Why is press drying/impulse drying delayed?

A critical review

Ernst L. Back

For commercial press drying of paper in the most useful temperature range, machinery has to be developed with long enough nip retention times and low enough rates for pressure deloading.

The terms "press drying" and "press drying pulses" are used here for any hot pressing operation, regardless of nip dwell time or applied pressure, in which operation temperatures above 100°C are created within the wet web, usually by applying one very hot surface against the wet paper web backed by a wire or a felt. The term "impulse drying" has been used for short nip dwell times without defining this period. Besides, the term "press drying" has been in use for several decades for a number of commercial processes.

Research on press drying was first concentrated on densifying the paper web and achieving high strength even with low-strength pulps (*1-3*). Later, potential opportunities came into focus for saving energy and gaining drying efficiency using lower ingoing solids contents. These potential advantages have diminished with the commercial progress of double-felted and steam-heated shoe presses. Besides, the extended nips currently available are not long enough to make the best use of press drying without risking delamination of the wet web.

Here, the dewatering and densification by press drying pulses is explained as being due to a combination of a superhot wet pressing with some simultaneous drying.

Brief history

Single-nip press drying of wet lignocellulose webs to almost complete dryness in a discontinuous operation was invented by William Mason in 1925, using a coarse thermomechanical pulp to produce hardboard. This commercial process today uses temperatures around 220°C and pressures of about 5 MPa. Twenty-five years later, Hans Tschudi introduced a similar process for single-nip press drying of unbleached kraft pulp to transformer board, using lower temperatures to secure electrical properties (*1-3*).

In 1973, independently, we at STFI (*4*) and V. Setterholm at the Forest Products Laboratory in Madison (*5*) started experiments on single-nip press drying of paper to utilize its great potential for densifying paper and increasing its strength. In both cases, the approach was applied to linerboard—in our case, to permit higher-yield softwood kraft (*4*) or TMP (*6*) to be used and in Madison to permit the use of Southern hardwoods. Our work continued with repeated 100-ms press drying pulses applied to webs backed with fine wires, using temperatures up to 450°C on the hot side. The results were first published in 1977 (*7*). We used the words "multinip" and "multistage press drying" in that work. This early work also underscored the large dewatering effect achievable by a series of such nips repeated until the web was dry (**Fig. 1**). The repeated nips were found necessary to overcome the tendency to partial delamination in the first nips (*7*). Setterholm was concentrating on pressure or *z*-direction restraints at lower temperatures, while our work was directed to higher temperatures.

Later, D. Wahren with a patent application in 1978 at KMW (*8*) and thereafter in work at IPC/IPST published in 1983 with Arenander (*9*) concentrated the approach toward energy saving and rapid dewatering. His co-workers at IPC (F. Ahrens, C. Sprague, and J. Lindsay, as well as others) have continued this effort (*10-12*). When further developing the idea of hot press pulses, Wahren renamed it "impulse drying," considering the short retention time in the hot press nip. Research work at IPC and elsewhere has covered press drying pulses up to about 200 ms. Later phases of IPC research concentrated on backing the wet web with a felt instead of a fine wire on the nonheated side.

At International Paper, R. Svensson early built pilot equipment for press drying of liner (*3*), while J. Lehtinen at Tampella developed vacuum press drying, first around a large cylinder and more recently in a band press (*13-14*). Naturally, a number of research institutes and companies have since focused some of their development work on press drying (*15-19*).

It was early recognized that since press drying makes the web more dense, it has the potential to produce good

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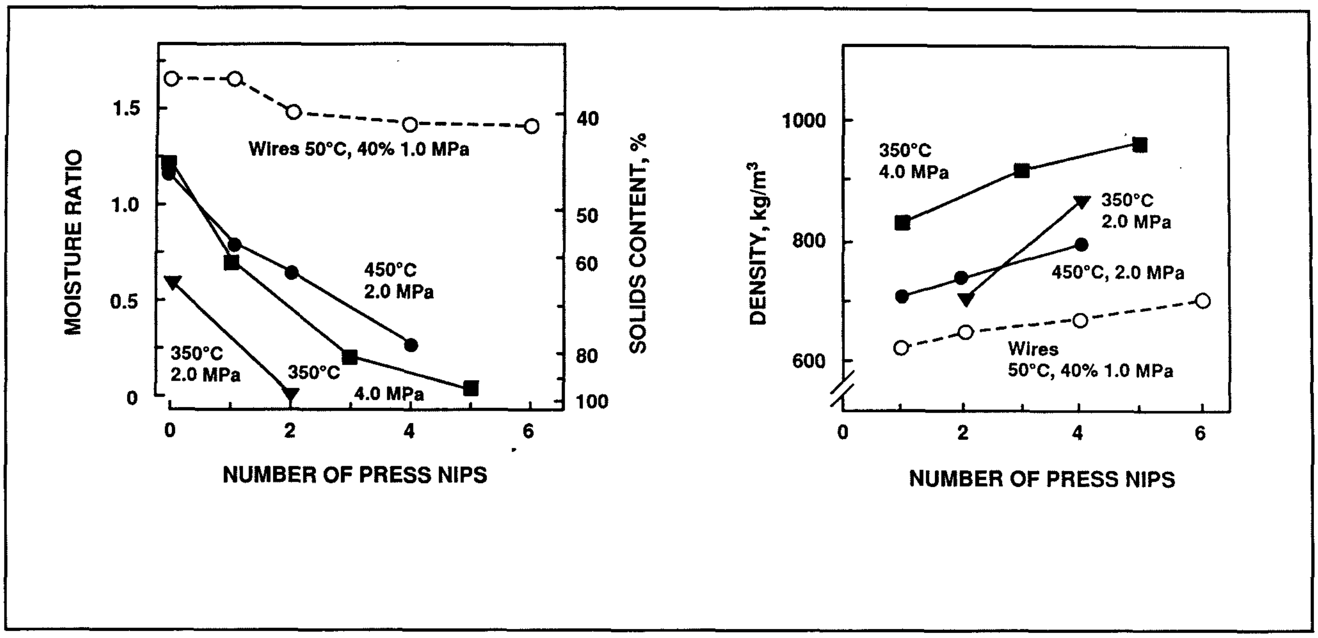
1. The number of nips vs. outgoing solids content (left) and paper density achieved (right). Ingoing condition indicated at nips = 0. Data at 450°C hot platen temperature and 2 MPa refer to one 320 mesh wire on each side of the sheet, those at 350°C and 4 MPa refer to backing with one such wire and a gloss platen on the other side, and those at 350°C and 2 MPa refer to gloss platens on both sides starting at 65% ingoing solids. Press pulses with sheets between wires at 50°C, followed by conventional drying for comparison. [For strength data and details, see Back and Andersson (7).]



paper bonding and strength even with pulps that normally give only low strength papers. This potential to overcome a low auto-contraction between fibers with a lignin-rich surface is also the background of the hardboard process. All recent pilot plant work has reconfirmed these press drying effects with various pulps when using high outgoing solids conditions. With the exception of a minor amount of auto-crosslinking—indicated by an improvement in wet strength—the increase in dry strength is due to an increase in interfiber bonding area.

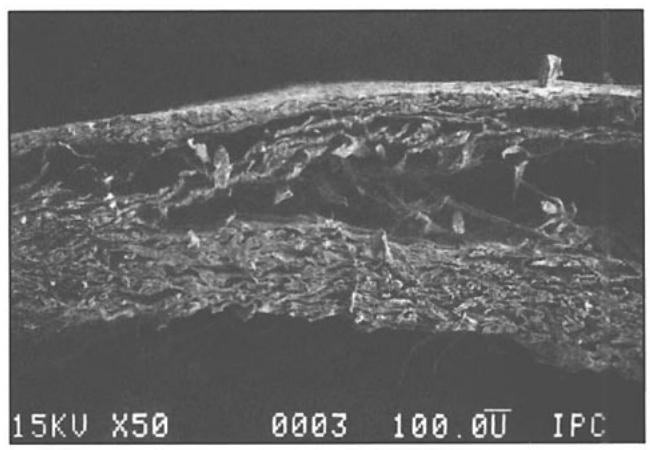
Nip dwell time and delamination

Limitations

In currently developed shoe press nips of about 250 mm in length, the nip dwell time on modern machine speeds corresponds to about 12 ms for newsprint, about 20 ms for a 150-g/m² liner, and 40 ms for a 300-g/m² liner. This nip dwell time also limits the outgoing solids content attainable in such a press drying nip. Consequently, it limits the outgoing wet web strength, which determines the delamination risk. In only a few of the recent reports for press drying are the data within these limits of nip dwell time at corresponding basis weights. When the web passes through a press nip at low speeds, as in a pilot plant, the pressure is deloaded more slowly, which reduces the risk of delamination and apparently has been the reason that this risk has been overlooked.

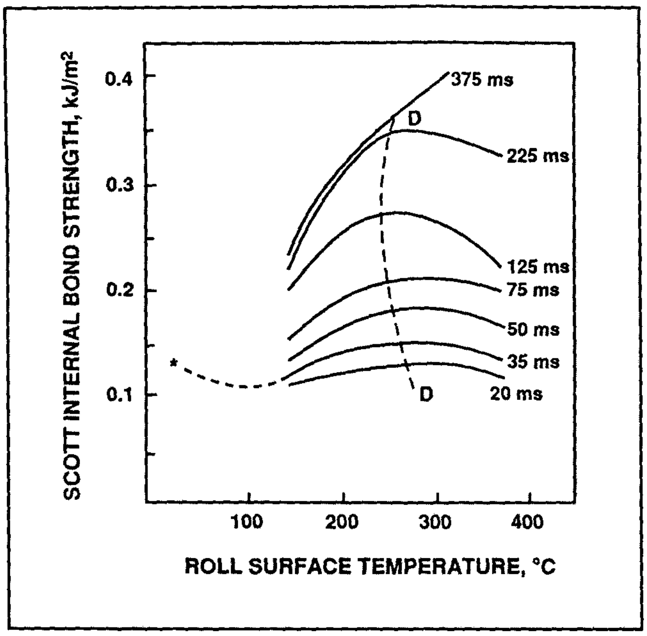
The fact that delamination reduces the strength achievable in single-nip press drying was evident in the mid-1970s with 100-ms press pulses (*7*). A meaningful gain in paper strength was possible at that time only by repeating these pulses to complete dryness—thus repairing some of the microcracking in the wet state. Delamination risks were occasionally pointed out in laboratory work at The Institute of Paper Chemistry (now the Institute of Paper Science and Technology) (*20*). Quite recently, the pilot plant work at Beloit has focused on this most important limitation (*21*). Several types of delamination problems have been observed, such as complete sheet delamination, delamination bubbles at the felt side, and a reduction in *z*-direction strength and compression strength. Examples are shown in **Figs. 2 and 3.** As determined by visual observation, a cold 200-g/m² liner web entering a 35-ms shoe nip of 7 MPa at 35% solids content visibly delaminated before the roll temperature reached 190°C. If steam were used to preheat the web, a hot roll temperature of only 150°C was permissable (*21*), as indicated in **Table I.**

2. Visually observable delamination in the sheet (*21*)

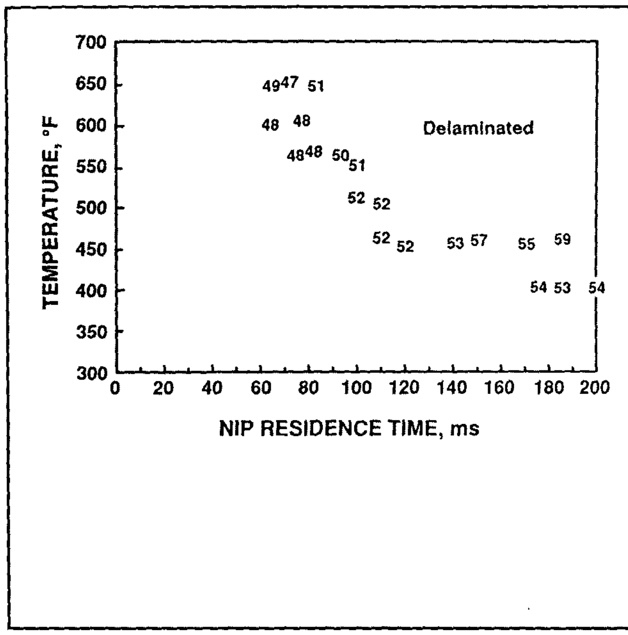


It appears from this difference in delamination temperature under given press nip conditions that the delamination occurs when pressure is deloading at the nip

3. The Scott internal bond strength of (dried) unbleached kraft samples vs. hot platen temperature in press drying nips over a range of nip dwell times [data from Crouse, Yung, Woo, and Sprague (*21*)]



4. The borderline for delamination in a hot plate temperature vs. nip dwell time, with the outgoing web solids printed as experimental dots. Data for laboratory press drying at 3.1 MPa using a hot aluminum plate according to Santkuyl (*22*) for 210-g/m² handsheets of 55%-yield unbleached Southern pine kraft of 620 mL CSF.



I. Delamination limits observed for linerboard (*21*)

Grammage, g/m²	*Nip dwell time, ms*	*Limiting temp., °C*
205	35	Steam = 150
		Cold = 190
340–440	50–70	Steam = 135

35% ingoing solids, 7 MPa.

exit, provided that a given superheated water or vapor temperature has been reached within the web. Therefore, there is a lower delamination limit as a function of nip dwell time and platen temperature, as shown in **Fig. 4.** Such delamination border lines have been determined by Santkuyl (*22*). The one in Fig. 4 also gives the outgoing solids content, which is somewhat higher near the delamination border when using longer nips and lower platen temperatures. Most probably, there is a similar upper border line at much longer nip dwell times. Above this line, at a given temperature in the most critical web layer, a sufficiently high solids content is achieved with high enough wet z-strength to prevent delamination.

Both increasing densification and increasing web solids content increase the z-direction strength and thus reduce the delamination risks. On the other hand, over a range of hot roll temperatures, the one of about 200°C in Fig. 3 gave maximum strength at each nip dwell time. Local delamination or cracking reduced the strength above this temperature. (Also pertinent is the experience from hardboard production mentioned below.)

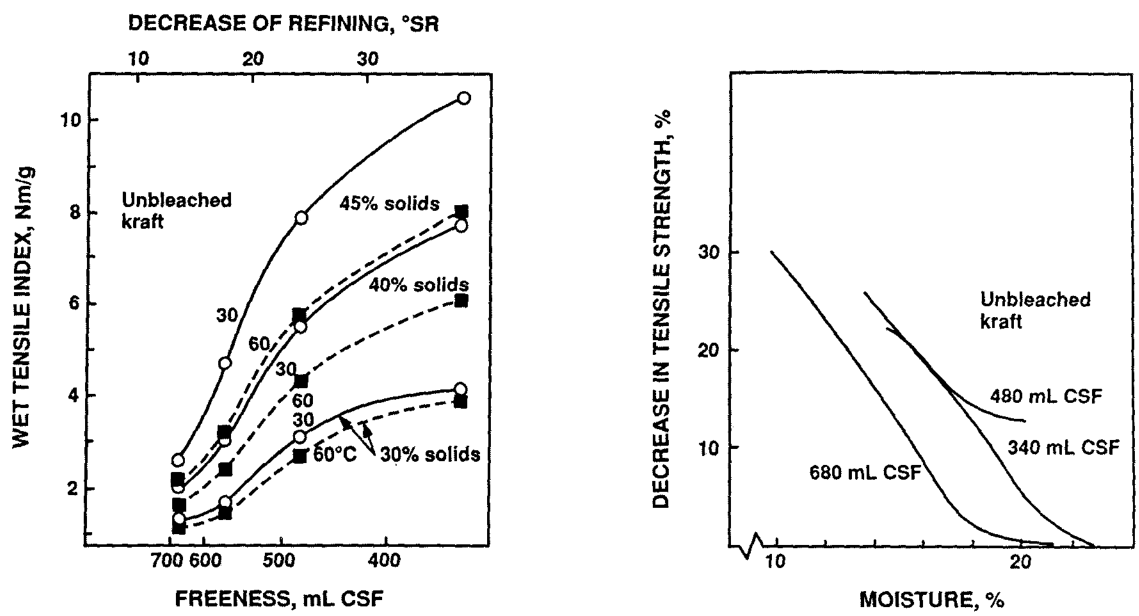
Additional refining increases the wet web strength but reduces dewatering. Thus, it can also reduce the permissible hot roll temperature for the 200-g/m² linerboard of Figs. 2 and 3 (*21*). This temperature was lowered from 177°C to 149°C from 720 mL to 640 mL CSF. With pulps of less strength, for which press drying is most promising for improving paper properties, the permissible hot roll temperatures will probably be still lower because of the lower wet web strength.

Conditions to prevent delamination

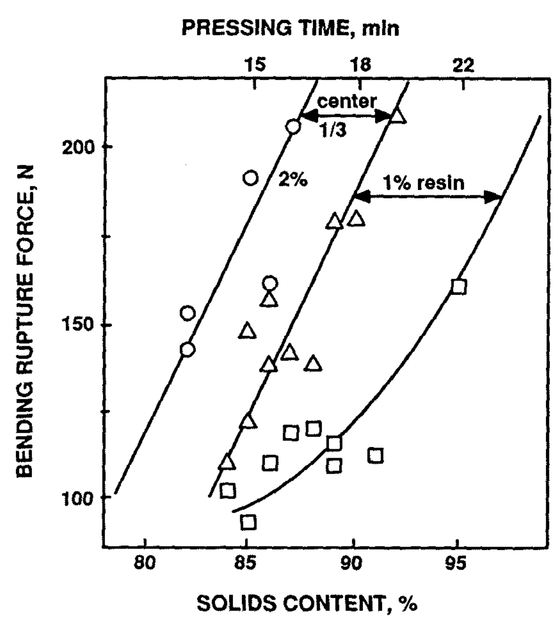
Accordingly, conditions to prevent delamination can be summarized. The bonding or the stiction between the fibers—in an arbitrary layer of the sheet and in any sheet direction at any moment within the press nip and especially at the nip exit—must exceed the drag forces of water, gases, or vapor moving in any direction within the web. This condition refers especially to the vaporization of superheated web water on deloading of the nip— that is, at the nip exit conditions. Such drag forces are proportional to the pressure of water vapor at the web temperature prevailing at the point from which vapor has to escape when the nip is deloaded. The drag forces decrease with increasing web porosity and with decreasing distance from the pressurized vapor layer to the web surfaces (that is, with decreased grammage, or basis weight). They also depend on the deloading rate. Similar requirements were also established for pulp suspension squeezing by Steenberg (*23*), simulating conditions of press nip closing.

The stiction or bond strength within the sheet here refers

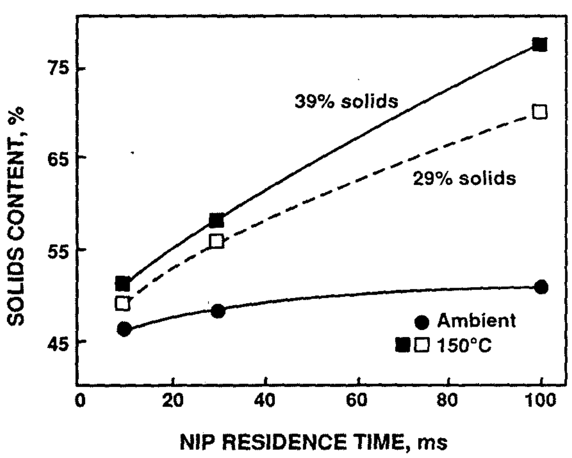
5. Left: the wet web tensile strength vs. the degree of refining for unbleached softwood kraft at 30°C and 60°C for three solids contents. Right: The relative decrease in wet web tensile strength between 30°C and 60°C as a function of solids content (*24*).



6. The bending rupture force for multi-layer formed 6-mm-thick medium-density board of 700 kg/m³ from a 785-ml-CSF, coarse TMP pulp, measured within a few seconds after nip exit, vs. the press opening solids content and the corresponding nip retention time in the 230°C hot laboratory press. Data at two levels of overall phenolic resin addition, either distributed throughout the mat thickness or concentrated to the middle layer, which constituted 1/3 of the web thickness (*25*).



7. Outgoing solids content vs. nip dwell time for a 45-g/m² newsprint at a hot roll temperature of 150°C at two ingoing solids contents, compared with pressing at ambient temperature. Data from the PAPRICAN pilot plant using a linear load of 106 kN/m and varying the machine speed. A nip dwell time of 12 ms represents the longest available extended press nip at newsprint machine speeds (*29*).



to hot, moist conditions, or to the initial wet web strength in the weakest direction, which is the z direction. This wet z-direction strength decreases with increasing temperature but increases with increasing solids content, with increasing refining, or with an increasing number of fibers oriented in the z-direction. There are no published data for this wet internal bond strength under press drying conditions. A few data on the initial wet tensile strength in the x,y plane as a function of refining at three solids contents and at both 30°C and 60°C are given in **Fig. 5** (*24*). In the range of 40-50% solids content, this initial wet web tensile strength decreases by about 1% per C° in the range of 30-60°C. At the much higher web exit temperatures involved in press drying, the wet z-direction strength thus is expected to be quite low, probably only 10-20% of that at room temperature. Naturally, pulp type has a large effect on wet web strength, the unbleached kraft for linerboard being quite a strong pulp.

What can be learned from building board

With these limitations, there is now a greater interest in press drying low-grammage papers such as newsprint. Delamination is a common productivity restriction in the production of wet-process, medium-density, fiber building boards. A single-nip press drying operation with a coarse wire backing the fiber mat is used. One successful example of a means to increase production capacity, developed at STFI (*25*), may be of interest for the press drying of paper. It relates to medium-density boards of 700-750 kg/m^3 and 6-8 mm thickness, where the total press dwell time period to near dryness is about 30 min or more. A large part of this period is required for the final drying operation by evaporation, while a solids content of 60-65% is reached within a few minutes by pressing.

A certain bending rupture strength is required for the handling of the board, after it leaves the press. Usually, it is achievable at 95% outgoing solids content. To reach this outgoing solids content in a 6-mm-thick board of 700 kg/m^3 density with 1.0% phenolic resin on a dry basis added all over the pulp, a press time of about 28 min was necessary. When all this resin was added to the middle layer of this three-layer web, the pressing time could be reduced by 15-20% to achieve the same strength. When 2% of phenolic resin on total pulp was added to this middle layer instead of 1%, the press time could be reduced by another 20%. The outgoing solids content was naturally lower, but the moist bending rupture force was the same, as shown in **Fig. 6**.

Phenolic resin reacts at this press platen temperature of 230°C in the press drying operation even before the web is dry. Thus, it gives considerable moist web strength especially in the z-direction. This web strength has to be developed in the most moist region, the middle layer of the board, where delamination risk is greatest when the press is opened. Other wet strength resins might react in a similar way. The process described has now been in commercial use for 13 years, and STFI holds a patent (*26*).

The so-called "dry" processes for fiber building board use a press platen temperature of 190°C usually and ingoing solids contents of about 85%. There is no means for moisture to escape— except at the outermost edges of the mat. Delamination in the middle of the several-meter-wide presses and in the thickness center of the mat occasionally takes place with a big bang on press opening. This can happen if the press deloading rate is too high, if the nip retention time is too short for the binder to fully react, or if the binder or hardener addition is too low to produce enough moist z-strength, etc. (*27*).

Possible equipment

From these considerations, a few requirements can be set up for press drying equipment to be most suitable:

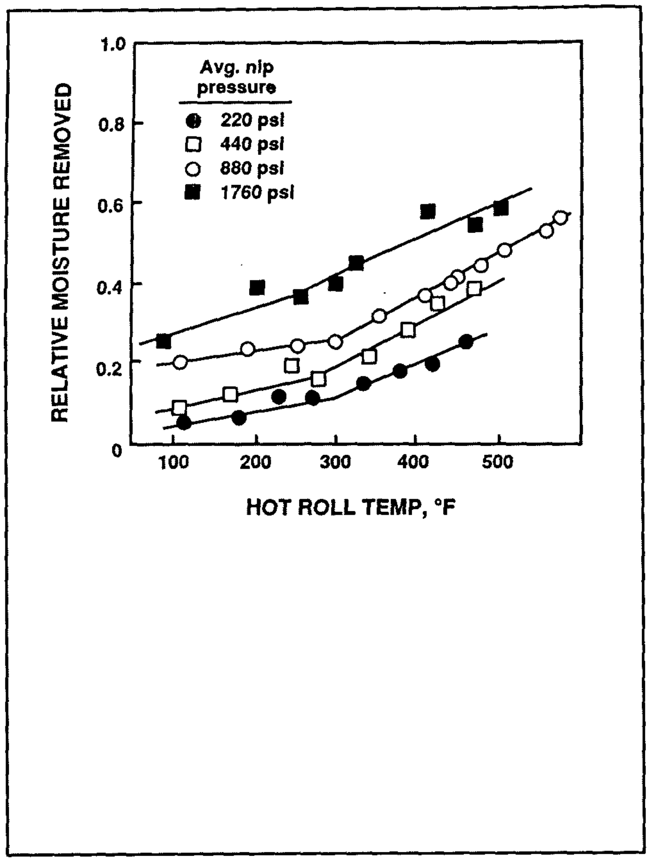
1. The longest possible dwell time in a single-felted nip to achieve by maximum outgoing solids a maximum z-direction wet strength
2. A low-pressure deloading rate to reduce drag forces causing delamination—possibly by modifying the shoe of the shoe presses
3. A low outgoing maximum temperature in the wet web, especially where the web is most moist. This could mean monitoring a temperature gradient in the hot press roll mantle, so that the ingoing surface temperature is high but the outgoing surface temperature is low after heat has been transferred.

In modern practice, various extended shoe press nips with a loading zone of about 0.25 m produce the longest possible retention time. They do so at pressures of several megapascals. Paper machine builders have naturally considered suitable modifications of these for press drying. Such extended nips have to be single-felted and with sufficient heat provided or monitored to the hot roll under controlled conditions from inside and/or outside (*28*). Extended press nips three times this nip length or more would certainly be most useful indeed, especially when modified to a low deloading rate. Band presses of about 1 m would be most useful.

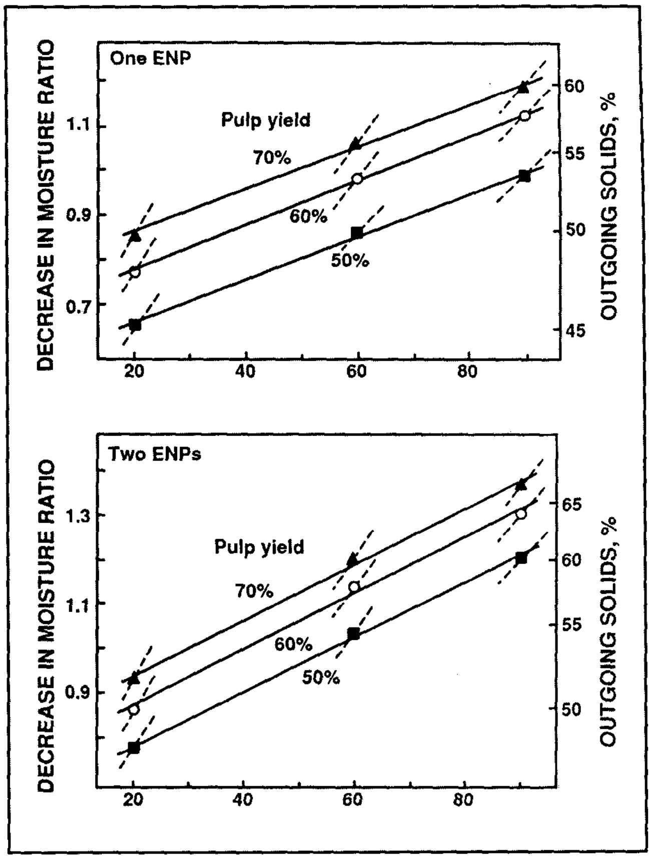
J. Lehtinen and Tampella have been building a pilot-scale dynamic band press of the so-called "Condebelt" type (*14*). The approach has the principal advantage of permitting an elongated nip dwell zone—although maximum pressures will probably have to be somewhat lower than for shoe presses. Band presses with various design features and band temperatures up to 200°C are in commercial use for paper lamination and for continuous particleboard or fiber building board production after mat formation at 85% solids. Their present design permits variable temperatures and pressures along the band, but speeds are below 100-150 m/min. The engineering effort necessary to bring them up to paper machine speeds is extensive.

Accordingly, development effort is required for machinery with long enough nip retention times and low enough pressure deloading rates for commercial press drying of paper in the most useful temperature range. At higher ingoing solids contents, press drying can be used only for web densification and paper strength development. More data are required to evaluate both potentials— the most suitable ingoing solids and temperatures and the delamination risks. Overall results have to be compared with those obtained with one or several extended press nips with steam-shower-heated webs.

8. Water removal expressed as moisture ratio vs. hot roll temperature for a 100-g/m^2 paper in a 40-ms nip at an ingoing solids content of 41% at various pressures up to 12 MPa. This is nearly twice a realistic nip dwell time in an extended nip for this basis weight at modern machine speeds (31).



9. Water removal expressed as moisture ratio and as outgoing solids for 205-g/m^2 unbleached softwood kraft sheets of three pulp yields all at 685 mL CFS in a 50-ms single-felted 1050 kN/m linear load ENP run at 300 m/min as a function of the web temperature, achieved by preheating. Press roll at ambient temperature (32). The nip dwell time is twice the realistic one, but the relative effect is about the same, since preheating takes place outside the nip.



Results within current restrictions

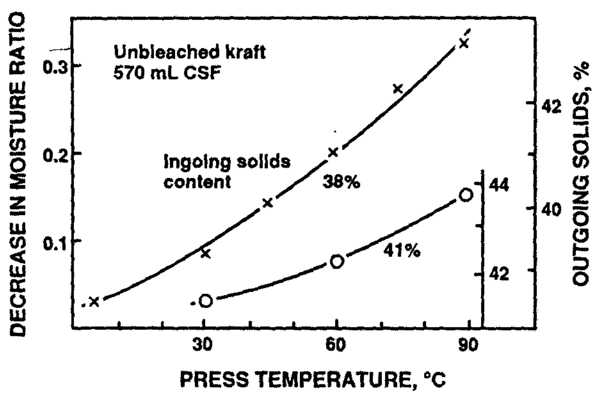
PAPRICAN has reported results from its pilot plant work with newsprint and standard press nips achieved by externally heating one press roll. A Beloit ENP (extended nip press) will be installed there later. A considerable increase in outgoing solids content occurs at a sufficiently low machine speed, as **Fig.** 7 shows (*29*). At a roll temperature of 150°C, no delamination was observed in this low-grammage material. With the retention time of 10–12 ms, corresponding to a standard extended nip in a modern newsprint machine, the outgoing solids content was increased from 46% at room temperature to 51% when the ingoing solids content was 39%. On the other hand, such an increase in outgoing solids content would also be expected in one or two extended shoe press nips after preheating the web by steam boxes to, say, 85°C. This would be especially true if the first of these nips were double felted. This type of experimental comparison is desirable because it is commercially relevant.

After a 10-ms nip at 200°C, there was a 1.5% loss in brightness and 2% loss in scattering coefficient measured on the hot roll side. In an economic comparison, such a loss of brightness has to be taken into consideration. For printing papers, a deterioration in optical properties can impose quite a limitation in regard to useful temperatures for press drying. Such a loss in brightness occurs even within a few milliseconds at that temperature in the hot calendering of papers containing mechanical pulps (*30*), as a result of the well-known rapid discoloration of native lignin at elevated temperatures. The loss in scattering coefficient is due to increased bonding area in the web. Its negative effect on opacity was partly compensated for by the increase in absorption coefficient associated with the loss in brightness.

An example from the IPC work is shown in **Fig. 8** (*31*). It uses a 40-ms nip of up to 12 MPa for a 100-g/m^2 sheet, which is twice the common dwell time in modern extended nips for this grammage. The ingoing solids content was about 41%. With a hot roll temperature of 200°C, which might be possible without delamination, water removal was doubled compared with that at 20°C at 12 MPa.

With the current state of the art, merely double felting the nips in these two examples would have at least doubled the water removal. A steam box heating of the web from 20°C to 90°C alone would also have increased water removal by about 50%, as shown in **Fig. 9** (*32*). Such a steam box preheating of the web can be combined with double felting. The data in Fig. 9 refer to a 50-ms, single-felted ENP nip with the webs preheated before entering the nip. Thus, the gain can be about proportional at other nip dwell times. Using present techniques, the water

10. Water removal in a single-felted, 3-ms nip as a function of web temperature at two ingoing solids contents for an unbleached kraft paper of 120 g/m² (*34*).



removal to the left in Fig. 9 might therefore refer to two consecutive 25-ms, single-felted or one 20-ms, double-felted, extended-nip-press shoe nip—dwell times that are quite relevant for this 200-g/m² paper. As shown in the lower part of Fig. 9, two such consecutive 50-ms extended nips at 90°C brought the solids contents of these three pulp webs up to 60%, 63%, and 67%, respectively (*32*). This constitutes currently available techniques.

A relevant comparison should include densification with subsequent strength development. The strength does not necessarily correlate with the outgoing solids content, as is often said to be the case (*33*). One advantage of press drying is the additional single-sided smoothness achievable.

The "relative" dewatering effect achievable by hot web pressing from 30°C to 90°C, for example, generally increases with higher ingoing solids. In **Fig. 10**, a 3-ms nip with a maximum pressure of 8 MPa (*34*), at an ingoing solids content of 38% for a 120-g/m² sack paper, tripled the water removed within this temperature range. At an ingoing solids content of 41%, it increased the amount of water removed by five times.

In both press drying and in web heating with steam boxes, heat consumption goes mainly into heating the wet web, at least at solids contents below 70%. The auto-efficiency for heating the web with current steam boxes usually decreases above 70°C (*32*). A measurement of this auto-efficiency in press drying would be useful.

Theory

Thermal softening of wet webs

Wahren and other IPC researchers propose that vapor (or air pressure, if applied) forces or blows water from the capillary fiber network into the felt. This mechanism is proposed as an explanation of the high solids content achievable in press drying in the 35-45% solids range. Researchers at IPC have measured and analyzed the temperature gradient as a function of time in an extended press drying nip. They have also shown a surprisingly high heat flux maximum occurring within 5-12 ms after applying the hot nip (*11-12*). A model has recently been presented to simulate this temperature gradient with a maximum heat transfer occurring just when loading the press. Also mentioned in the description of this model is the development of vapor pressure (*12*). With this model, as well as an earlier one (*35*), it is assumed for simplicity that the paper web is rigid, or incompressible, at the solids contents in question (that is, above 45%). I fear that this is an unrealistic simplification. Naturally, water vapor is formed on deloading the hot nip. At a high solids content, it can also form near the hot surface in the press nip.

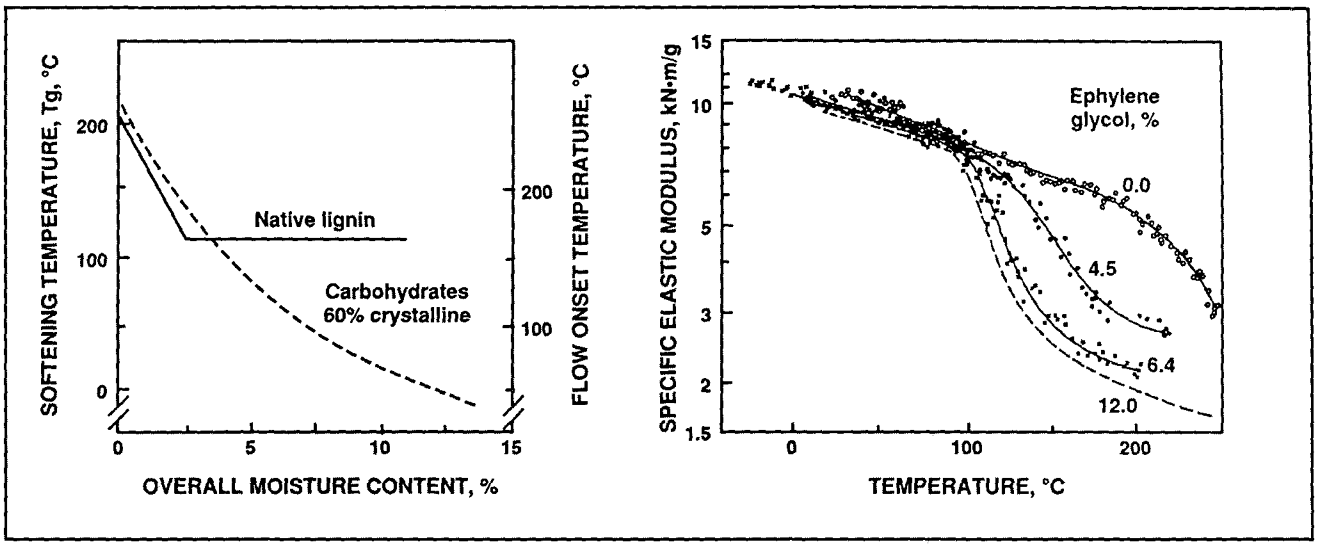
Moist and even dry paper webs are quite compressible. This compressibility increases considerably with temperature but especially around the glass transition temperature of the wood polymers. This glass transition is at about 170°C for hemicelluloses, about 200°C for native lignin, and 220°C for amorphous cellulose when dry. It is much lower when the material is moist (*36, 37*). Within the moisture and temperature ranges of press drying, the thermal softening and flow of lignin is most dominant, with the other amorphous wood polymers always being above their glass transition temperatures, as indicated in **Fig. 11**.

Additional hydrodynamic pressure

With this softening, the remaining pores become very small, so that even at high solids content and with a minor flow of water, the hydrodynamic water pressure can be quite large. The mean effective pore radius in the z-direction varies around 10% of that in the x,y direction but falls off about one decade for a given pulp from a paper density of 400 kg/m³ to a density of 800 kg/m³ (*38, 39*). This is also the background of a significant web densification at the hot roll surface. It also answers questions raised when proposing the necessity of a vapor phase (*40*). According to my understanding, this increase in compressibility with increasing web temperature is the very basis of press drying. In only one modeling approach has the attempt been made to consider these aspects (*41*).

Figure 12 shows the outgoing solids after a dynamic wet pressing with a 3-ms nip and after a "static" 3 min of pressing as a function of applied pressure (on a logarithmic scale) over a range up to 90°C (*42*). For dynamic wet pressing, the fact that the superheated water viscosity decreases a further 35% from 100°C to 150°C is important. On the other hand, the results of 3-min (i.e., static) wet pressing are mainly independent of any effect of water viscosity. They show the pure effect of temper-

11. Left: the glass transition temperature of native lignin and of amorphous cellulose as a function of overall moisture content. The one for hemicelluloses is around 30-40°C lower and about parallel to that given for cellulose (*36*). Right: corresponding experimental background. The modulus of elasticity measured in tensile and given in logarithmic scale for an NSSC paper vs. temperature at various ethylene glycol contents (*37*).



ature on the wet fiber network compressibility. It has to be realized that both these effects, that of water viscosity and that of wet network compressibility, with their separate temperature dependences, play an active role in the wet pressing or press drying operations. The dotted lines for the 3-min static pressure indicate that with this pulp at a "static" pressure of 5 MPa and 30°C, dewatering has almost ceased at 53% solids content. Thereafter, when the temperature is raised to 90°C, a hydrodynamic pressure is again created within the web until a new equilibrium solids content of 66% occurs, and so forth. In other words, this fiber network at 70% solids can sustain a pressure of 20 MPa when at 30°C, whereas at 90°C it can only sustain 11 MPa without further dewatering. This is an approximation, indeed, with respect to the slow plastic flow which continues with time. The actual data from a prolonged, 100-ms nip are therefore slightly different. Data for various pulps are given elsewhere (*42*). As expected, refining appears to have little or no effect on this static dewatering limit. For a coarse TMP, approximate data up to 150°C and 5 MPa are also available (*1*).

Figure 13 shows experimental data from measurements by Carlsson of the total applied pressure and the hydrodynamic pressure on the roll side (*43*), which here are replotted without a time scale. An equilibrium line for the network pressure then is introduced, and the excess hydrodynamic pressure is indicated separately. Whenever, in an extended nip or at high solids content, the total pressure exceeds the pressure supportable by the moist network (because of heating this network, for example), additional water or superheated water is forced by hydrodynamic pressure into the direction of the felt. Thus, while a temperature gradient is built up in the web by press drying, an additional hydrodynamic pressure occurs, and dewatering continues. This process is indicated in **Fig. 14**. Water vapor can be formed at the hot roll side only at a temperature in equilibrium with the hydrodynamic pressure prevalent there or in the nearby layer. Before this occurs, the water is superheated and pressurized. Some or most of the drag forces at the nip exit of press drying are due to this rapid evaporation of superheated water.

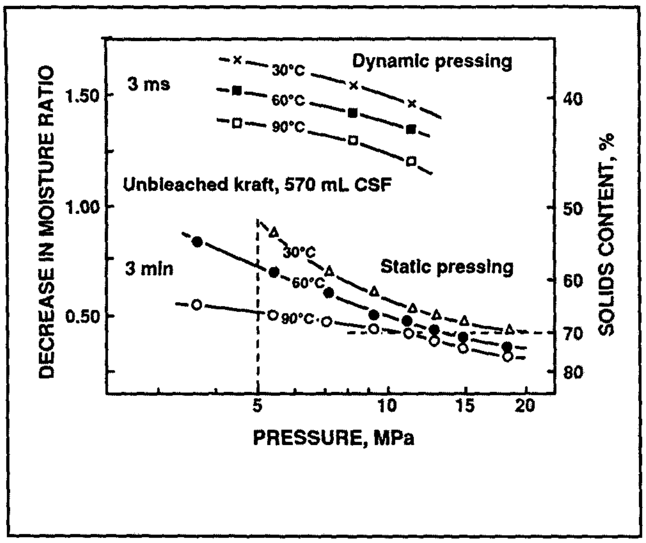
Can vapor blow water from the web to the felt?

There is little support for the hypothesis that the vapor phase with its corresponding pressure formed produces a dewatering action on water in the pores. On the contrary, the data of Macklem and Pulkowski (*44*) show that the dewatering is mainly independent of grammage (basis weight) at an ingoing solids content of 35%. The 50% increase in dewatering achievable in their 70-ms press drying nip at 250°C with the corresponding temperature gradient produced as compared to room temperature is about that expected in merely hot or super-hot wet pressing.

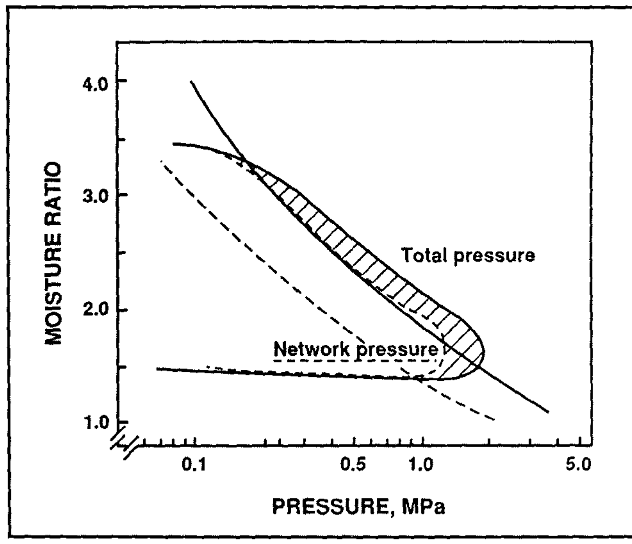
The considerable effect of external pressure on outgoing solids content achieved at up to 316°C hot roll temperature shown in Fig. 8 and separately plotted for 100-ms press drying pulses on hardwood kraft by Sprague (*11*) also contradicts any significant effect of vapor pressure.

Naturally, at solids content above, say, from 70% to about 75% or 80% (depending on temperature, on pulp compressibility, and on energy transfer rate), a vapor phase can be formed at the hot surface. There, it "replaces" water within the network. Its vapor pressure together with the network pressure at the border line to the water phase has to be in equilibrium with the sum there prevailing of (wet) network pressure and hydrodynamic pressure. These sums are both equal to the applied mechanical

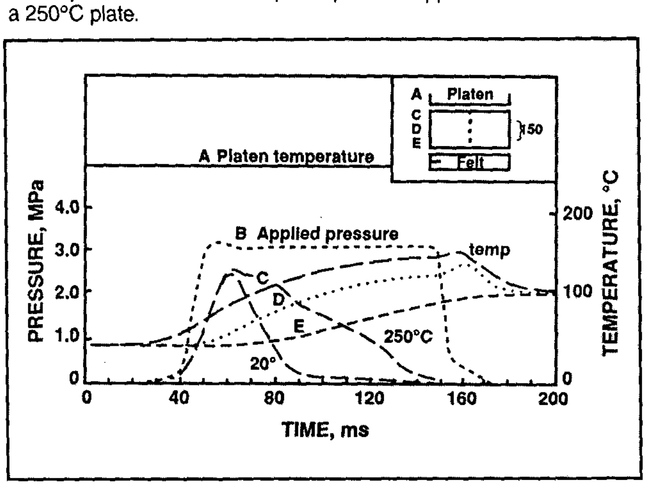
12. The effect of temperature on solids content achieved, above in a single-felted 3-ms nip at various dynamic maximum pressures, below at various static pressures maintained for 3 min between blotters. All data for an unbleached softwood kraft sheet with an ingoing solids content of 38%. The lower part shows with dotted lines how the solids content at 5 MPa decreases, respectively how the network pressure sustainable at 70% solids falls off, when the web temperature increases with time as it does in press drying (*43*).



13. Data from press simulator work of Carlsson (*43*) with a 15-25 ms nip and 150-g/m² bleached kraft and 1.35 ingoing moisture ratio replotted according to Fig. 12 (*32*). Both the total pressure and the hydrodynamic pressure on the nonfelted side are given. A solid border line for the network pressure sustainable at this ambient temperature nip is introduced. An additional dashed border line for a higher temperature is also given, indicating how the hydrodynamic pressure increases, when the network "softens"—i.e., when it can sustain a lower pressure nip.



14. The measured temperature distribution in three intermediate layers (C, D, E) of a 150-g/m² sheet and applied pressure (B) vs. nip dwell time with 250°C upper platen temperature and felt on the back side (*11*). Shown by a broken line is a tentative hydrodynamic pressure at the platen side when the press pulse is applied with a 20°C and a 250°C plate.



pressure. In each layer of the compressible web thickness, this externally applied mechanical pressure has to be countered by a sum of network pressure and either hydrodynamic or vapor pressure, as indicated in **Fig. 15**.

Most probably, the vapor pressure of the vapor phase does not exceed the hydrodynamic pressure at its boundaries, against the liquid phase in the pores. On the other hand, even if it does, for a grammage above some 50 g/m², it cannot act separately on the water in its pores within a compressible network. On the other hand, the boundary of a vapor phase can move over to the felt side during continued press drying. It finally reaches the felt at perhaps 70-80% web solids, depending on pulp type.

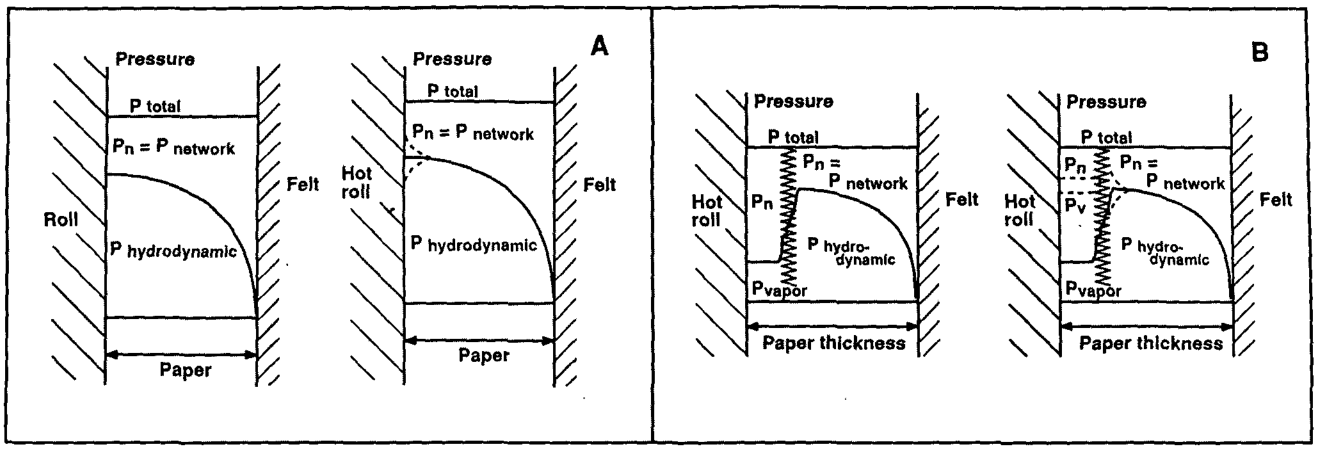
The vapor pressure in any zone or layer of the hydrodynamic (hydraulic) pressure in any nearby layer cannot exceed the externally applied pressure. This is a boundary requirement to be introduced in various extrapolations of press drying data used over a larger temperature range. For example, with a roll temperature of 250°C, producing a vapor phase of maximum 4 MPa at this surface, the applied mechanical pressure has to be somewhat higher to prevent the steam from lifting the roll.

On the hot side, the network, although it is softened, takes up considerable pressure and produces a high web density in this layer—in press drying—usually higher than on the felt side. Network pressure is a complicated parameter related to moist fiber stiffness, to the restriction of water flow from fiber lumens and fiber walls out into the interfiber area, to fiber anatomy (such as fines fractions), and to the speed of press loading and load dwell time (*45, 46*). For a given pulp, it is mainly a function of temperature and solids content, as is apparent in the lower part of Fig. 10.

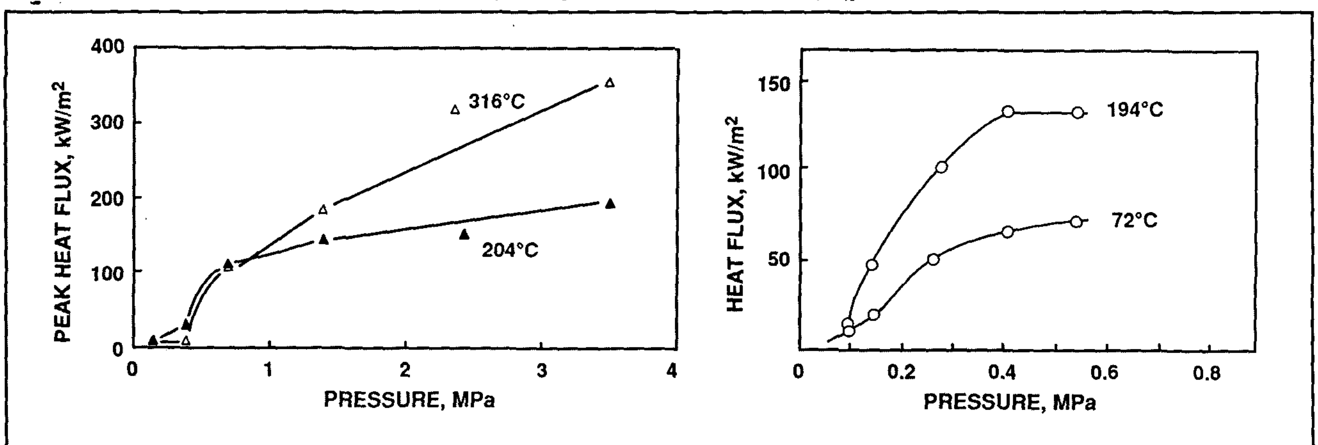
The heat flux

The large heat flux values of about 0.5-1.0 MW/m² or higher, occurring at roll temperatures above 300°C, can be explained by the greatly increased temperature difference in the transfer layer. These high heat flux values may be compared with heat transfer coefficients in drying of a few kW/(m²°C) at temperature differences of, say, 30°C. For example, mean heat flux values in the range of 0.1-0.15 kW/m² occur in a gas-fired impingement hood on a Yankee cylinder (*47*) when large temperature differences between gas and web occur, as shown in **Fig. 16**. On the other hand, the heat transfer coefficient metal to paper web naturally increases with increasing mechan-

15. A tentative distribution of the pressure over the paper thickness. A: in standard cold wet pressing (left) or in single-sided hot wet pressing (right) such as there is in the initial part of press drying. The pressure distribution is about the same, but the network density at the roll side is much higher when hot than when cold. B: in a later part of press drying, above 70% solids in the hot web layer drying nip. If the vapor phase is formed and that layer is dried out, the compressed network can withstand a higher pressure. Within each web layer, the sum of network pressure plus vapor pressure is always equal to applied mechanical pressure in the later part of press drying. The vapor pressure on the hot platen side probably does not exceed the hydrodynamic pressure in the nearby zone of superheated water. It cannot exceed the applied mechanical pressure.



16. Left: the maximum heat flux according to Sprague (*11*, corrected scale) indicating its proportionality to the temperature difference between platen and wet web. Right: the heat flux on a pilot plant Yankee dryer with a high-speed air hood using two forced air temperatures (72° and 194°C) plus the 3.5-bar steam pressure Yankee cylinder [data from Pinter and Stark (*47*)]



ical pressure, since thereby the atomic distance contact area has been increased. Also, increased web densification has some effect. The problems involved in the rapid measurement of such a heat flux in the press nip are indicated by two facts. The IPC so-called "MIPPS" calculations (*12*)—as expected—show the maximum heat flux occurring just in nip closing with a measured heat flux of 0.8 kW/m² after 0.05 s at 240°C platen temperature. For a hardboard press of 20 openings with a press closing time of several seconds, the maximum heat flux over the single nip press drying is only 0.08 MW/m². This is evaluated "directly" from the flow and the temperature of the ingoing (240°C) and outgoing superheated pressurized water used for heating the press (*48*), as indicated in **Fig. 17.**

Summary of theory

In press drying experiments, the reduced spring-back of wet mats with increasing temperature can have an additional water removing effect (*49*), although rewetting at rapid felt-paper separation is usually not very pronounced (*45*).

Accordingly, press drying in the 10–15-ms range can be considered a hybrid of hot or superhot wet-pressing combined with a minor amount of evaporation, which takes place partly on pressure deloading on the heated side at the nip exit or possibly within the nip when solids contents above about 70–80% are reached there. For example, in the commercial single-nip press drying of hardboard using a hot press platen at 200–220°C, a solids content of 60–68% is achieved before the rest of the water is evaporated after partly deloading the press from, say, 5 MPa to a pressure of 1 MPa. This has been shown by both simple LiCl tracer and other techniques (*48, 50*). The LiCl tracer technique also indicated that 50% more water was evaporated within the uppermost 20% layer against the hot platen of a 3.2-mm hardboard of density 1000 kg/m^3 than within the rest of the board. This indicates a vapor phase with a heat pipe effect taking place in the later part of this single-nip press drying at reduced press load (*48*).

In this commercial, single-nip, press drying operation, the pressure of about 5 MPa, first applied for a minute to transfer heat and to press out water, has to be released to about 1 MPa about a minute later. This is quite necessary to prevent microcracking of the network when the dewatering ceases and the web mid-thickness temperature reaches about 150°C. It is part of the original Masonite patents. The understanding of this effect is relevant for delamination. On deloading, evaporation starts within the wet web. The temperature falls off to about 100-115°C, while the web springs back from the initially reached dry weight density of about 1000 kg/m^3 in the nip. Apparently, vapor formation at higher web temperature than this 110-115°C causes microcracking in the web, occasionally with a big bang. (Compare the strength maximum at 200°C hot platen temperature shown in Fig. 3.)

The final drying process

As indicated elsewhere (*49*), the spring-back on pressure deloading is reduced by elevated web temperatures. Its rate and effect on web microcracks has been insufficiently investigated. In the final drying operation, the web auto-contracts due to surface energy forces, so-called "Campbell forces."

Single nip (also called "static") press drying to near dryness, without completely deloading the nip pressure, is the commercial process for hardboard and transformer board. Optimum strength properties over the range of density are thus obtained, rather than with various pressing combinations including complete deloading before drying. On the other hand, for this strength optimum, the pressure required in the later drying operation is lower than in the earlier wetter part. Even after deloading a wet press nip of paper, a continuous low pressure of 35-40 kPa held during drying results in better strength than does common drying at a very few kPa (*51*). Today, there is no such commercial drying process available.

The future of press drying

This analysis of press drying illustrates some of the limitations of press drying pulses (also named "impulse" drying) by comparing the results with those of the best available hot wet pressing techniques. It improves the understanding through due consideration of the thermal softening of the moist fiber network—i.e., its reduced capability to sustain applied pressure at elevated temperatures. Current press drying pulses are limited by:

1. Nip dwell times available for the basis weight in question in present equipment for modern machine speeds. These speeds also limit the hot roll temperatures at the wet web *z*-strength of the outgoing web. The development of presses for a narrow band of paper machine speeds would be a useful approach.
2. A large risk of delamination for hot roll temperatures above 200°C—or for a steam preheated web even above 150°C. These limits are valid for a 200-g/m^2 linerboard at useful nip dwell times and outgoing solids or web *z*-strength at the current pressure deloading rates. Press shoes with slower deloading rates and more knowledge about wet *z*-strength would be useful.
3. The loss in brightness, especially above 200°C for mechanical pulp components (for newsprint, for example) and the loss in opacity for other printing grades. More knowledge of the effects of prebleaching the furnish should clarify these limitations.
4. The limited dewatering effect compared with the best available technique of 90°C hot wet pressing, especially if double felted. Press drying results must be compared with this current state of the art.

Considering these limitations, only a cumbersome and slow evolution can be expected for press drying pulses: pulses that are probably best combined with steam preheating of the web. More optimistic expectations of rapid development have recently been published by others (*52-53*).

This analysis also indicates that extended nip press drying pulses within the current limits of nip dwell time is just one technique for achieving hot or superhot wet pressing without involving any new mechanism. Displacement drying with steam or gas is not understandable for a moist compressible paper network, only for low-grammage, porous sheets such as tissue.

Research on wet web *z*-direction strength over a range of temperatures and other conditions might be useful to achieve a larger range of press drying temperatures without delamination. Machinery for longer nip dwell times and slow pressure deloading would also increase the economic potentials.

Nips at high ingoing solids content (such as 70% solids), merely to achieve sheet densification, have an economic potential, for which delamination risks and other restrictions should be analyzed in detail. This opportunity is of special interest for high-yield pulps, some hardwood kraft pulps, and wastepaper furnishes.

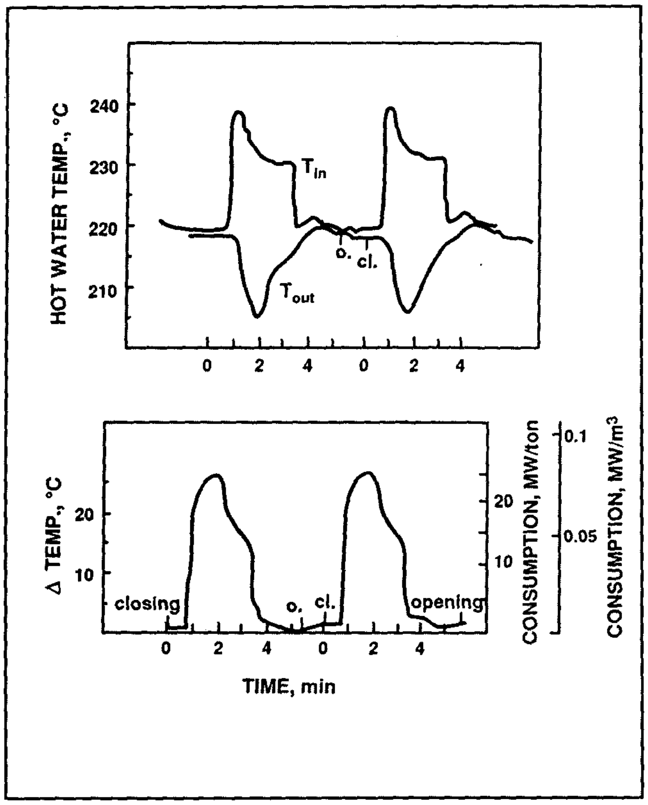
A hot extended nip as gas phase reactor

The fact that vapor formed on the hot side of the web cannot leave the nip and should condense before deloading makes it possible to use hot extended nips as self-sealing reaction vessels for gas phase modifications of paper webs. These possibilities are illustrated by gas phase redistribution of an ASA (alkenyl succinic anhydride) sprayed onto one side of the web before the nip in **Fig. 18**.

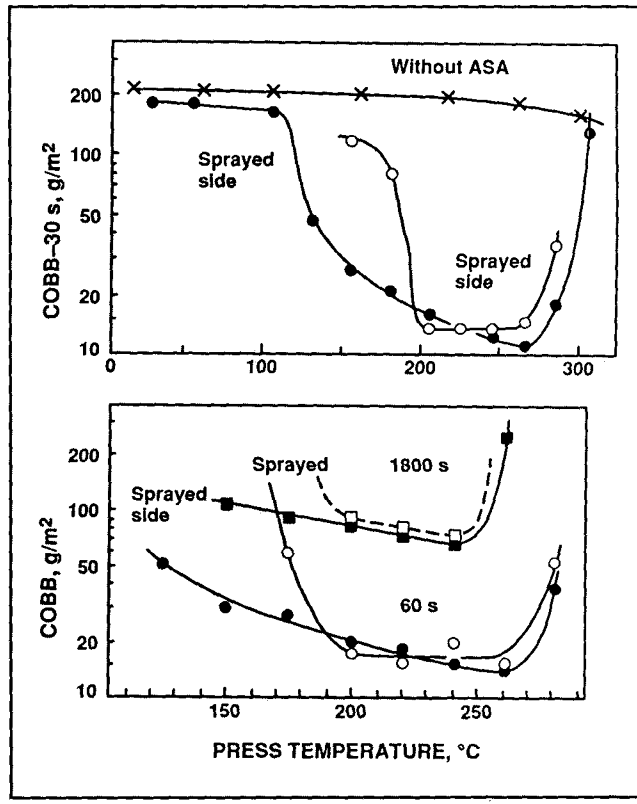
For a web of 94% solids, a nip of 100 ms and 0.4 MPa produced an excellent two-sided hydrophobation—Cobb values below 15 g/m^2 with 0.06% AKD (alkyl ketene dimer) sprayed onto one side when both sides of the hot nip were at 240-260°C. With a nip of 200 ms and 5 kPa, such hydrophobation required a temperature on both sides of 350°C. With the AKD used and a single-sided hot nip of 100 ms and 0.5 MPa, a temperature of about 350°C produced good hydrophobation (*54*).

Figure 19 illustrates the auto-crosslinking reaction within a two-side hot 100-ms nip of 0.4 MPa leading to wet strength. It also again illustrates the sizeable heat transfer in such a nip. This reaction also takes place at

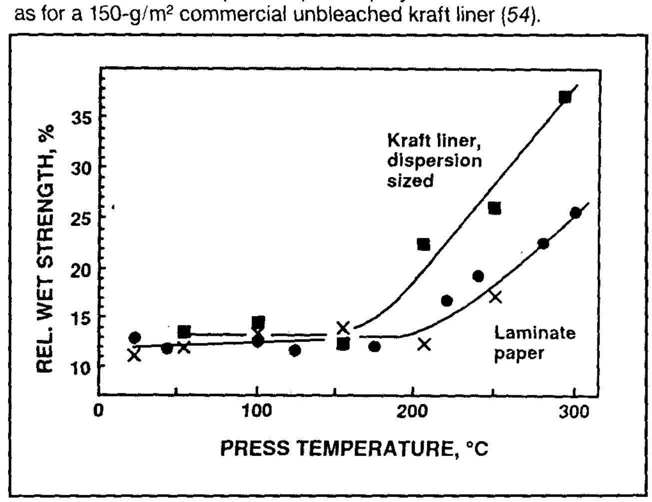
17. Example of energy consumption and heat flux in pressing of 3.2-mm hardboard in a superheated, water-heated, 20-opening press with nonsimultaneous closing. Consumed energy is evaluated from the ingoing and outgoing temperature of the superheated water during the press cycle (*48*).



18. The effect of 0.1-s, 0.4-MPa, two-sided, hot extended nips on the water repellency of an unsized unbleached kraft laminate paper of 162-g/m² sprayed on one side with 0.06% ASA diluted with 20% acetone. Data for sprayed side (filled dots) and unsprayed back side (open dots) (*54*).



19. The auto-crosslinking effect of a two-sided hot extended nip of 100 ms and 0.4 MPa on the relative wet strength (after 24 h immersion) vs. press platen temperature. Data for the laminate paper of Figs. 17 and 18, both unsized (crossed) and sprayed with 0.06 ASA as well as for a 150-g/m² commercial unbleached kraft liner (*54*).



higher moisture content, although probably at a lower rate, as has been indicated by others (*55*).□

Literature cited

1. Back, E. L., OFE Tech. Meeting (Berlin), OFE, Amsterdam, 1984; STFI medd. D: 224(1984).
2. Back, E. L., The Role of Fundamental Research in Paper Making, Mech. Eng. Publ. Ltd, London, 1983, p. 344.
3. Swenson, R., The Role of Fundamental Research in Paper Making, Mech. Eng. Publ. Ltd., London, 1983, p. 365.
4. Andersson, R. G. and Back, E. L., Pulp Paper Mag. Can. 77: T260(1976).
5. Setterholm, V. and Auchter, R. J., Forest Products Laboratory, USDA Forest Service, Research Paper FPL256, 1975.
6. Andersson, R. G., Back, E. L., Salmen, L., and Wahlstrom, C., STFI medd. B: 463(1977).
7. Back, E. L. and Andersson, R. G., Svensk Papperstid. 82(1): 35(1979).
8. Wahren, D., U.S. pat. 4,324,613(April 13, 1982).
9. Arenander, S. and Wahren, D., Tappi J. 66(9): 124(1983).
10. Burton, S. W., Sprague, C. H., and Ahrens, F., Drying '86, Vol. I, (A. S. Mujumdar, Ed.), Hemisphere Publishing, New York, 1986, p. 364.
11. Sprague, C. H., Fundamentals of Paper Making II, Mech. Eng. Publ. Ltd., London, 1989, p. 637.
12. Lindsay, J. D. and Sprague, C. H., J. Pulp Paper Sci. 15(4): J135(1989); Fundamentals of Paper Making II, Mech. Eng. Publ. Ltd., London, 1989, p. 679.
13. Lehtinen, J. A., Proc. 2nd Intl. Symp. on Drying, Vol. II, (A. S. Mujumdar, Ed.), Hemisphere Publishing, New York, 1980, p. 347.
14. Lehtinen, J. A., Papier (Darmstadt) 42(10A): V154(1988).
15. Hartwell, P. R., Press drying in tomorrow's paper machine, 23rd EuCePa Conf., (Harrogate, Pita, London), EuCePa, Helsinki, 1988. p. 435.
16. Ceragoli, G., Capretti, G., and Bianco, G., Ind. Carta 25 (2): 69(1987); in English as EEC (European Commonwealth) Research Report Contract BOS-0551.
17. Yang, C. F., Esufzai, A. R. K., Sanka, R., Mark, R. E., *et al.*, Svensk Papperstid. 81(13): 164(1978).
18. Michell, A. J., Seth, R. S., and Page, D. H., Paperi Puu 65(9): 536(1983).

19. Michell, A. J., Appita 37(4): 325(1984).
20. Burton, S. W., Thesis, Lawrence Univ., Appleton, Wis., 1986.
21. Crouse, J. W., Woo, Y. D., and Sprague, C. H., Tappi J. 72(10): 211(1989).
22. Santkuyl, R. J., M.Sc. thesis, Institute of Paper Chemistry, Appleton, Wis., 1989.
23. Steenberg, B. K., Paper Tech. & Ind. 20(10): 282(1979).
24. Andersson, L. I. and Back, E. L., STFI medd. B: 620(1983).
25. Nordin, S. B. and Sandstrom, E., internal report, STFI, Stockholm, April 1976.
26. Nyren, J. O., Nordin, S. B., and Flodman, L. A., U.S. pat. 4,113,555 (Dec. 19, 1978); Canadian pat. 1,122,045 (April 20, 1982).
27. Back, E. L., Hanetho, P., Holst, G., and Johansson, I., Particle boards from wood of freshly felled timber, Trateknikcentrum Stockholm, Report 8705035.
28. Busker, L. H., Lange, D. V., Macklem, E. A., and Pulkowski, J. H., U.S. pat. 4,738,752 (April 19, 1988).
29. Sparkes, D. G. and Poirier, D., paper presented at the Conf. Technologique Festivale, CPPA, Montreal, 1989.
30. Back, E. L. and Mataki, Y., Svensk Papperstid. 87(12): R83(1984).
31. Sprague, C. H., High-intensity drying processes, Report 1 for U.S. Dept. of Energy, DOE/CE/40738-T1, August 1985.
32. Back, E. L., Appita 41(3): 217(1988).
33. Back, E. L., Paper Tech. & Industry 28(3): 454(1987).
34. Andersson, L. I. and Back, E. L., Tappi J. 65(7): 75(1982).
35. Pounder, J. R., Tappi J. 70(2): 97(1987).
36. Back, E. L. and Salmen, L., Tappi J. 65(7): 107(1982).
37. Salmen, L., Back, E. L., and Alwarsdotter, Y., J. Wood Chem. Tech. 4(3): 347(1984).
38. Didriksson, E. J. E. and Back, E. L., Svensk Papperstid. 69: 769(1966).
39. Back, E. L., Svensk Papperstid. 69: 219(1966).
40. Zavaglia, J. C. and Lindsay, J. D., 1989 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, p. 357.
41. Pounder, J. R. and Ahrens, F. C., Drying '86, Vol. I, (A. S. Mujumdar, Ed.), Hemisphere Publishing, New York, 1986, p. 341.
42. Andersson, L. I. and Back, E. L., STFI Scan. Forsk. 452 (1985).
43. Carlsson, C., Some fundamental aspects of wet pressing of paper, Thesis, Royal Inst. of Technology, Stockholm, 1983.
44. Macklem, E. A. and Pulkowski, J. H., 1988 Engineering Conference Proceedings, TAPPI PRESS, Atlanta, p. 447.
45. McGregor, M. A., Fundamentals of Paper Making II, Mech. Eng. Publ. Ltd., 1989, p. 511.
46. Szikla, Z. and Paulapuro, H., Fundamentals of Paper Making II, Mech. Eng. Publ. Ltd., London, 1989, p. 587.
47. Pinter, R., Gab, H., and Stark, H., Wochbl. Papierfabr. 114(18): 765(1988).
48. Jensjo, H. and Back, E. L., STFI medd B 548 (1979).
49. Back, E. L. and Norberg, K. G., Effect of temperature on the compressibility of wet pulp pads, Consolidation of the Paper Web, Trans. Cambridge Symp., 1965, Tech. Sect. British Paper & Board Makers, p. 569.
50. Back, E. L., Bucko, J., and Bjorklund-Jansson, M., Svensk Papperstid. 81(5): 153(1978).
51. Gunderson, D., Hunt, J., and Setterholm, V., Tappi J. 69(4): 114(1986).
52. Stenstrom, S. and Wimmerstedt, R., Svensk Papperstid. 92(14): 44(1989).
53. Sprague, C. H. and Lavery, P., 1988 CPPA Annual Meeting Proceedings, CPPA, Montreal, p. 215.
54. Back, E. L. and Danielsson, S., Hot extended press nips as gas phase reactors, Tappi J., to be published.
55. Horn, R. A., Tappi J. 72(6): 85(1989).

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