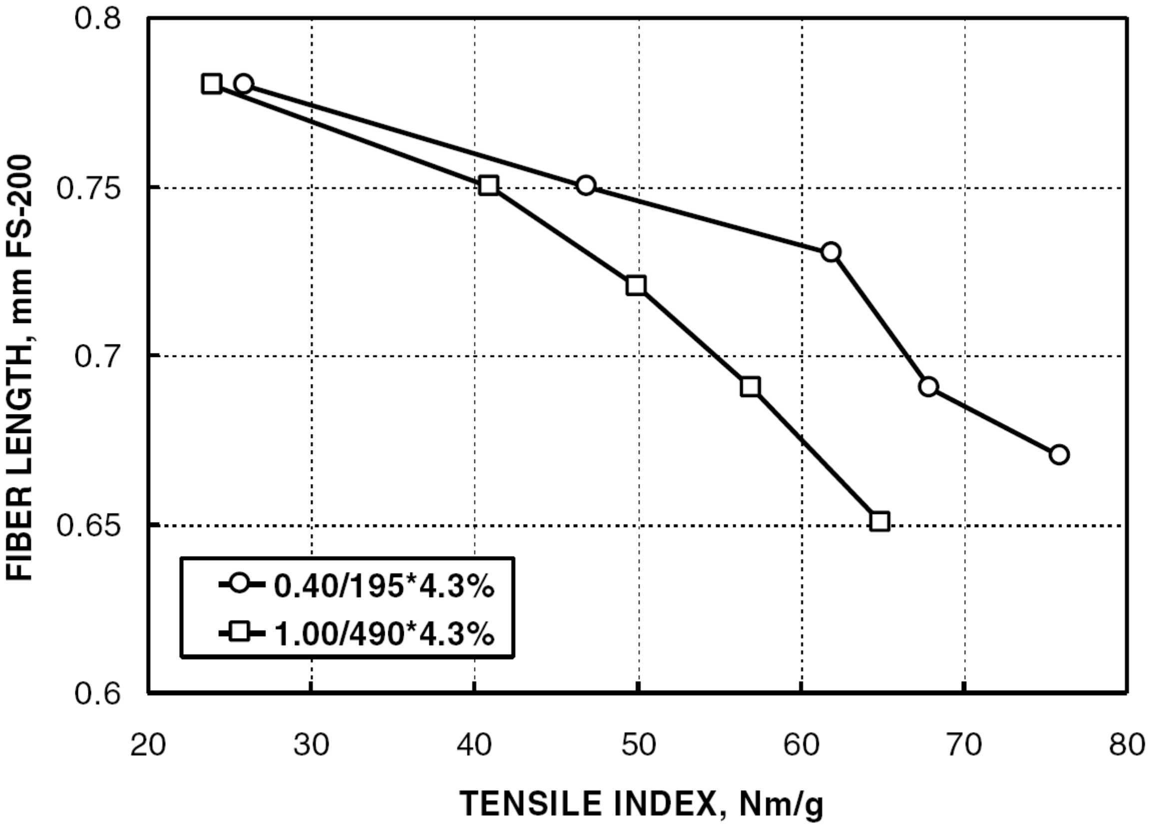


Figure 36. L.W.A. fiber length vs. tensile.

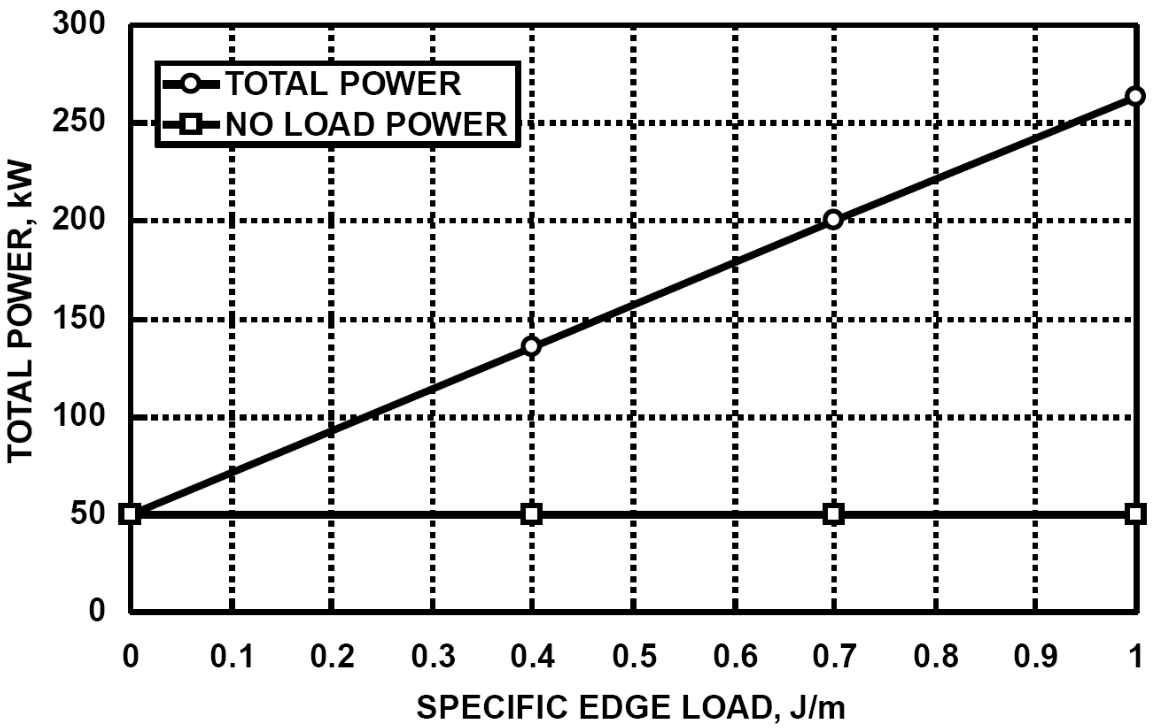


Figure 37. JC-01 refiner with SF fillings at 1 000 rpm.

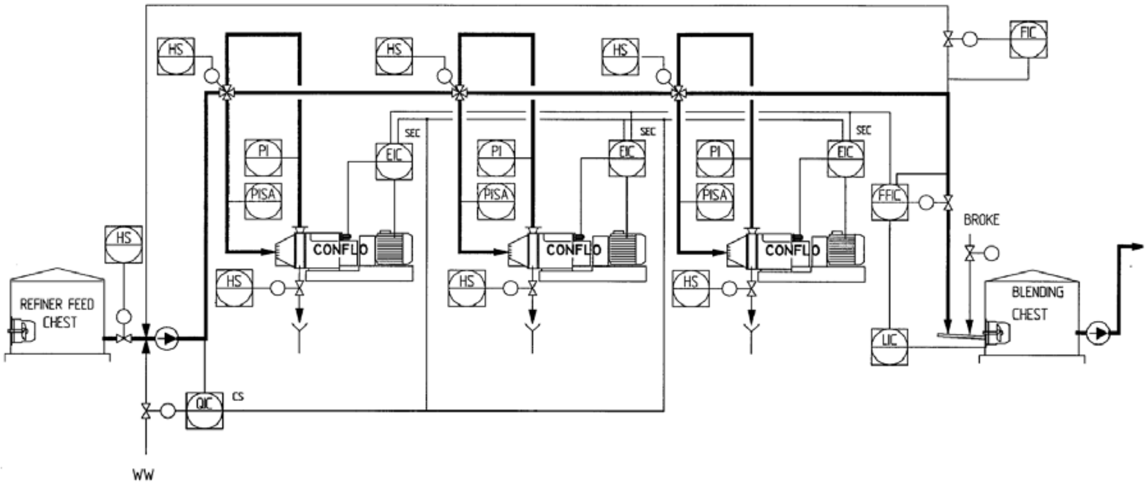


Figure 38. Typical refining line.

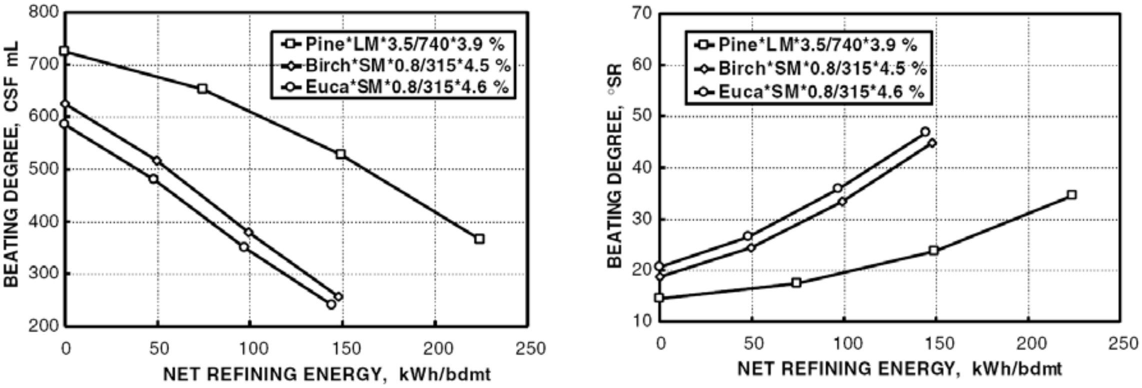


Figure 39. Freeness or Schopper-Riegler vs. net energy.

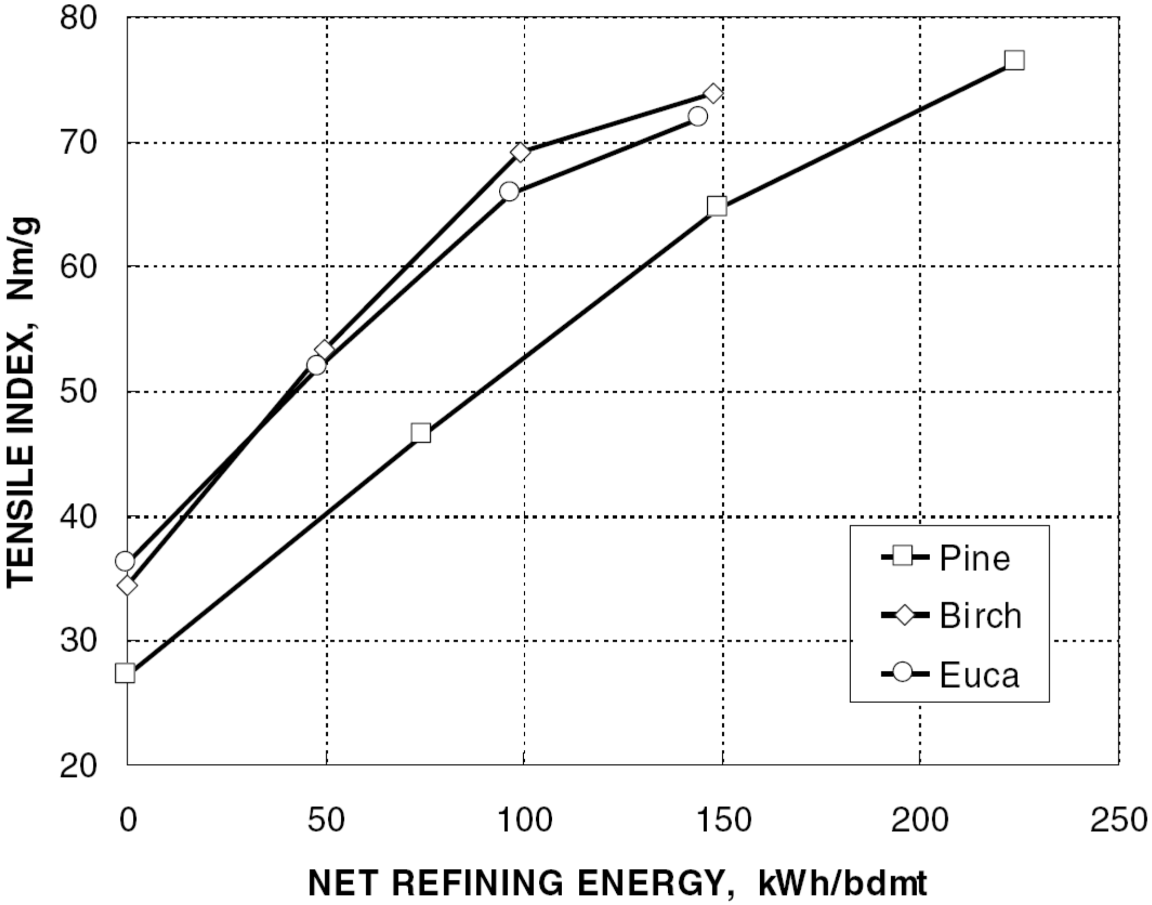


Figure 40. Tensile vs. net energy.

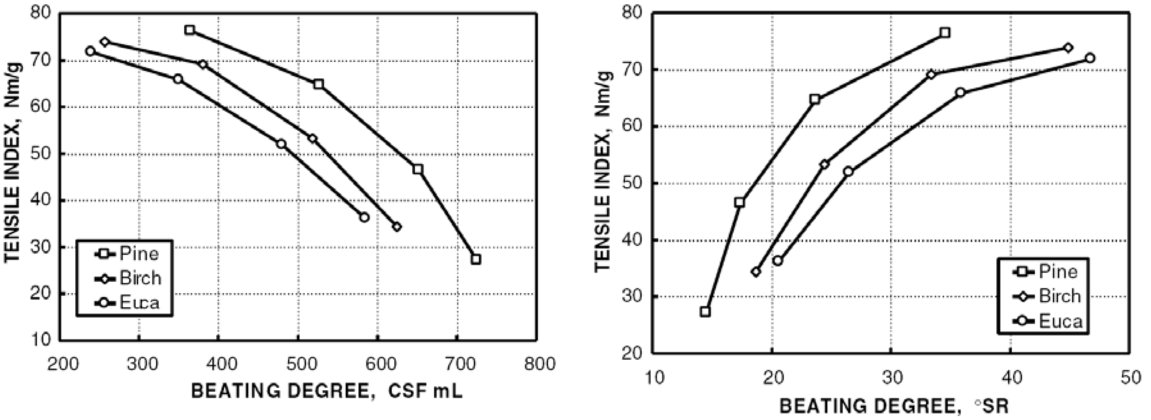


Figure 41. Tensile vs. freeness or Schopper-Riegler.

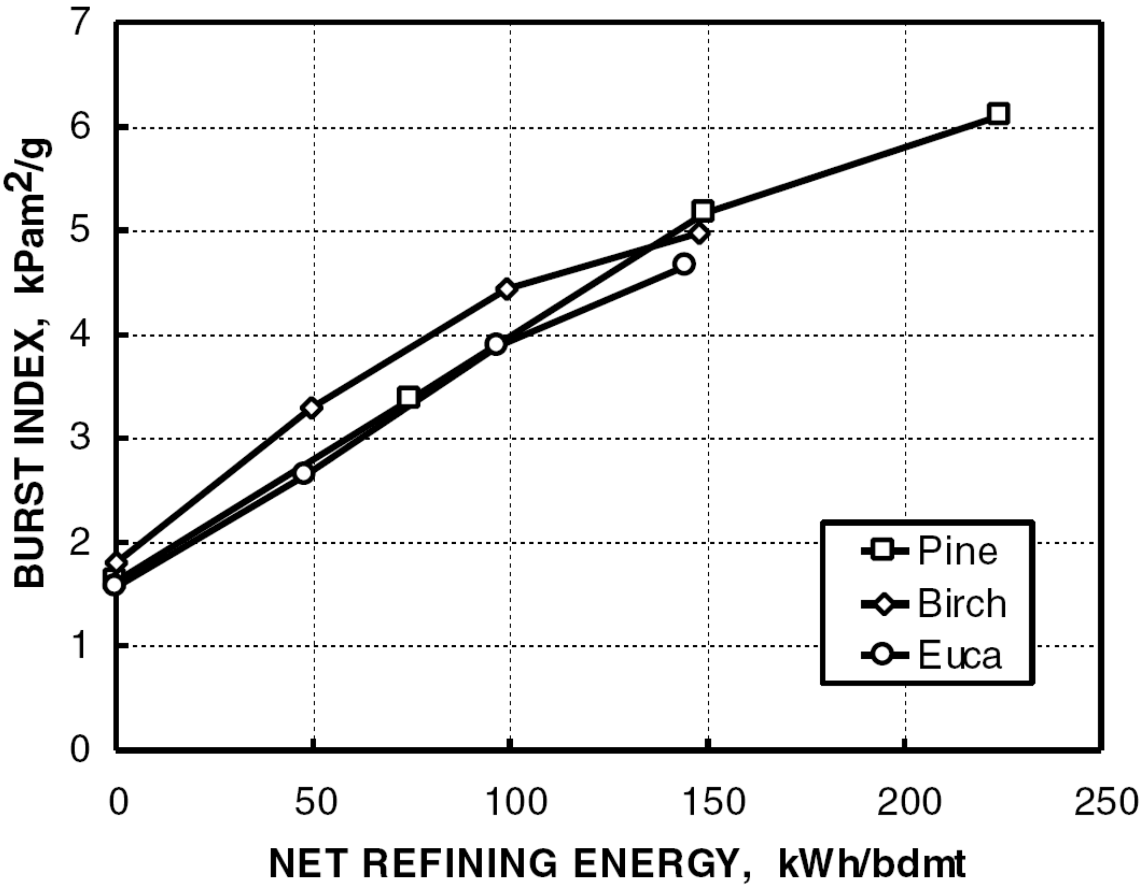


Figure 42. Burst vs. net energy.

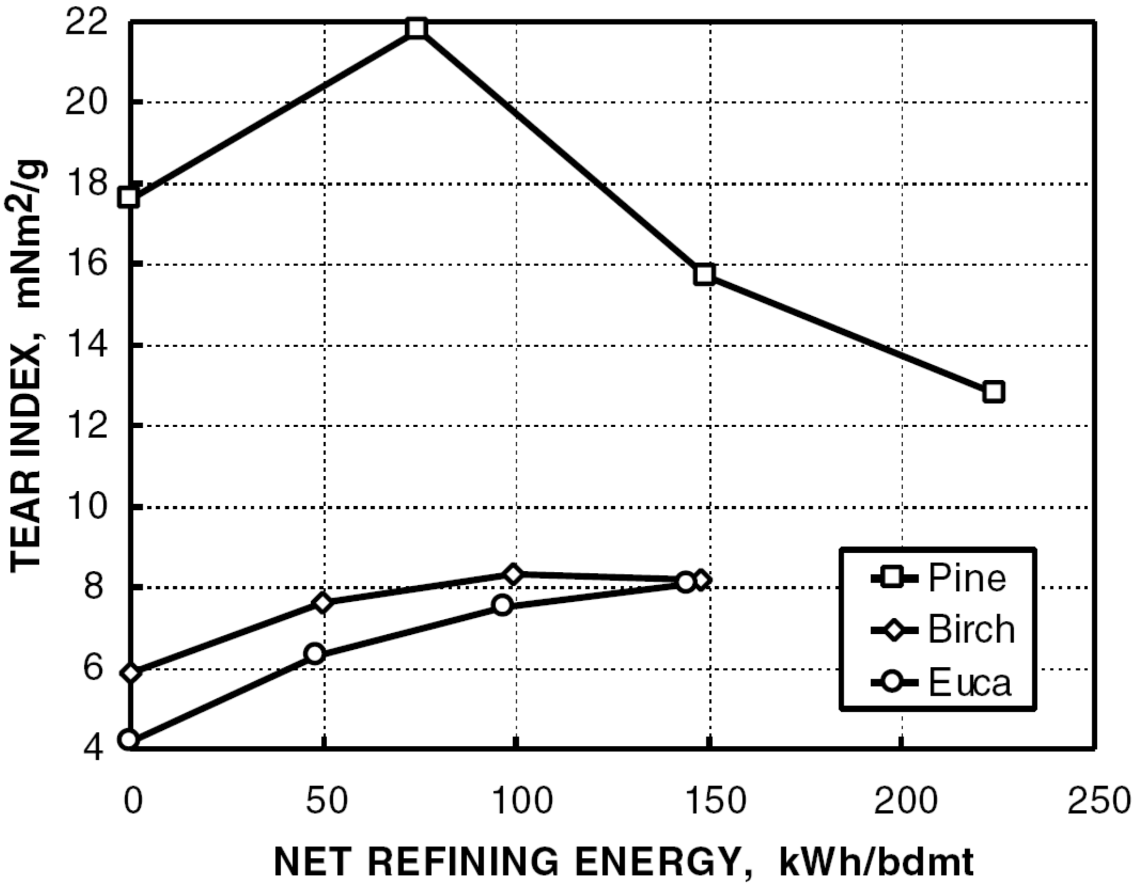


Figure 43. Tear vs. net energy.

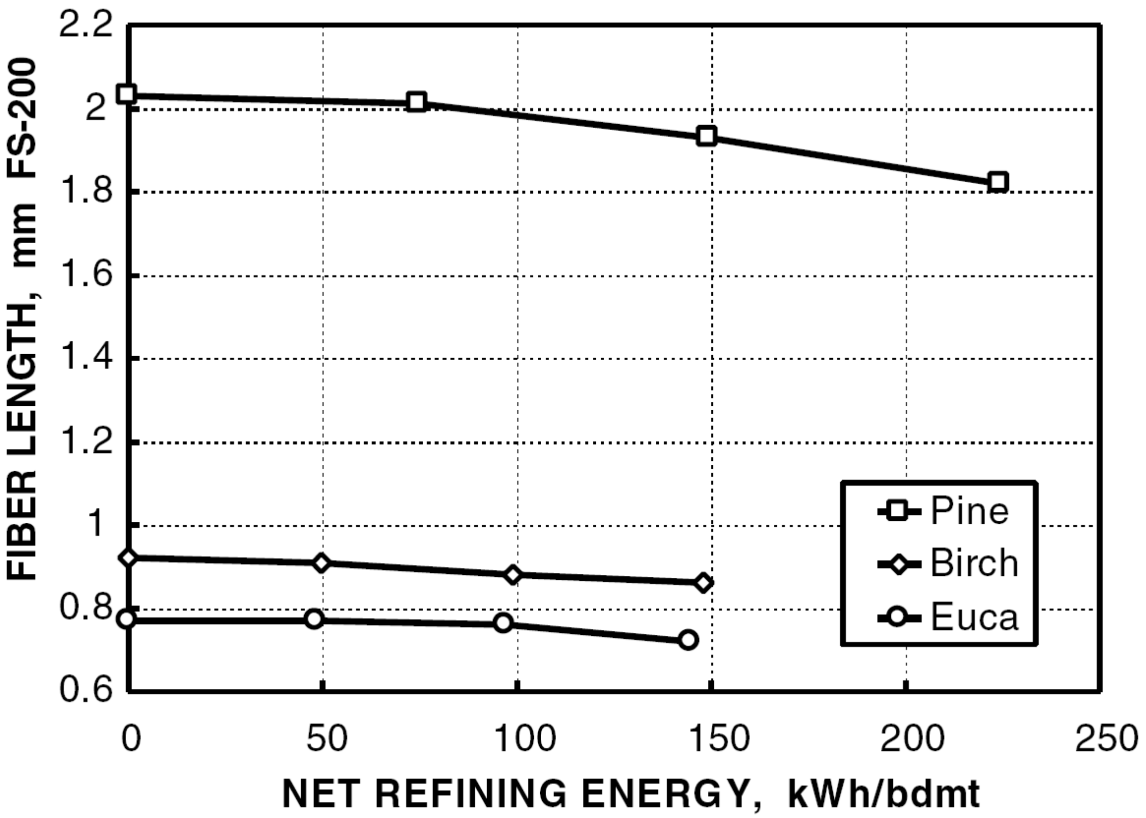


Figure 44. L.W.A. fiber length vs. net energy.

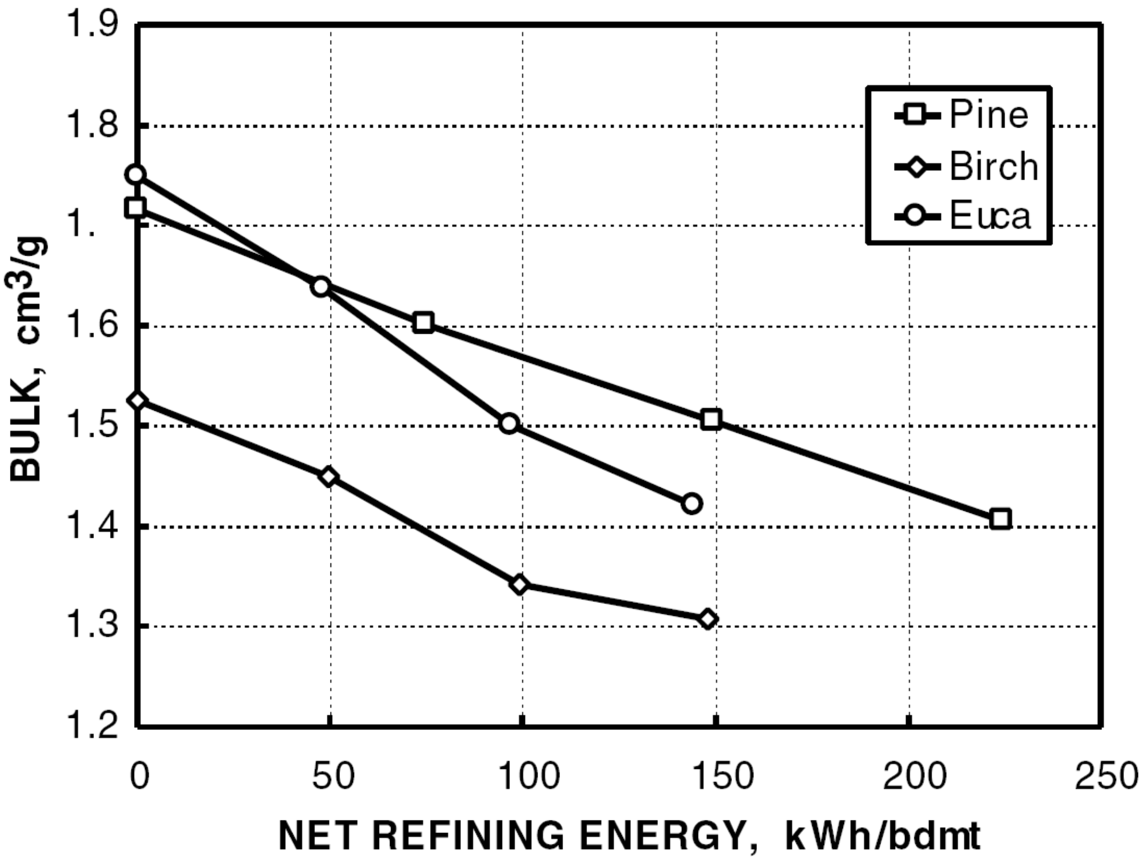


Figure 45. Bulk vs. net energy.

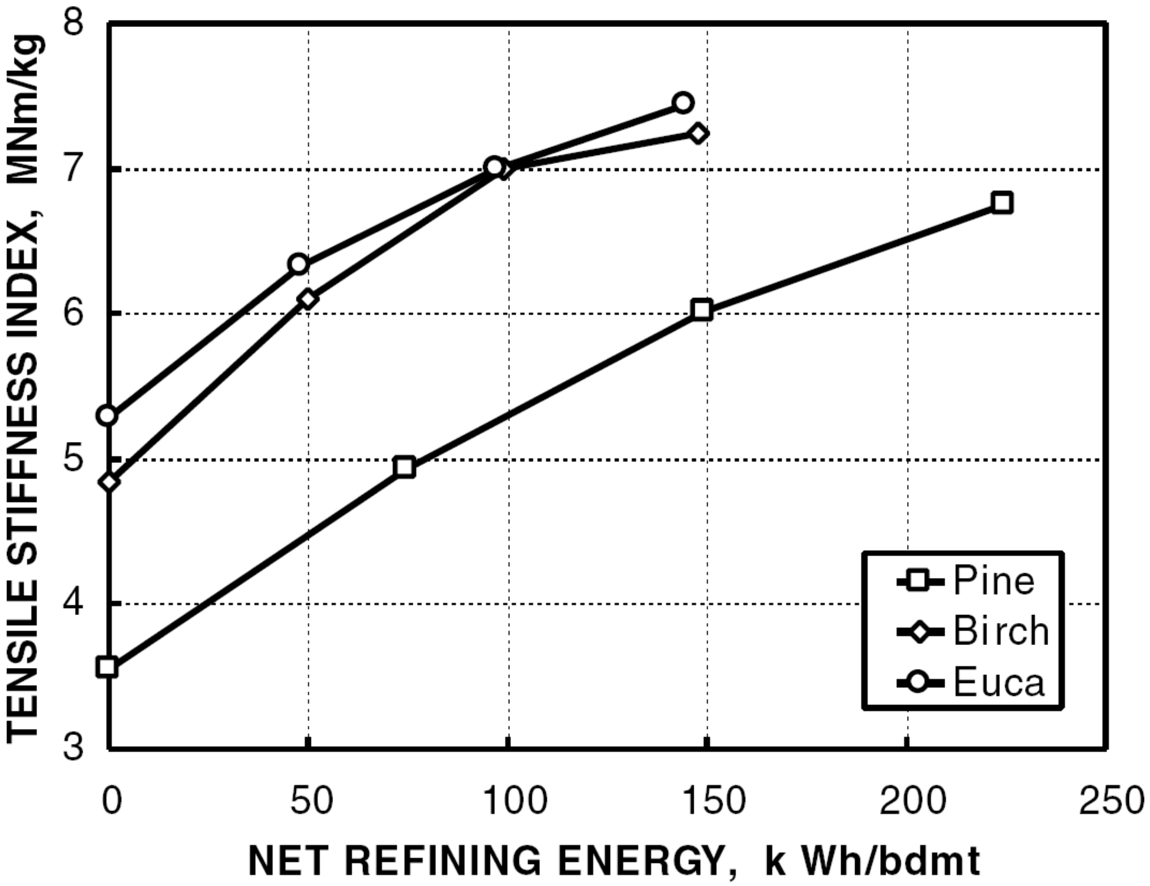


Figure 46. Tensile stiffness vs. net energy.

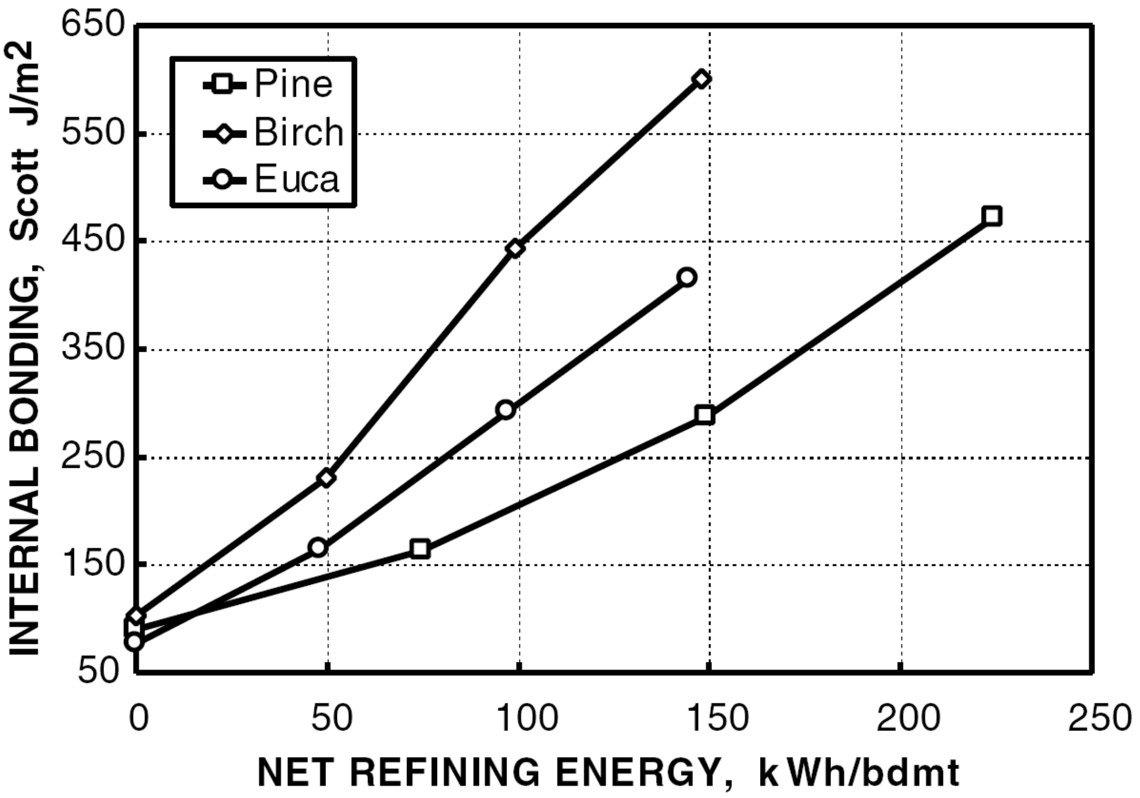


Figure 47. Internal bonding vs. net energy.

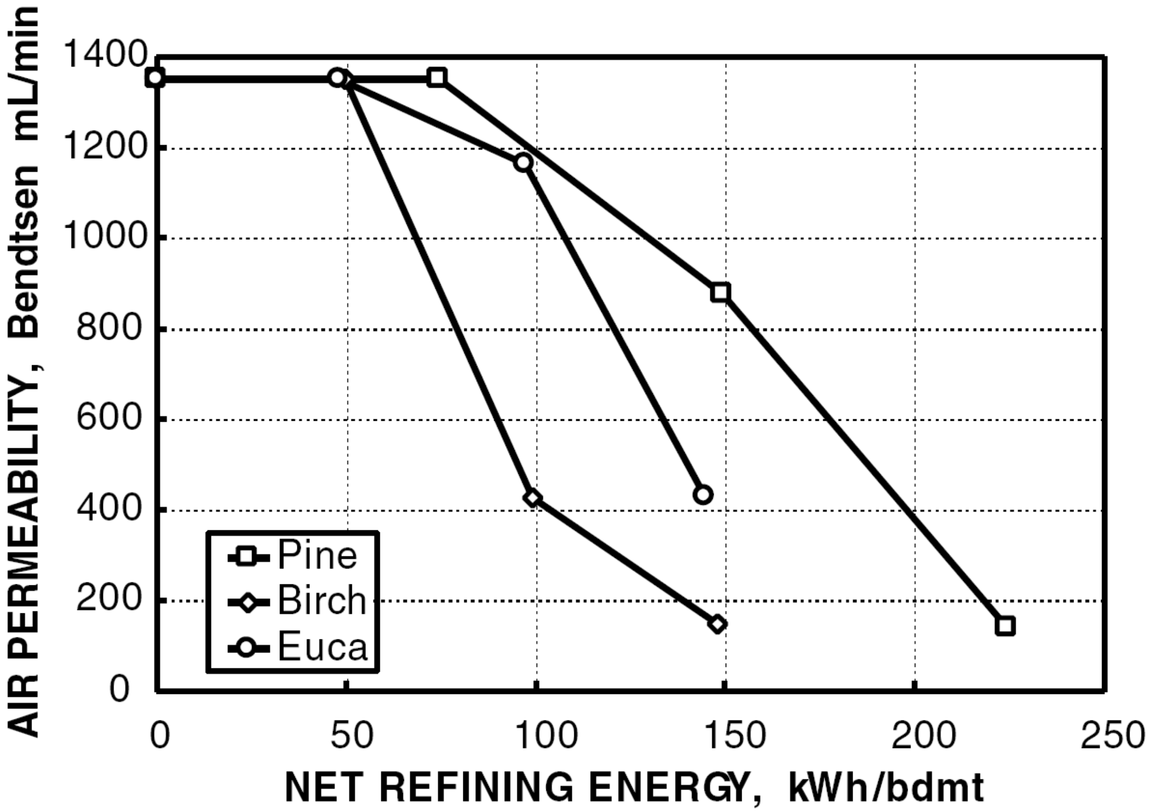


Figure 48. Air permeability vs. net energy.

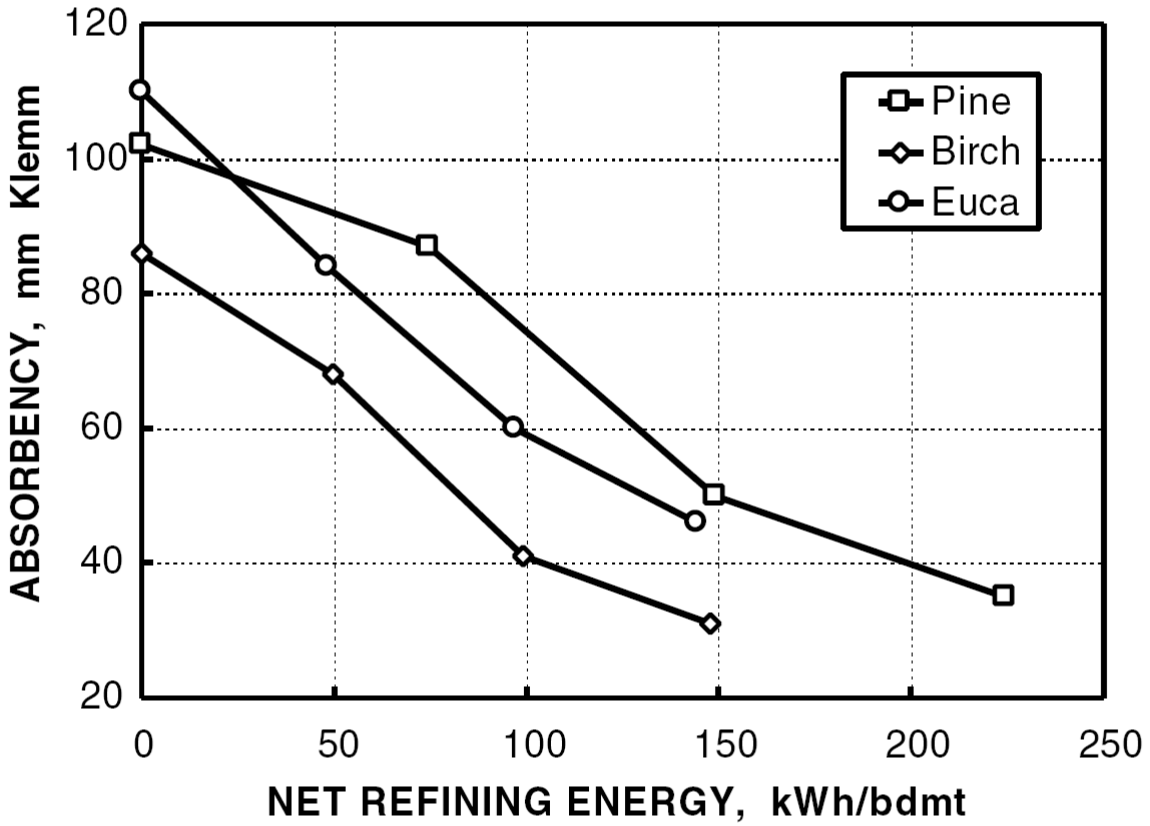


Figure 49. Absorbency vs. net energy.

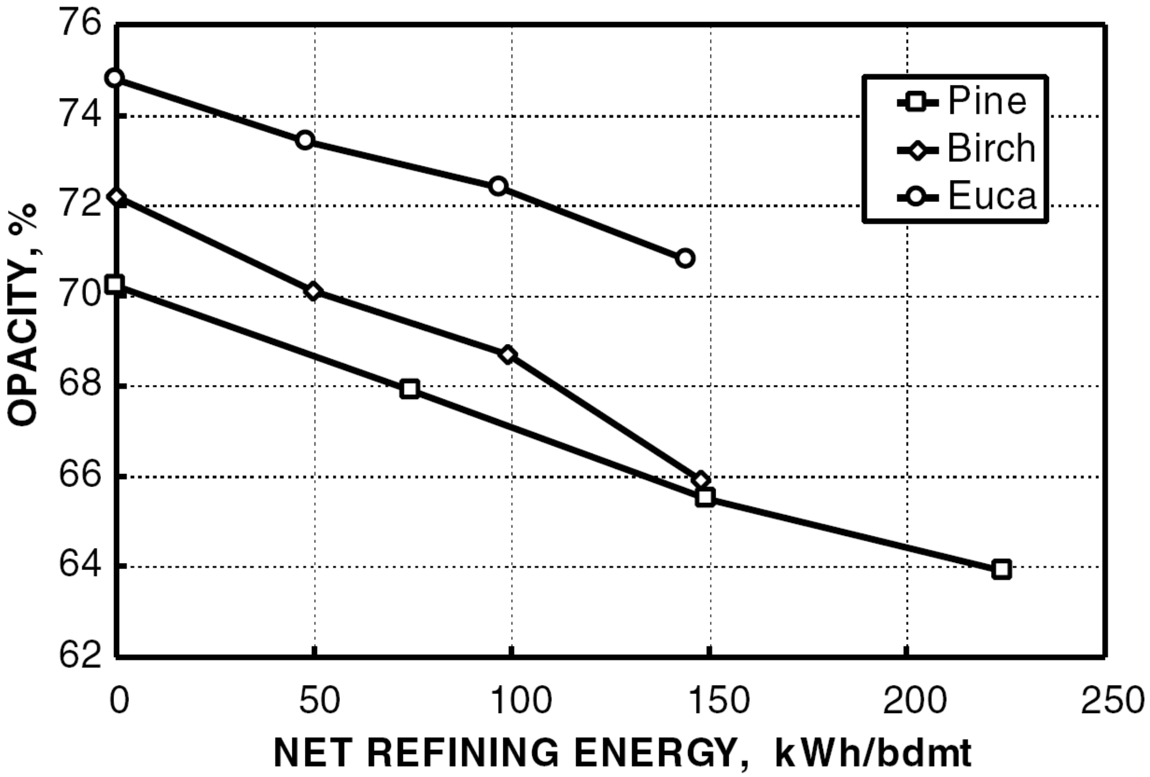


Figure 50. Opacity vs. net energy.

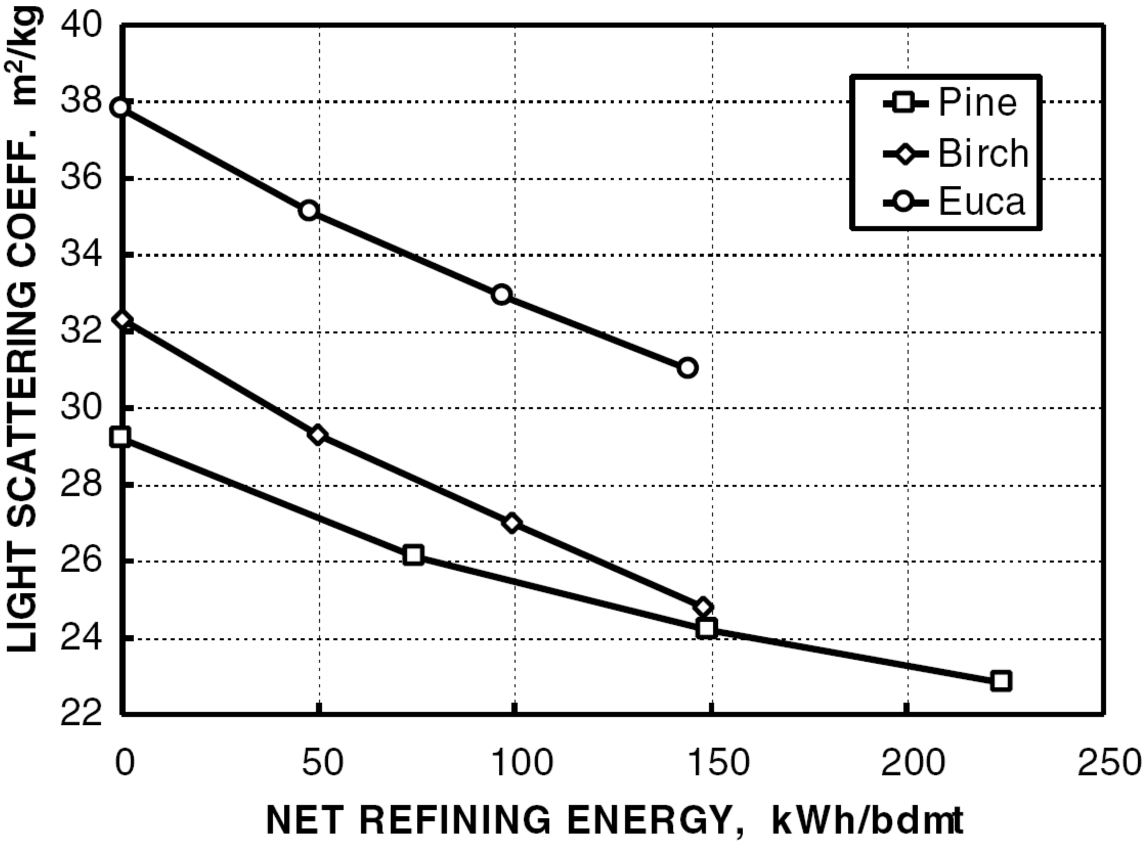


Figure 51. Light scattering vs. net energy.

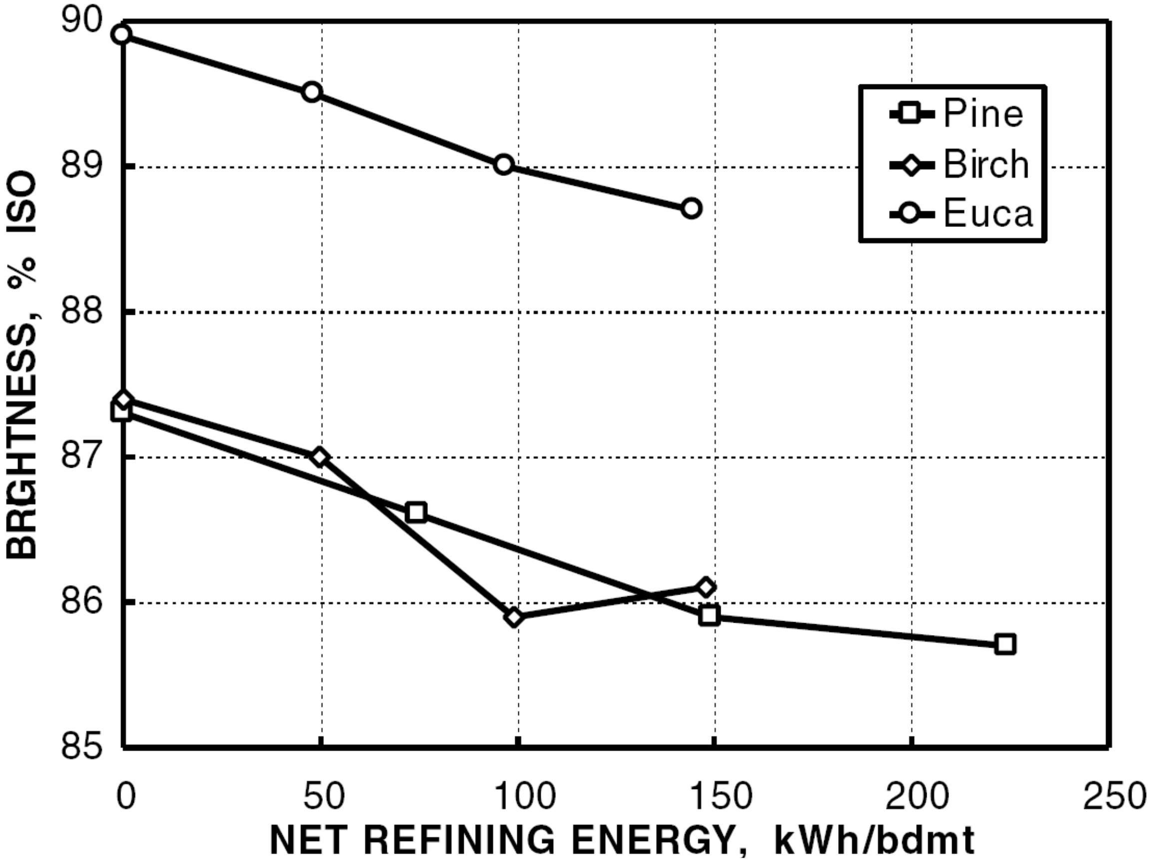


Figure 52. Brightness vs. net energy.

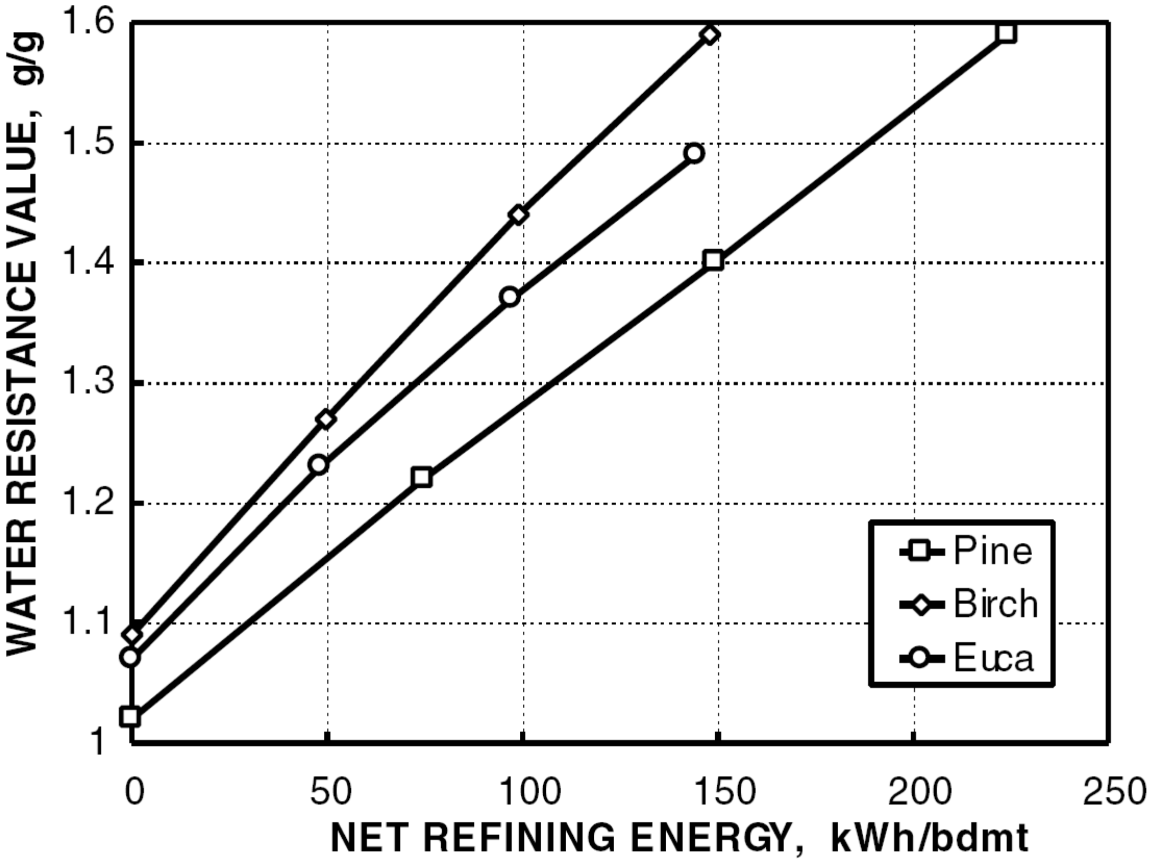


Figure 53. WRV vs. net energy.

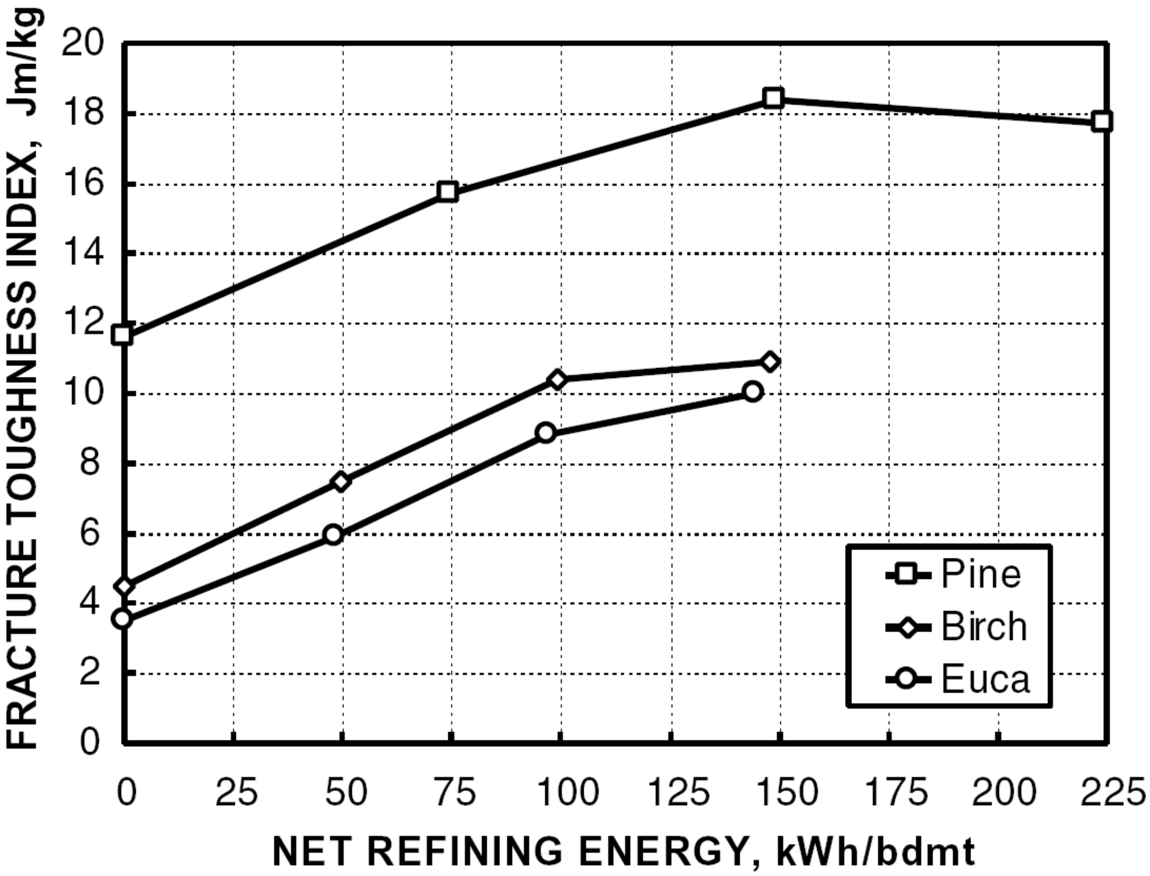


Figure 54. Fracture toughness vs. net energy.