Preferred citation: M.A. MacGregor. Wet pressing research in 1989 – an historical perspective, analysis and commentary. In **Fundamentals of Papermaking**, *Trans. of the IXth Fund. Res. Symp. Cambridge, 1989*, (C.F. Baker & V. Punton, eds), pp 511–586, FRC, Manchester, 2018. DOI: 10.15376/frc.1989.2.511.

WET PRESSING RESEARCH IN 1989
An Historical Perspective, Analysis, and Commentary

Michael A. MacGregor[1]
Voith, Inc., Appleton, WI, USA

ABSTRACT

There is a large body of literature on wet pressing; almost all of it deals with water removal and much of it is empirical in nature. Though we have been forced to infer what happens inside a roll press nip by making observations from the outside, our qualitative and quantitative knowledge of the water removal process has improved greatly over the years. There have been some *direct* experimental measurements of several important variables *inside* the nip (applied pressure, fluid pressure, and midnip roll separation), but only at the system boundaries (the roll surfaces). Direct data is still lacking on other important variables inside the nip such as localized pressure gradients, sheet thickness and sheet dryness, localized deformation, a good definition of the interfacial region, direct measurements of parameters in the thickness direction, and thermodynamic properties. So far, wet pressing models have had limited success in making *a priori* predictions of sheet water removal and have not begun to address paper properties, the next major thrust of wet pressing research. We have conjured up a mental picture of wet pressing which seems to fit well the observations made from the outside. It is quite possible that this picture is more inaccurate and incomplete than we imagine, but this state of affairs is actually exciting because it means much remains to be learned about the fundamental mechanisms of wet pressing. In this learning process, paper property development is expected to receive equal, if not greater, attention.

Outline

INTRODUCTION

Wet pressing is a popular and fascinating subject, with a large body of written and unwritten knowledge. Most of this deals with equipment, the process, and anecdotal experiences. Even the research portion of the literature is extensive. This research is comprised mainly of empirical studies relating to water removal while paper property development has usually been a secondary issue. Even though wet pressing is now considered a mature technology, a more fundamental approach based on first principles could still yield improvements in our understanding, if not our practice.

There have been a number of excellent reviews and discussions of wet pressing (1,2,3,4,5,7,8,43). These are valuable not only for their extensive bibliographies, but also for the insights offered. Therefore, the first part of this paper will not be a comprehensive nor necessarily an evenhanded review of all literature in wet pressing research, but instead will use some highlights of the past (Figure 1) as a framework for expounding upon lesser known aspects of certain work, interjecting viewpoints, and discussing current issues. No new research will be presented and no revelations will be made in the second part. Instead, several previously known but often overlooked areas will be discussed, some opinions and speculations given, several new questions raised, and suggestions for future research offered. If this stimulates thinking about wet pressing in a renewed light, then this review paper will have achieved its main purpose.

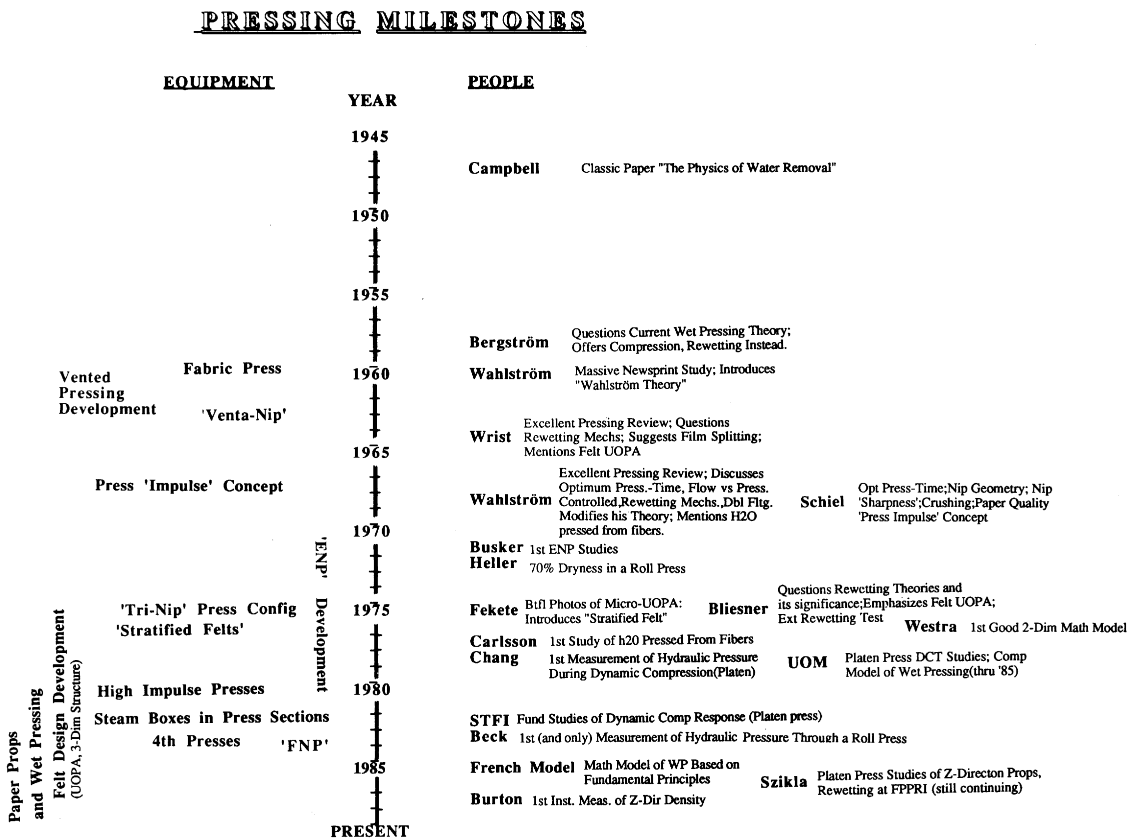


Figure 1. Milestones in Wet Pressing Research.

PART I -- HISTORICAL PERSPECTIVE

The Scientific Method requires us to search out, critically examine, and acknowledge the work of those who came before. In so doing, we are not only reminded how few truly original ideas there are, but we attain a better perspective of our own contributions.

Early Work

Campbell (9) introduced concepts from soil mechanics which form the basis for many later wet pressing studies. His much underquoted paper seems to be the first to discuss or imply the following fundamental concepts:

--the separation of the total applied press load into the mechanical and hydrodynamic[1] pressure components

--the variation of sheet density in the thickness direction

--the dependence of water removal on the product of applied pressure and pressing time (later given the name 'press impulse')

--machine-direction pressure gradients resulting from roll geometry, accompanied by an explanation of 'crushing'

--the concept of pressing 'achieving completion' (this author's words) for a given press load when the hydrodynamic pressure associated with water flow ceases

Several attempts were made after Campbell's work to develop a theory of wet pressing, but the first

---

[1]In the wet pressing literature, the term 'hydraulic' pressure has often been incorrectly used to denote *any* pressure associated with water. See Part II for more discussion on the topic of pressures in the press nip.

substantial advance[1] came from the work of Bergström (10). After performing a large number of wet pressing experiments with a platen press, he concluded that water must be removed on the compression side of the nip--something unquestioned today, but contrary to views of the time. He also added another new concept--that some water could perhaps *return* to the paper from the felt in the expanding nip. He envisioned this to occur as a combined result of surface tension and suction forces arising from both expanding structures. To support this 'rewetting' idea, Bergström offered data from pressing experiments using various felt/sheet/plastic/blotter combinations, as well as evidence from some of the first dye transfer experiments. Besides rewetting, Bergström discussed the variation in sheet density through its thickness as a result of the division between hydrodynamic and mechanical pressures, as predicted by Campbell. Lastly, he believed that a press felt should have high permeability to water, "even when subjected to a high pressure" and it should have a pore size "small enough for the water to remain in the pores when the sheet expands and tries to pull it back". Almost all these ideas remain valid today, but much of the research was considered proprietary at the time and, though discussed at several symposia (6,14), was never formally published.

About the same time period, Wahlström (11,12) was involved in an extensive water removal study of a newsprint machine in Canada. Now considered a classic study, his paper contained the first successful attempt at bringing together all the reasonable postulations then known into a comprehensive theory of wet pressing. The 'Wahlström Theory' was a distillation of scientific principles, logical reasoning, and experimental evidence from his newsprint study and the parallel research of several others. In the ensuing years, Wahlström modified his theory several times (1,2) but

---

[1]Sweet (24) later stated that they had been performing wet pressing studies concurrently. Undoubtedly, Bergström, Wahlström, Sweet, and others were aware of and discussed each other's work during this time period.

its essence has withstood the scrutiny of almost 30 years, making his papers required background reading for anyone involved in wet pressing.

Vertical Flow Pressing

Bergström and Wahlström had theorized and then demonstrated the benefits of minimizing the pressure drop along the flow path. To accomplish this it was necessary to avoid nip saturation[1] which was thought to create longitudinal flow in the felt and sheet. This was insured by providing a suitable temporary storage volume within and under the felt and was given the name 'vertical flow' pressing. There were several groups of people, each taking a somewhat different approach for achieving vertical flow pressing. Separate groups led by Wrist and Brauns concentrated on utilizing press fabrics and sleeves to provide the necessary venting--the 'fabric press' (13,22). Somewhat later, the Justus and Cronin (14) work resulted in the development of the very simple but effective grooved press roll cover.

1964 Water Removal Symposium

At the 1964 International Water Removal Symposium, Wrist (4) gave an excellent critical review of the existing fundamental understanding of wet pressing. He also presented new work recently completed by him and his colleagues supporting their views of wet pressing. Wrist's summary of this work includes one of the first specific references addressing the importance of felt uniformity during the compression phase of pressing (Wahlström (11,12) had mentioned it earlier in connection with the expanding nip).

---

[1]Nip saturation refers to a condition where all voids in the paper, felt, and press roll vents (if any) are filled with water at some point into the nip

Wrist considered Wahlström's theory a useful way to visualize pressing and said that it was in superficial agreement with qualitative observations, but he did not think it provided the means for predicting press performance, analyzing quantitative data, or determining the ultimate commercial potential of wet pressing. He pointed out the need for greater fundamental understanding of fluid flow through rapidly compressed networks, network mechanics, and pressure distributions in deformable nips. He also called for direct experimental evidence of the fluid pressure distribution (only the total applied pressure had been measured at that time) and studies of film splitting as a possible mechanism for rewetting. Many of the statements he made 25 years ago could be repeated today.

There were several other important contributions at the 1964 Symposium. For example, Asklöf *et al.* (15) presented work dealing with platen pressing of wet webs. They were among the first to provide data that flow resistance in the paper web was a significant factor in its water removal. Another original work by Asklöf *et al.* (16) showed for their plain (solid roll) press that the felt left the press wetter than could be accounted for by its measured midnip void volume. They reasoned there must be some lateral flow of water in the felt as it passed through the midnip. Logically, this lateral flow could only occur if the static water pressure was lower at the midnip than before it. Thus, their work originated the idea that, *in a roll press*, the maximum static water pressure in the felt was located *before* the midnip. Their idea was independently supported by Lyall's (17) observations, by Westra's (18) and Roux's (19) models, and experimentally demonstrated *for felts* by Ershov (20) and more recently by Beck (21). However, Carlsson and Lindström (56) showed this wasn't always true for paper pressed in a platen press. Asklöf *et al.'s* idea has never been experimentally substantiated for a broad range of *roll* pressing conditions *when paper is present*.

1968 Water Removal Symposium

At the 1968 International Water Removal Symposium, Wahlström (1) presented the next comprehensive review of wet pressing research, including a number of refinements to his 1960 theory. One major change was to divide his original two pressing phases (compression/expansion) into **four** phases to better describe events newly thought to occur in the midnip vicinity. This modification was based on his involvement with Asklöf *et al.'s* (16) earlier work and familiarity with the work to be presented at the same conference by Nilsson and Larsson (23). In his review paper, he also introduced an empirical equation which listed how the sheet moisture out of the press was affected by five factors. Eventually, several more terms were added to this equation (2) and, while not based on first principles, the equation formed a good framework for describing wet pressing.

In the same review paper, Wahlström modified his earlier stands on rewetting by (a) including the possibilities of rewetting both by a suction process and by Wrist's (4) film splitting mechanism; (b) viewing the capillary transfer mechanism as being so rapid compared to the nip expansion time that it could be considered essentially time **in**dependent; and (c) stating that rewetting was probably an interfacial, not a bulk flow, phenomenon. He still maintained his view that rewetting was controlled mainly by the capillary structure of the paper and felt and their respective wetness, adding for emphasis that "capillary transfer in the expanding part of the nip is firmly established as present for all press conditions". Much of this conviction appeared based on the Sweet (24) plot technique for representing the results of pressing experiments. It was later questioned (25) , however, whether this method actually proved the existence of physical phenomena or was simply an empirical means of displaying the data.

From today's perspective, the rewetting issue seems to have overshadowed parts of the Wahlström group's work which had greater impact on wet pressing theory. For example, showing how Campbell's (9) pressure and time terms could be combined to give a maximum sheet dryness for each pressing condition was a major advancement in the understanding of pressing at the time. This concept, independently conceived by Schiel (29), led to the conclusion that, for many situations the problem was not in applying enough press load (this wouldn't bring much dryness improvement), but in applying enough pressing time (especially with increasing machine speeds). Wahlström also coined the well known terms "pressure controlled" and "flow controlled" pressing as a way to denote whether the water removal was restricted by fiber compression response or by fluid flow resistance inside the paper.

Wahlström was one of the first advocates of double felting as a way to simultaneously reduce the effects of sheet flow resistance and slightly increase the nip residence time. Double felting was later combined with large press rolls, soft covers, and high loads and implemented as 'high impulse' pressing. Soon after the Wahlström and Schiel papers, Busker (26) made his own investigations of extended pressing times, confirming the value of much longer time under pressure. Realizing a conventional roll press could never give the time increases their studies indicated were necessary, Busker, Cronin, Bergström, and Justus (27) embarked on a prolonged effort which culminated in one of the major equipment advances for wet pressing, the first commercial installation of a shoe-type press.

There were several other important contributions at the 1968 Symposium. Nilsson and Larsson (23) made one of the first references to water being pressed out from *inside* the paper fiber. They also were among the early workers to attempt a more rigorous theoretical and experimental approach to wet pressing. Using their previous work (28) and Wahlström's theory as a starting point, they mathematically modeled the static water pressure distributions in the sheet, both in the machine direction and in the sheet thickness direction--something not done before. They also closely examined the vicinity surrounding the midnip in Wahlström's theory and proposed that the mechanical pressure acting to compress the sheet actually reached a maximum *after* the midnip. This was a new idea at the time. They suggested that Wahlström's expansion phase should be modified to contain a new 'Phase 3' beginning at the point of maximum *applied* pressure and ending at the point of maximum *mechanical* pressure (sometime *after* midnip) where the sheet was no longer being compressed, where hydrodynamic pressure and the resulting water flow had ceased, and where maximum dryness had theoretically been achieved[1].

Pressing and Paper Quality

Schiel (29) had, independently of Wahlström, introduced the optimum pressure-time concept at the 1968 Water Removal Symposium. He also presented methods for approximating roll press nip geometry using the 'effective roll radius' and the felt compression response. Combining this nip geometry with the press load and speed, he introduced the now-familiar term 'Press Impulse' which led him to the optimum pressure-time concept. Schiel defined another nip geometry term he called 'Nip Sharpness' which correlated with the propensity for sheet crushing. This term not only took into account the roll and felt geometry, but also the increased 'stiffness' of an aging felt. He discussed at some length the important subject of how the press affected paper quality (something few people had done in the literature). He described three different kinds of crushing (99) and made the interesting observation that the paper became *drier* (*but weaker*) during "insipient" crushing by a "slipping action" of the fibers. It is inferred from his writing that the fibers slightly displaced by fluid and mechanical shear forces create microscopic flow paths which allow easier exit of water but which also weaken the network bonding. Schiel (30) later offered some interesting

----

[1]Subsequent measurements (56) of static water pressure and sheet thickness during dynamic compression (platen press) did not agree with this concept. In this work, the minimum sheet thickness (maximum solids content) always occurred *after* the point of maximum fiber structure pressure.

work on other paper quality aspects of wet pressing. For example, he showed how the number of press nips (pressing history) could influence the paper strength, bulk, and opacity, even when pressed to the same dryness level. He wrote about the two-sidedness in sheet surface density brought about by the pressing process and how this mechanism could be utilized to offset the two-sidedness from the Fourdrinier forming process (64). Lastly, he discussed how pressing could affect sheet topography two-sidedness. This and other work by Schiel forms an excellent reference for the effects of pressing on paper properties.

The Importance of Felt Uniformity (UOPA)

Heller *et al.* performed a number of wet pressing studies using laboratory and pilot plant roll presses in the early 1970's. Their first paper (31) has often been cited because they were apparently the first to report achieving 70% paper dryness in a felted roll press. They proposed this dryness approached the "equilibrium fiber moisture content" (their words)[1], a level beyond which was unavailable for removal by conventional pressing. In their work, these dryness levels could only be achieved by utilizing the *most uniform press felt possible* and pressing the unrefined sheet in a plain press with extreme maximum pressure (15 MPa) and time (500 msec).

Their next paper (25) gave a critical review of the existing understanding of rewetting and discussed why they believed it necessary to further investigate the importance of felt uniformity. In a follow-up paper (32), they gave the name "Uniformity of Pressure Application (UOPA) Principle" to the concept of pressure uniformity in the nip. In this concept the felt uniformity determines what fraction of the sheet is highly compressed, with the remainder undergoing little compression and perhaps even receiving water through a lateral redistribution process. Although not

---

[1] Some feel that the term "fiber saturation point" is more correct in this context.

claiming that pressure uniformity was their original concept, they were convinced it explained a sheet dryness loss over a much larger range of pressure nonuniformities than previously appreciated--from suction holes, grooves, felt yarns, down to felt batt fiber dimensions. During their studies they also developed a "High Speed Rewetting Test" (32) which was used by several others (34,35,36) to reaffirm the importance of separating the felt and sheet immediately after the nip if possible. The procedure was also used (with reservation) as another way to estimate the amount of rewetting inside the nip

At the batt fiber level, the pressure uniformity principle was referred to as micro-UOPA and was vividly illustrated by the photomicrographs of Fekete (37) and Smart (38). These photos revealed a surprisingly large number of relatively uncompressed regions in the paper which they believed must contain more water. Their work in trying to obtain a very uniform pressing surface without significantly increasing the felt's total flow resistance and filling propensity led to their invention (39) of the "stratified" felt[1], a major advance in felt design.

Since the Heller and Fekete work there have been a large number of studies of felt UOPA and a significant trend toward more uniform felt designs[2]. Wiseman (40) showed that only 25% to 33% of the felt surface is load bearing against a hard flat plate when considered at the batt and paper fiber dimension. Yamamoto (41), basing his calculations on experimental measurements of felt uniformity, concluded that improved micro-UOPA could potentially result in a 3 per cent sheet dryness improvement.

------

[1]This felt incorporates a thin layer of fine batt needled into a coarser batt underlayer to produce a very fine and uniform surface, but with a very low overall flow resistance and filling propensity.

[2]This trend was made possible by the ability to manufacture felt structures which allowed a more uniform pressure application and still maintain satisfactory void volume under compression. Multi- and monofilament yarn components and various needling techniques were important aspects of this trend which continues today (e.g., 45).

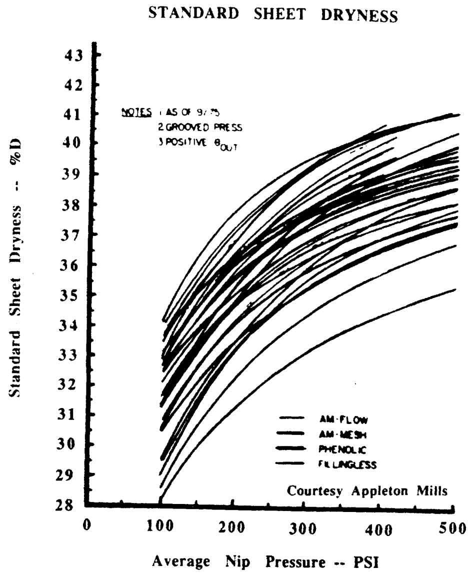


Figure 2. Standard Sheet Dryness for 50 Commercial Felts.

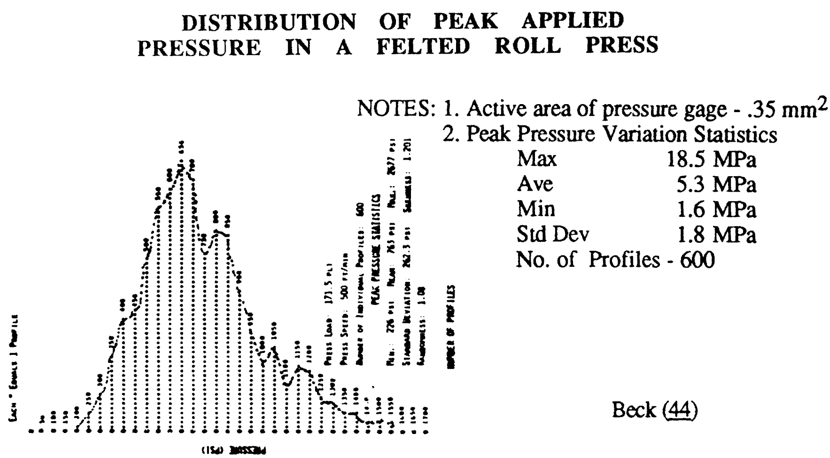


Figure 3. Localized Applied Pressure Variations due to Press Felt Nonuniformity.

Figure 2 shows the results of sheet dryness tests performed on a laboratory web former and roll press (42), using over 50 randomly chosen commercial press felts. The large 8 per cent sheet dryness range at standard conditions[1] was described well by an empirical equation which took into account the base fabric uniformity (macro-UOPA) and the batt fiber size (micro-UOPA). After examining all the variables affecting sheet dryness, Busker (43) stated that felt UOPA was second only to the sheet flow resistance and the press impulse in its effect on water removal. Beck's (44) and Jewett's (75) work presented data generated in roll presses demonstrating that even supposedly uniform felts give extremely large in-plane pressure variations (e.g.,Figure 3). Ballard (45) showed the significant effects of batt fiber size and orientation on the felt 'contact density' with the paper. Sze (46) used various novel techniques to quantify felt UOPA and then correlated it with sheet dryness on a pilot paper machine. Finally, Norman (7) and Paulapuro (102) recently brought us full circle by again showing photos (Figure 4) similar to Fekete, with Norman giving a good critical discussion of UOPA and rewetting. Faced with evidence like this, many feel that there still are some improvements to make in felt UOPA and its effects on water removal and sheet properties.

------

[1]The nondeformable steel press rolls were accurately instrumented to determine midnip separation. The incoming felt caliper was also accurately instrumented. The dynamic nip width (77) could then be calculated and combined with the known press load to give the average nip pressure. The machine speed was 380 mpm and the standard sheet was a 50 gsm bleached unrefined northern kraft (36) whose dryness at these conditions was expected to be dominated by nip pressure and not by the sheet flow resistance.

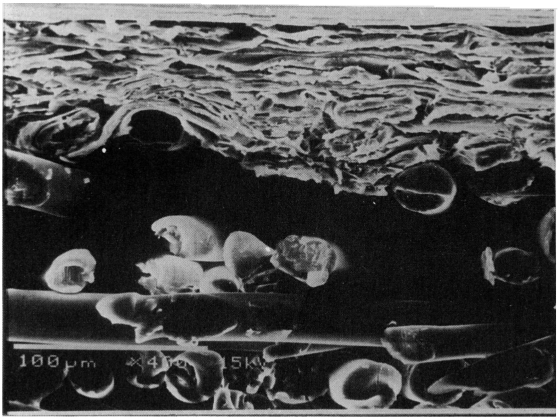


Figure 4. Localized Applied Pressure Variations due to Felt Micro-Nonuniformity Photo by Sze (46).

Dynamic Compression Studies

At the 1977 Fundamental Research Symposium Carlsson, Lindström and Söremark (47) presented fundamental work on water removal from *inside* the fiber lumen and cell walls--something mentioned earlier in the context of wet pressing (23) but never actually investigated. Their work and experimental methods were motivated by the widely recognized work of Stone and Scallan (48) and convincingly demonstrated for the first time that water *within* the fiber was an important component of the water removal process.

Although static water pressure had been *talked* about for more than 30 years (back to at least the time of Campbell), Chang and Han (49) presented the first actual static[1] water pressure measurements taken during dynamic compression of paper using a platen press. This historic and well-documented work, although performed using heavy handsheets (220-750 gsm) and

------

[1]Part II discusses this difficult and sensitive measurement.

relatively long compression times (30 msec or more), contained a great deal of insight and many thought-provoking concepts. The work was never formally published and even though a precursor to work performed at the STFI, the University of Maine, the FPPRI, and by Beck, Chang and Han's work appears to have been overshadowed by the others. Among other things, Chang added a new term to the lexicon --"Interfacial Controlled Pressing"--which we interpret as an extreme densification (or 'sealing') of the sheet surface by high water outflow which then controls the pressing process[1]. This concept may be analogous to 'sheet sealing' on the Fourdrinier and, while apparently associated with high water removal rates during pressing, the exact mechanisms are still not completely understood (see Part II).

Shortly after Chang's work, Ceckler (50,51) and others under his direction (Thompson, Thorne, Jewett, Hoering, Ellis) initiated an ambitious wet pressing project with representatives from the paper industry (feltmakers, machinery builders, and paper manufacturers). A group this large, devoted to a single purpose--development and experimental confirmation of a comprehensive and accurate wet pressing model--had never before been assembled in our industry.

The mathematical model which evolved from their experimental work (103) dealt *only with the paper thickness during compression* since they believed that what occurred after the point of minimum sheet thickness had little effect on final sheet dryness (52). They rationalized this approach partly on the basis of earlier literature questioning the importance of rewetting and partly on Thorne's investigations of capillary rewetting (53). When experimentally predetermined permeability and compression data for the given furnish were input into the computer model, there was excellent agreement (over a wide range of pressing

------

[1]Wahlström (1) had earlier mentioned a "compact layer" which controlled the flow and later mentioned a "blinding" of the sheet (2).

conditions) with the actual sheet thickness response measured in their dynamic compression tester (DCT)[1]. The computer model also clearly indicated where the pressing was flow- or pressure-restricted.

The DCT did not allow measurement of the final sheet dryness, however, and it was only later that verification tests revealed that the computer model systematically predicted a higher sheet dryness than actually occurred on pilot and commercial wet presses. That is, the model accurately predicted the DCT thickness response, but the DCT could not be used to accurately predict sheet dryness in a realistic nip unless the data was realigned using a 'nip efficiency' factor that ranged from 2 to 7 (50).

The literature cited earlier had shown this systematic dryness difference could easily have been accounted for by the UOPA principle and possibly some rewetting differences, neither of which were included in their model or in their DCT experimental work. The problem leading to the 'nip efficiency' factor is a good illustration of one faced by *all* mathematical models and platen press tests we are aware of--none adequately account for localized in-plane variations in applied, mechanical, and hydrodynamic pressure. When the basic water removal mechanism is one of fiber network volume reduction, these highly nonlinear pressure variations logically *must* lower the 'efficiency' of load application and give some reduced water removal.

During the same period, Carlsson, Lindström (54,55,56) and others at the Swedish Pulp and Paper Research Institute (STFI) were involved in similar platen press studies. They viewed their work strictly as fundamental studies of dynamic compression and

------

[1]Static water pressure was never given emphasis in their publications and there were problems making the model agree with the measurements. They attributed this to the experimental difficulty posed by such a sensitive measurement rather than to any problems with the model (50,106). See Part II for more discussion on the measurement of static water pressure in a platen press.

expansion behavior of paper. Because their platen press tester utilized a computer controlled servo-hydraulic loading system, it allowed the investigation for the first time of the dynamic thickness *and* static pressure during an entire compression/expansion cycle that ranged between 10 to 25 msec. Like the University of Maine DCT, they could not measure final sheet dryness. However, they were able to observe its thickness increase during the unloading portion of the cycle. Air (if any) could only enter from the porous plate during the expansion, the paper was held under a very slight pressure at the end of the pressure pulse, and the sample was not separated from the porous plate. Although these points were not emphasized in their publications, this likely accounts for the large disagreement with Jaavidaan's (57) later work on rewetting (see Part II). During their work they developed several novel experimental techniques and contributed new findings regarding uniaxial dynamic compression and expansion of paper in a platen press:

--The first experimental data of the static water pressure profile during the entire pressing cycle. This included the negative static water pressure produced during sheet expansion which they felt could cause cavitation and allow some sheet volume expansion without liquid water inflow;

--They found the maximum hydrodynamic pressure usually followed the applied pressure quite closely, but were the first to show that it could be located before *or* after the maximum applied pressure--at least in their platen press. They also demonstrated that the minimum sheet thickness corresponded to the point of zero hydrodynamic pressure, but not necessarily to the maximum mechanical pressure. These findings were contrary to the widely accepted classical wet pressing theory (1, 11, 12, 18, 23) and have not been challenged with subsequent data;

--They confirmed that sheet expansion after the minimum thickness had been reached was a strong function of the furnish, but concluded that rewetting by a bulk suction process was minimal;

--Lindström (56) introduced Reiner's (104) 'Deborah Number' into their Kelvin model for dynamic compression response. This number mathematically described for the first time the degree to which the pressing event was flow- or pressure-dominated;

--They demonstrated the very important role of water contained within the fiber lumens and cell walls, proving that dynamic compression removes some of this water and could greatly affect the pressing response--something never before investigated. This meant that even when the pressure drop through the fiber network was small, the pressing could still be 'flow controlled' by the high pressure drop required to remove water from *within* the fibers.

--They presented the first detailed data showing that irreversible cell wall collapse ('hornification') may occur at points along the fiber when cell wall water is removed during dynamic compression.

The body of work contributed by these two groups on the dynamic compression behavior of paper demonstrated that the wet pressing process was far more complex than a superficial reading of the classical theory would suggest.

Fluid Pressure Measurements In a Roll Press

The only one to ever measure and report static water pressure in a roll press has been Beck, a noteworthy technical achievement. He had to overcome numerous challenging problems, from accurately sensing the static water pressure at the top roll surface once every revolution, to transmitting a noise-free signal out of the rotating roll, and finally to computer processing the prodigious amount of data necessary to adequately characterize the profiles. His first papers (21,58) described the equipment and presented data showing very large variations in the felt pressure uniformity and how the static water pressure was affected by press type, felt design, and felt condition. Beck's data seem to support the earlier theories (16,23,28) regarding the maximum static water pressure being located ahead of the maximum applied pressure--at least for a felted roll press with no sheet present. As with Carlsson's work, Beck's data showed that some vacuum was produced during the felt expansion.

Beck (59) next presented the first fluid pressure data taken on a plain (solid) roll press *with paper present*. The details of the static water pressure instrumentation are not available, so it is unknown how he prevented the capillary entrance to the static pressure chamber from being partially plugged with paper fiber on every roll revolution (This formidable problem had previously plagued Ceckler (50) and Carlsson (54)). Also unknown is why some of the pressure transmitting fluid wasn't withdrawn from the capillary entrance at each revolution[1].

While additional investigations are required to achieve independent confirmation, the fluid pressure data ***with the sheet present*** appear to dramatically demonstrate the sensitivity of Beck's plain press to the incoming felt water content. In these experiments, the press was operated at fairly high simulated commercial speeds (for a plain press) of about 610 mpm with a very lightweight (30 gsm) sheet formed from long fiber unrefined northern kraft[2]. As the incoming felt moisture approached the theoretical nip saturation value, there was a sudden *tripling* of the static pressure drop across *both* the 30 gsm sheet and the felt. Logic suggests the pressure drop across the sheet could not increase this much if the water was leaving directly downwards.

This data is thought to provide the first experimental substantiation that, as the nip becomes saturated, a sudden **extra** pressure drop occurs across the sheet which is probably due to longitudinal water flow conditions. The significant increase in static pressure at the felt/sheet interface (due to the felt being saturated) probably acted to produce a longitudinal water flow component in the sheet (even though catastrophic crushing did not occur). The

---

[1]There are other difficulties which are encountered with any dynamic measurement of static water pressure. These are discussed in Part II.

[2]Possibly to minimize the static water pressure measurement problems.

increased pressure drop through the sheet led to only a 10% reduction in mechanical pressure acting on it, but a 20% reduction in sheet water removal was measured. A small reduction in water removal might be due to the slightly lower mechanical pressure, but the remainder was likely a result of the increased pressure drop from the longer flow path. This experiment demonstrates why a single pressure profile--e.g., at the roll surface as normally assumed by the classical wet pressing theory--does not give a true appreciation for flow direction and the resulting pressure drop in a roll press. It also dramatically emphasizes how sensitive the water flow is to pressing conditions Interestingly, this data could not have been obtained using a platen press.

A commercial plain press probably could not successfully operate at or near the kind of conditions run in Beck's work so it would have been interesting to perform the same experiment for the more common vented press. According to his earlier fluid pressure data for different felt designs and pressing conditions (21), the high fluid pressure condition at the felt/sheet interface, leading to lateral flow and reduced sheet dryness, would probably be unusual. This may explain why most investigators have not observed much effect of felt water content or flow resistance on the sheet dryness for a vented press utilizing today's felt designs and conditioning equipment (36,60,61,62)[1].

Beck's pressure data gave a new, direct insight into the pressing process not seen before. He then proceeded to use his press instrumentation to apply a 'differencing' method for estimating sheet dryness inside the press nip (89) which is intrinsically inaccurate (see Part II). His conclusions about the effects of felt design on sheet dryness and rewetting mechanisms must therefore be given careful consideration.

---

[1]Beck's plain press data did suggest, however, that *localized* flow conditions, while perhaps not significantly affecting overall sheet dryness in a vented press, might be important to paper properties.

Z-Direction Research

The effect of pressing on sheet properties in the thickness direction had been alluded to as long ago as Campbell (9) but hadn't been explicitly described or quantified until much later (58,64,65,66,67). Szikla and Paulapuro (68,69) were the first to attempt actual measurements of the effects of platen pressing on fines, filler, and fiber redistribution in the thickness direction. MacGregor (65,66) had presented evidence that strong compressive and fluid shear stress gradients might contribute to the z-direction density gradients observed in commercially pressed paper. He also showed evidence that fines, fillers, and fiber redistribution *in the sheet plane* might be associated with in-plane fluid shear stress (78). Based on this evidence and work by Brooks (70), MacGregor had postulated that fluid shear forces might be strong enough to cause a redistribution of the fines and fillers *in the z-direction*. To test this idea, Szikla (68) used a radioactive tracing technique to experimentally demonstrate that a major redistribution of fines and filler material did not occur during their platen pressing experiments--even under the most severe conditions. Busker (71) reached a similar conclusion after performing laboratory and pilot roll press trials, finding a maximum of only 15 per cent movement. He was cautious, however, in concluding whether this amount was significant for commercially produced paper.

In explaining their results, Szikla hypothesized that the particle movement by fluid shear force must just be balanced by particle entrapment in the rapidly collapsing fiber network. If this theory is valid, it may indicate something profound about local water movement and the size of flow channels in the fiber network during pressing. Perhaps by the time the water velocity becomes high enough to create significant fluid shear force, the flow paths in the collapsed network are already so small (e.g., substantially less than 1 micron) that particle movement is precluded. Obviously, even these microscopic flow paths are large enough for a significant amount of water to still leave the sheet.

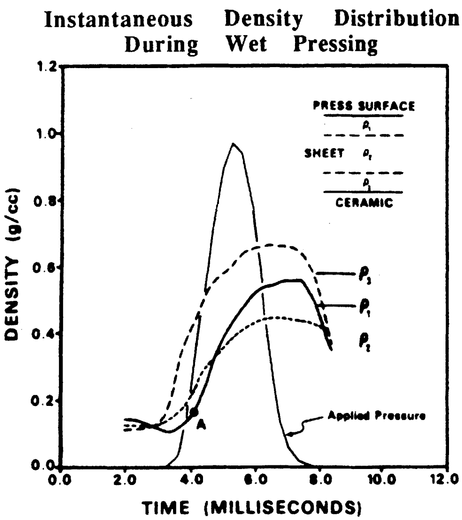
Placing these works in perspective, it should be noted that (a) because paper is a layered structure, movement of small particles *within* its plane is more likely than vertical redistribution (63), (b) the in-plane movement shown by MacGregor for commercially pressed sheets was also only about 15 per cent and that (c) in-plane movement probably has a much greater perceived effect on paper properties than an equal z-direction redistribution. Despite the various findings on fines and filler redistribution, most papermakers believe that water removal during wet pressing 'washes out' significant fines and fillers at the surface where it is especially important for certain properties.

In their next work Szikla (69) made the first actual measurements of z-direction sheet density associated with platen pressing. In this work they utilized Andersson's (72) new staining and image analysis technique to measure the z-direction density of pressed and dried paper samples embedded in resin. They also measured oil absorption on each side of the paper. Their findings agreed with earlier descriptions of "stratification" (65,66), as well as "2-sidedness" measurements using K&N ink stains (67,58). There is another very interesting aspect of their work not discussed. Their data reveal the possibility of an interaction of the z-direction sheet density gradient created during pressing with the evaporative drying process. This subject is addressed in Part II.

Instantaneous Z-direction Density Measurements

Using thin metal grid targets formed into a 170gsm sheet, Burton and Sprague (73) provided for the first time a unique *direct* look at the instantaneous density development of various layers in the paper during a high speed platen pressing event. They also observed visual evidence of radial crushing in the layers next to the *solid platen side* and could measure a rapid density rise in these layers. They believed this density rise could have been an artifact from the crushing process caused by radial fiber and water movement.

Another explanation for these observations might be that fluid shear forces displaced fiber slightly and created small paths for water to more readily escape, thus relieving the static water pressure in that layer and allowing it to collapse (densify) more. Schiel (99) had made similar observations on commercial paper machines and MacGregor (74) had shown the dramatic densification and flow patterns that could occur during crushing (e.g.,Figure 14). In addition to measuring a strength loss, Jewett (75) believed he also observed the same 'channeling' effect in his work. Except for the crushing phenomenon disrupting the z-direction distribution later in the compression, Burton and Sprague found their initial sheet density profiles to be in essential agreement with the "stratification" described earlier (65,66).



Burton and Sprague (73)

Figure 5. Z-Direction Density Distribution During Wet Pressing.

Burton's data (Figure 5) showed a substantial and rapid overall sheet density loss ('springback') during the expansion portion of the pressure pulse (30% to 40% within only several milliseconds). This trend agrees with the sheet thickness measurements reported by others (55,76). However, their data showed that most of the density loss occurred in the *dense layer next to the porous plate* (water exit side); near the end of the pressure pulse, almost *none* of the large midnip z-direction density gradient remained. This seemingly contradicts Szikla's earlier findings, but unlike Szikla, Burton did not evaporatively dry the sheet. It therefore would have been interesting to measure how much density gradient recovery would have occurred during evaporative drying (see Part II).

Recent Wet Pressing Models

There have been a number of mathematical models of wet pressing (23,18,103,105), beginning with Nilsson and Larsson. Most of these appear to rely heavily on experimentally *pre*determined data and

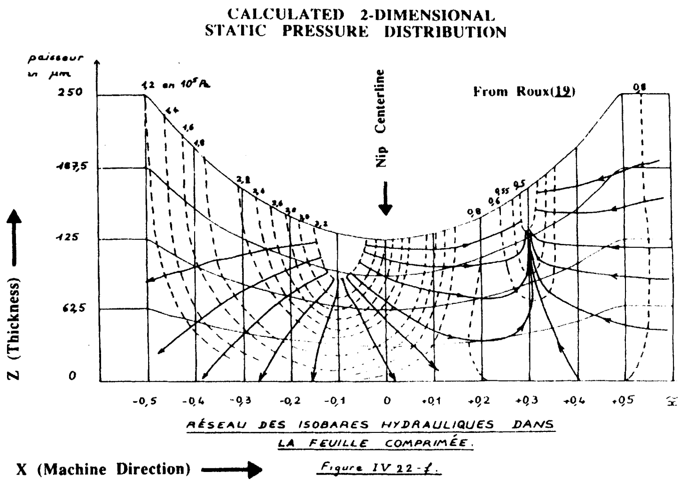


Figure 6. Some Results of Vincent and Roux's (19) Pressing Model.

empirical relationships and thus cannot be classified as truly fundamental or predictive models. Roux and Vincent's (19) recent model of the roll pressing process, while not yet accounting for realistic boundary conditions, is one of the first which is predicated primarily on the physical laws governing conservation of mass and energy, and the behavior of stress, strain, and two-dimensional, two-phase fluid flow (water and air) through the fiber network.

Roux and Vincent's applications of the model to date (e.g., Figure 6) have already shown the deformations, water flow vectors, and pressure distributions occurring in the paper web for their assumed conditions. Apparently, work continues at incorporating a better computation method and accounting for permanent sheet deformation and the presence of a felt in the system. In order to evaluate the basic parameters of the model (elastic moduli, permeability coefficients), they are carrying out a parallel program based on microscopic image analysis and ultrasonic velocity measurements. They also intend to validate the model with an instrumented pilot press similar to the one used by Beck. If successful, this work should provide a significant step toward improving our fundamental understanding of wet pressing in a rolling nip.

Concluding Remarks

This historical perspective has attempted to show the progress made in wet pressing research over the last 3 decades, elucidate some of the lesser known aspects of the work, and interject some comment. Major research accomplishments are seen as the optimum pressure-time concept, studies of dynamic compression and water removal from wet paper, fluid pressure measurements, and mathematical modeling. There have been major advances as a direct result of the improved understanding afforded by this research. These are viewed as 'vertical flow' pressing, double felting, 'three-dimensional' felt structures, uniformity of pressure application, and the shoe press. There are still some major gaps remaining, namely our lack of fundamental wet pressing knowledge on a microscopic dimension, our inability to make certain direct measurements, and an incomplete understanding of how wet pressing affects paper properties. The next part of this paper gives more detailed comment on some of these topics, as well as suggestions for future research.

PART II -- Views on Selected Wet Pressing Topics

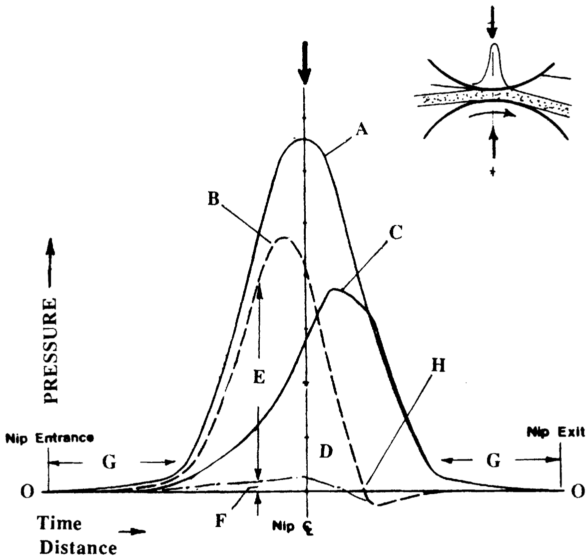
Introduction

It is convenient to think of wet pressing as a one-dimensional volume reduction process, with the sheet, felt, and water assumed to be a more or less homogeneous continuum. However, when visualized in the microscopic realm, wet pressing is a complex process which combines important mechanical changes in the fiber network with three-dimensional, highly unsteady, two-phase flow through a rapidly collapsing interconnected porous maze. This part of the paper addresses a number of areas where we have a possibly inaccurate or incomplete mental picture of wet pressing, discusses the implications, and offers suggestions for future research.

Stresses, Deformations and Displacements of Paper in a Roll Press

General. The classical wet pressing pressure curves are generally well accepted, but there are some details worth further comment. This section points out that only two special cases of these pressure curves have been experimentally verified for a roll press and suggests that the fluid stress curve should be added to the family of pressure curves. It also emphasizes the importance of wet pressing to paper property development.

**PRESSURE PROFILE DEFINITIONS
FOR A
FELTED NIP WITH HARD ROLLS**



O-O Pressure Reference Line. In the case of water pressure, this baseline is normally assumed to be the ambient pressure (1 atm).

A Applied Pressure Profile resulting from the pressure distribution between two hard rolls, acting through the sheet and felt at any MD position in the nip. This pressure profile can be experimentally measured and is not symmetrical about the geometric nip center due to felt hysteresis (the area under the expansion side is less). The Long Low Pressure 'Tails' (G) are associated with the felt compression response (high initial compression of the felt under low applied pressure) Not all the applied pressure is transmitted to the sheet and felt fibers because some is taken up by static water pressure. 'Press Impulse' is the area under Curve A, while 'Effective Impulse' is the area under Curve A integrated to Point H. .

B Static Water Pressure Profile at the *top layer* of the sheet next to the smooth roll. The static pressure at this surface has been experimentally measured on one occasion for a roll press. Static pressure in the water at any location in the sheet or felt does not include the pressure caused by water in motion (sometimes called the 'hydrodynamic' or the 'velocity pressure'). See text for further discussions of pressure and fluid stress associated with water flow.

C Mechanical Pressure Profile for the *top layer* of the sheet next to the smooth press roll. This pressure has never been experimentally measured. The mechanical force from the press rolls is transmitted through the fiber network in a very complex unknown fashion, acting to bend, compress, and translate fibers toward one another.

D Static Water Pressure profile *at the sheet/felt interface*. This has never been experimentally measured in the presence of a sheet but it can be measured without the sheet present. Other above comments apply.

E Static Pressure Drop Across the Sheet *in the z-direction* at a given MD position in the nip. Equal to the hydrodynamic pressure drop (velocity pressure) corrected for friction losses.

F Static Pressure Drop Across the Felt *in the z-direction.*

Figure 7. Definitions of Various Pressure Profiles in a Roll Press.

Figure 7 defines the various types of pressure profiles in an idealized roll press having nondeformable surfaces[1], each representing a *single* pressure pulse through a felted rolling nip. The significant pressure variations due to felt and cover nonuniformities (e.g., Figure 3) make it necessary to collect many such profiles before the press nip can be adequately characterized(44,75). Besides not accounting for small-scale pressure nonuniformities, none of the classical pressure curves account for the nonuniform vertical compressive stress distributions arising from loading between curved surfaces (Figure 18). Wet pressing in a roll press is therefore more accurately viewed as a simultaneous compression, shear displacement, and stretching process which has important effects on paper properties.

While the applied pressure profile (Curve A, Figure 7) in a roll press has been accurately measured for many years, the static water pressure profile for the felt (Curve D) has only recently been measured (21). The static water pressure profile *at the top of the sheet* (Curve B) has been measured on one occasion (59) but never formally reported in the literature. These static water pressure measurements were made at a single point in the upper press roll surface only and therefore do not reveal the pressure distribution for various layers in the sheet. There also have been no measurements of the compressive stress ('mechanical pressure') profile (Curve C) or the fluid stress profiles (dotted lines in Figure 13). Interestingly, all these unmeasured curves (except for the fluid stress curves) have appeared extensively in the literature and gained widespread acceptance.

---

[1]Deformable roll covers can significantly alter the *shape* of the pressure profiles shown, but since the following discussion is concerned mainly with pressure relationships, the effects of cover deformation will not be considered.

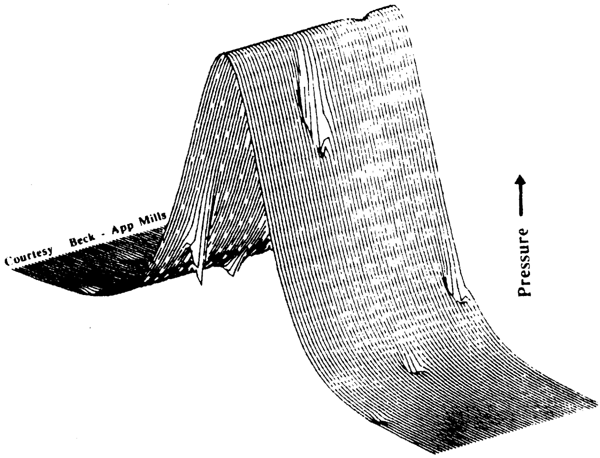


Figure 8. Gradients in Applied Pressure due to Suction Holes. Computer Depiction Based on Actual Data.

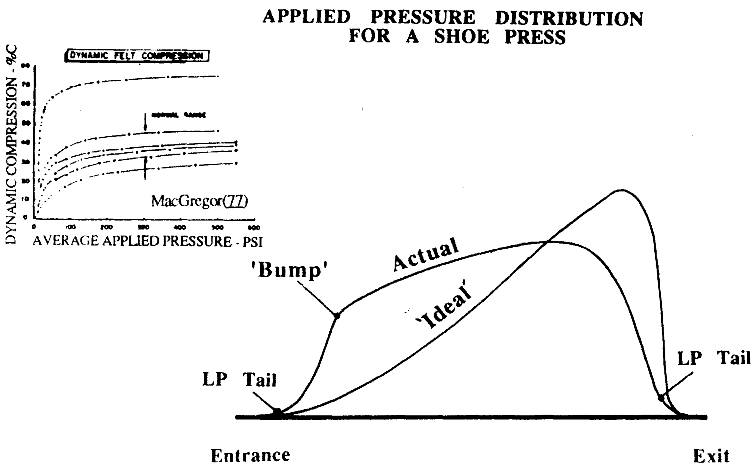


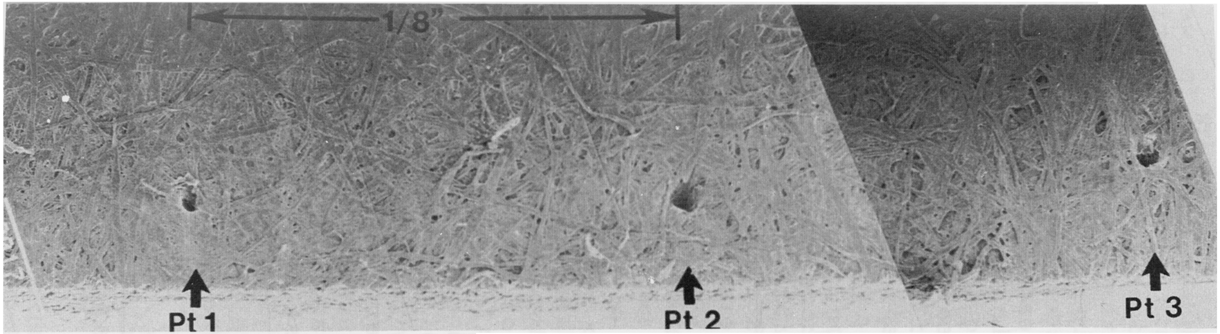
Figure 9. Applied Pressure Profiles for a Shoe Press.

Applied Pressure Profile (Curve A, Figure 7). Even for hard nips, the highly complex dynamic compression response of the felt does not permit an accurate theoretical calculation of this profile[1]--it must be measured. At first, the felt compresses easily under low pressure and this results in the low pressure 'tails' (G) seen at the nip entrance and exit (77) which shorten as the felt ages. The entering tail is essential for providing the gentle load transition and significant initial water removal (77) necessary to avoid in-plane flow and sheet crushing in early press nips. However, the companion exiting tail increases the rewetting potential (32). Press roll vents (e.g., a suction hole or groove) and felt yarns can give precipitous localized lateral and longitudinal gradients for all pressure components. The depiction for a suction press (Figure 8) is based on actual data, and gives an appreciation why fiber and other components can be displaced within the sheet, in addition to giving nonuniform sheet density (78,79).

For the special case of a shoe press, the convergence between the shoe and the mating press roll cannot perfectly match the continuously changing and highly nonlinear dynamic compression response of the sheet and felt (Figure 9 inset). The 'knee' region of the felt compression curve (77) results in the 'bump' seen in the applied pressure profile (Figure 9). The 'bump' is sharper when the mating press roll has a hard cover and also as the felt ages. Because large quantities of water are removed from a never-pressed sheet in this early stage of compression (77), the entering shoe curvature is important for preventing excessive pressure gradients which lead to sheet marking (Figure 10). The small-scale nonuniform sheet densification is especially noticeable for dark colored furnishes where the shoe press is primarily used today. The denser areas of the sheet surface absorb more light, making them appear darker than the more reflective adjacent areas.

---

[1]The same is true for the sheet (although one does not get this impression from much of the literature)--the dynamic compression response cannot yet be theoretically calculated.



Surface Density Marking - L'BD

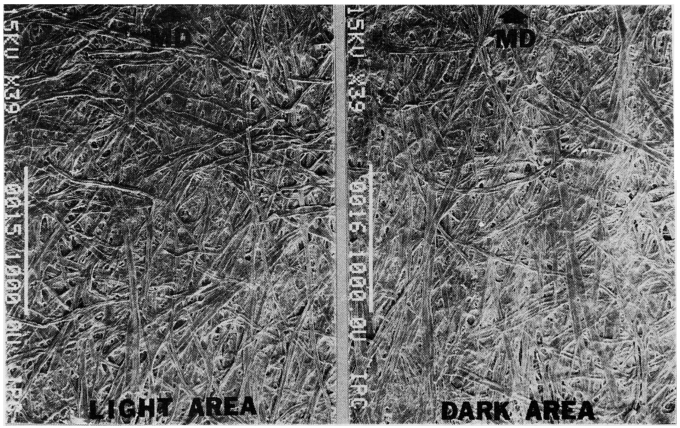


Figure 10. Marking of Linerboard From Surface Density Variations. Denser surface areas correspond to the grooved roll spacing. These areas appear darker in reflected light. Light bar equals 1000 microns in magnified view.

Static Water Pressure (Curve B). In wet pressing, volume reduction, fluid flow, and static water pressure gradients are intimately interrelated. Classical Fluid Mechanics states that the static water pressure is reduced in the direction of flow by conversion to kinetic energy (water velocity). Some of the total energy available at each layer is lost to friction with the surrounding fiber and by microturbulence in the narrowing flow paths. This loss is associated with fluid shear stress (discussed later). However, the water-filled fiber network should not really be considered a continuous confined system (e.g., water flowing in a pipe). The local velocity vector changes direction frequently as the water is forced to take a tortuous path around and along the rapidly collapsing fiber network in the *general* direction of the average static water pressure gradient. The exact path is determined by the *local* static pressure gradient in the narrowing flow channels (the so-called 'path of least resistance').

Despite the simplifications offered by classical fluid mechanics, it seems safe to say that the static water pressure is highest at the smooth roll surface (where water is not in motion relative to the fibers) and lowest at the felted side of the paper (where water velocity is highest). Although it has not actually been measured, each successive plane (starting from the smooth roll) must have a lower average static pressure profile, perhaps as depicted in Figure 11. The top curve (paper + felt) and bottom curve (felt only) have been measured, but the middle two curves are interpolations and their positions could be quite different from those depicted. Because it cannot be measured, it is often assumed (incorrectly perhaps) that the felt-only curve would be unaffected by the presence of the sheet.

In a roll press the largest static water pressure gradient is not directly downward--it is oriented slightly upstream and,

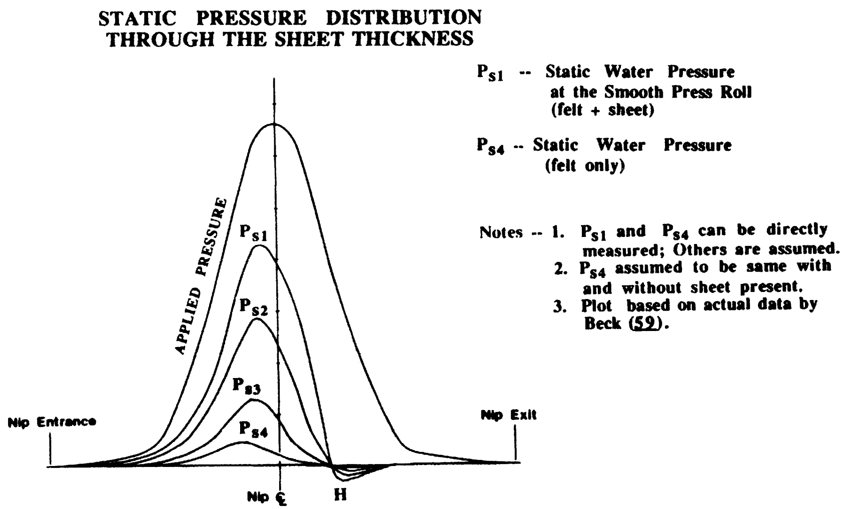


Figure 11. Static Water Pressure Distribution Through the Sheet Thickness for a Roll Press.

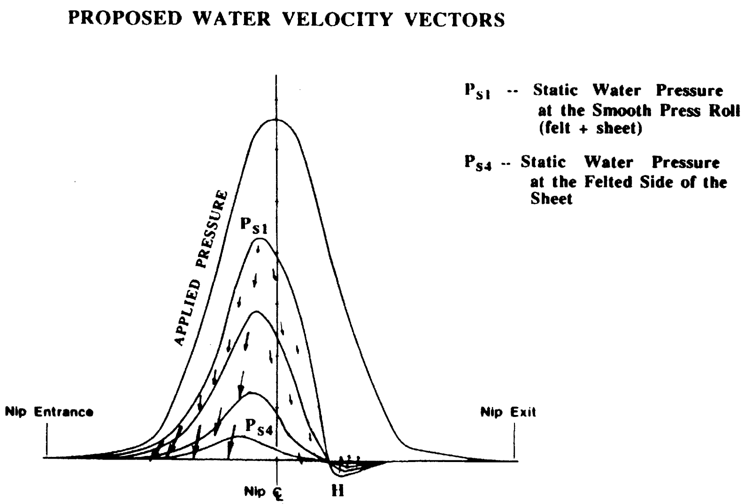


Figure 12. Depiction of Water Flow Vectors Through the Sheet in a Roll Press.

coupled with the significantly higher inplane sheet permeability (63)[1] must create some longitudinal water flow component toward the nip entrance (Figures 6 and 12). This component is present to some extent in any roll press and is rarely mentioned in wet pressing discussions. Lateral and longitudinal water pressure gradients have never actually been experimentally measured but their aftereffects (e.g.,Figure 14) have been observed on many occasions (This topic will be discussed later).

Fluid Shear Stress. Classical wet pressing theory separates the applied pressure into only two components--the static water pressure and the network compressive stress (usually called the 'mechanical pressure'). The drag force created by water flowing past the rapidly collapsing fiber network is not mentioned. This force, and the accompanying network deformation, has been discussed and experimentally measured in filtration studies (80), but not for wet pressing conditions.

The stress associated with the fluid drag force--here called fluid shear stress--and the static water pressure drop always appear together; one cannot exist without the other. The vertical component of fluid shear stress should be added to the fiber network stress (discussed below) to obtain the total compressive stress acting at each layer. Fluid stress is highest at the outflow side of the paper and nonexistent at the smooth press roll. It is also nonexistent after the point of zero hydrodynamic pressure (H) since water flow has ceased. Fluid shear stress also has an in-plane component which must be included when considering paper properties.

Figure 13 (shaded area) depicts how the fluid shear stress family might appear if it could be measured. It is presently unknown how significant

---

[1] This can range from 2.5 to 10 times higher, depending on sheet density (63).

these stresses are, but various degrees of crushing (Figure 14) and displacement of fines and fillers in the sheet plane suggest that they play a role in the pressing process.

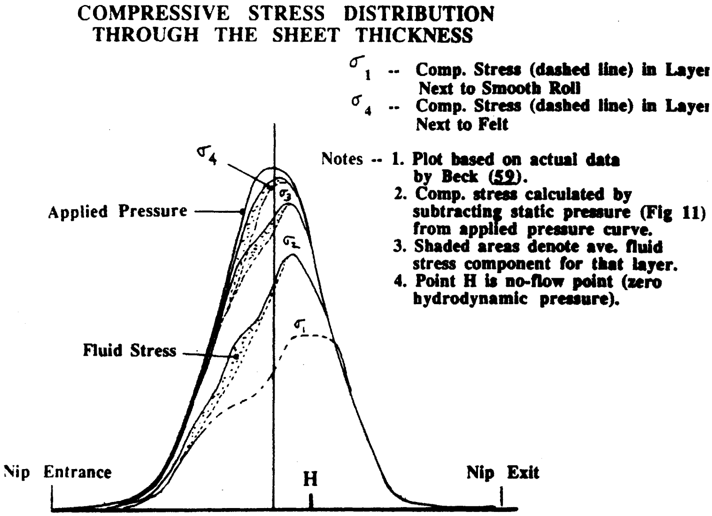
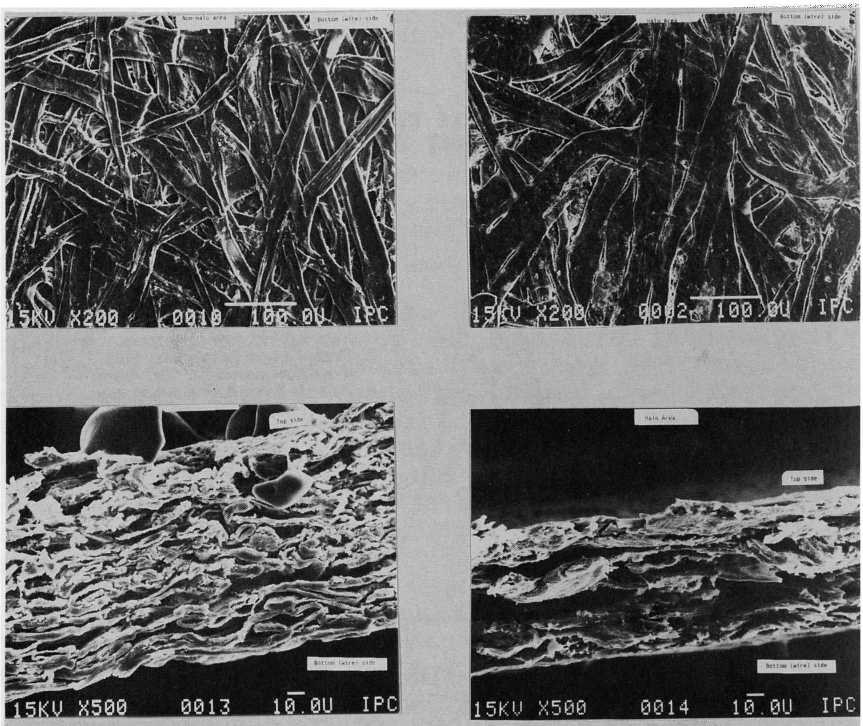


Figure 13. Compressive Stress Distribution Acting on the Fiber Network Through the Sheet Thickness for a Roll Press.

Compressive Stress (Curve C, Figure 7), **Shear Displacement, and Stretching**. Classical wet pressing theory only addresses water removal and does not consider the mechanical responses of the fiber network. Compressive and shear stresses result in fiber bending, deformation, and even displacement. To help emphasize this, the term 'compressive stress' is used here in place of the familiar 'mechanical pressure' term.

Some of the externally applied load is converted to static water pressure and the remainder is transmitted in a complex fashion through the fiber



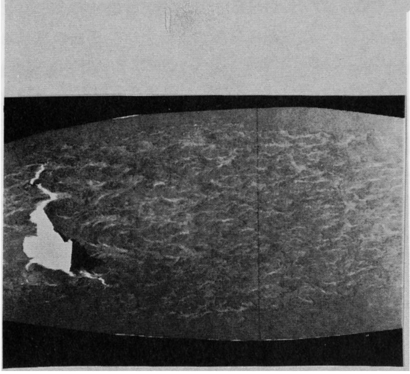


Figure 14. Crushing of Commercially Pressed Paper (74).

Basis Weight - 100 gsm
Machine Speed - 425 mpm
Furnish - Refined Softwood,
Preref. Hardwood,
Unref. Softwood,
Various fillers, Ctd.
and Unctd. Broke.

MD-oriented flow patterns (e) typically follow the borders of flocs. Smooth roll side of the sheet is more disrupted. Evidence of intense pressure in the crushed area (b,d) and the gloss image (not shown).

network[1]. Figure 13 (dashed lines) shows the family of compressive stress profiles which accompany the previously discussed static water pressure family (Figure 11). The compressive stress profiles have never actually been measured and we are not aware of any attempts to theoretically estimate them. Today these profiles can only be derived by subtracting the static water pressure profile from the applied pressure profile. The z-direction compressive and fluid stress gradients shown in Figure 13 have been associated with density gradients ('stratification') in the dried paper (65,66).

Although Schiel (30,99) mentioned it many years ago, there is another aspect of the compressive stress profile family not usually considered in the classical wet pressing theory but which may be important for paper properties--the role of shear during pressing. Due to loading between curved surfaces, a nonuniform stress distribution exists between the press rolls (Figure 18) and a rolling shear stress is created on either side of the nip center as the roll couple rotates.

It is not intended to elaborate on the complicated stresses, strains, displacements, stretching, and relative motions that can occur as the sheet and felt pass through the rolling nip. It seems sufficient to state that, because the fiber layers on the smooth roll side are less compressed and more fluid, they can slip backwards with respect to the highly compressed layers against the felt. The sheet can also be irreversibly widened and lengthened by the rolling action of the nip. These possibilities are depicted (in an exaggerated way) in Figure 15 which shows the sheet being simultaneously compressed, displaced by shear, and stretched during the pressing process. The degree and character of these effects have not been measured. However, dimensional changes in the sheet observed during roll pressing,

------

[1]This includes thc effect of hydrostatic pressure inside the fiber.

longitudinal movement of fines and fillers (e.g., groove and shell marking (78)), and unexpected losses in sheet strength prior to observable crushing (75) all seem to indicate such effects exist and may contribute to final sheet properties.

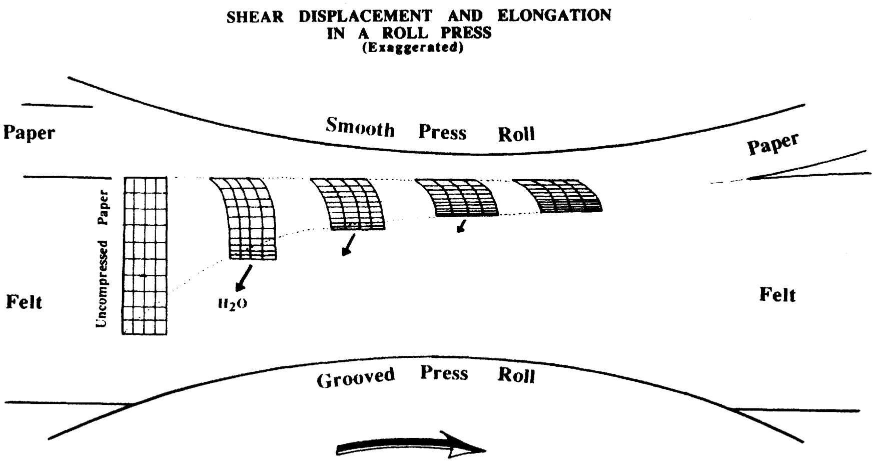


Figure 15. Pressing is a Simultaneous Compression, Shear Displacement, and Stretching Process as Depicted Here (Exaggerated).

Optimizing Pressure, Time, and Paper Properties

Schiel (29) and Wahlström (1) independently introduced the optimum pressure-time concept many years ago in connection with sheet water removal. Since that time there has been much research and many applications of this concept, which basically states that when mechanisms of similar strength 'compete'[1], a

---

[1]For wet pressing the two 'competing mechanisms' are water displacement and fiber network compression.

maximum (or minimum) must exist--in this case final sheet dryness. Although the optimum pressure-time concept applies to all press types, the concept gained renewed interest with the advent of the shoe press, which can extend the pressing time by a factor of 3 to 10 times over a conventional roll press. Although not introducing any new principles, the following may be a somewhat more descriptive rendering of the optimum pressure-time concept.

Pressing to 'Completion'. For a given maximum applied pressure, there is a point in the nip where the static water pressure dissipates to zero (Point H in Figure 7) and water removal ceases. If the applied pressure had been prolonged at this maximum, the zero-flow point would have occurred much later in the nip for a flow-dominated condition but remained unchanged for a strictly pressure-controlled condition. Pressing is not considered 'complete' for a given maximum applied pressure until virtually no static water pressure remains in the sheet. This can take a surprisingly long time for some sheets (49)--longer than available in a conventional roll press operating at commercial speeds. With today's high operating speeds, it is likely that pressing is not 'complete' in many cases.

To illustrate this concept with an actual example, Figure 16 shows a very heavy-weight commercially pressed sheet that very likely had not been pressed to completion. The rather distinct density difference seen in this sheet is interpreted as evidence that considerable static water pressure remained in the upper layers at the time the applied pressure began to fall. More water would likely have left the sheet if the same applied load had been held for a longer time (e.g., slower machine speed, more and/or longer press nips). With more pressing time, the thickness of the denser region would be expected to increase towards the top press roll.

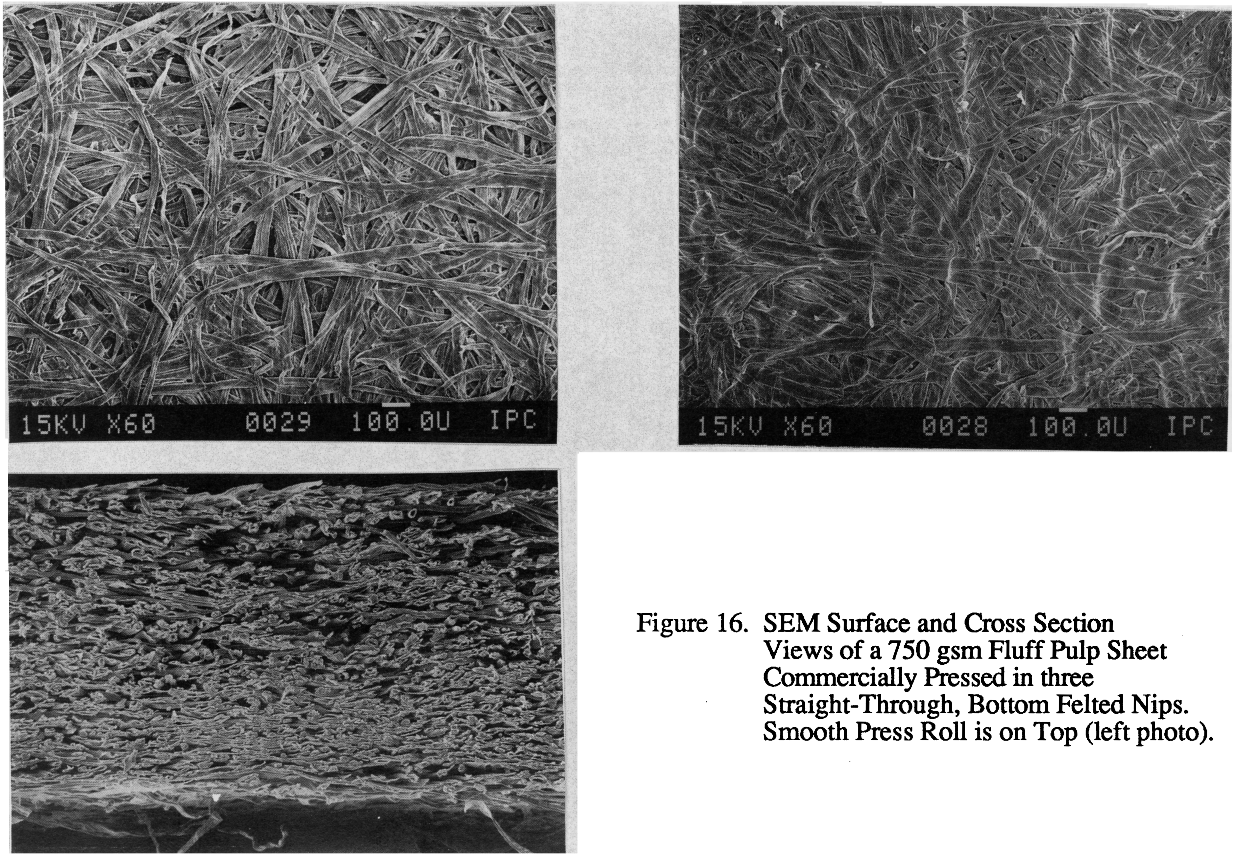


Figure 16. SEM Surface and Cross Section Views of a 750 gsm Fluff Pulp Sheet Commercially Pressed in three Straight-Through, Bottom Felted Nips. Smooth Press Roll is on Top (left photo).

'Effective' Impulse. The above leads to another abstract concept named 'Effective Impulse' and defined here as the area under the applied pressure profile, integrated to the point of zero hydrodynamic pressure (Point H). Because there is no flow of water out of the sheet after this point, the remaining impulse is presumably not effective at removing additional water[1]. Theoretically, to achieve the highest sheet dryness for the total press impulse available, the 'effective' impulse should just match the total impulse.

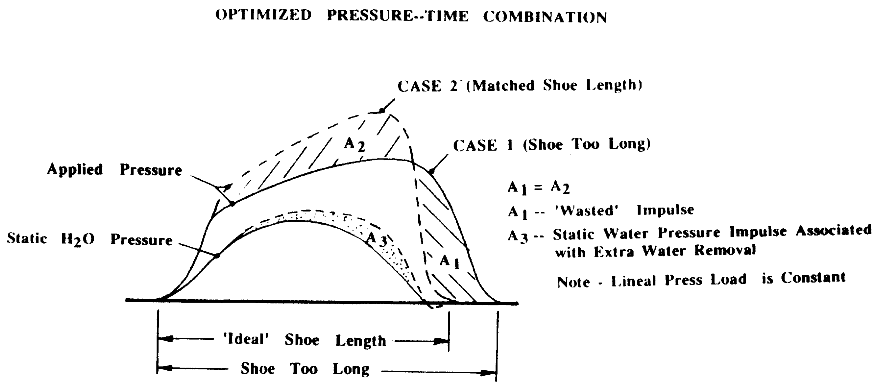


Figure 17. Illustration of Optimum Pressure-Time and 'Effective Impulse'.

The concept applies to any type of press but is easiest to illustrate using the shoe press. *Assuming the press is being operated at maximum lineal press load and machine speed,* Case 1 (Figure 17) depicts a situation where the pressing time (the shoe length) is much longer than necessary for the pressing conditions and some of the total impulse is 'wasted' (area A_1) in terms of removing water. Reducing the shoe length (with the external load remaining constant) would increase the applied pressure and give greater water removal due to the optimum match of this pressure with the sheet dynamic compression response and flow

------

[1]However, the effect on sheet properties is unclear.

resistance (Case 2)[1]. At this match-point all the available impulse is effective at removing water and densifying the sheet.

Press Impulse and Paper Properties. The concepts discussed above refer strictly to water removal. However, paper properties such as sheet density are equally important and here the literature is not as clear. Schiel (30) reported results from commercial paper machines showing that final sheet density was somewhat greater when more press nips were used to achieve the same dryness. Back (90,92) has shown with a platen press simulator that, for constant press impulse, the maximum applied pressure has a significant effect on final sheet density. He also reported some data (94) showing that increased time under pressure had little effect on the density at a given maximum applied pressure. On the other hand, Wicks (82) reports that for the flow-dominated grades like linerboard, sheet density and dryness are directly related--both relate to press impulse--with no significant effect of maximum applied pressure (pulse shape) on final sheet density. However, none of these workers observed how the compressive stress component related to the final sheet density and this might actually be the controlling parameter.

Another reason for the various findings might be related to sheet springback differences. A shoe press can give high impulse for much greater water removal in flow-restricted pressing conditions (primarily because of increased pressing time). However, it is not yet understood how extended time under pressure affects sheet springback, sheet marking, and surface characteristics compared to multiple nips which achieve the same dryness. Clearly, more investigations will be needed as shoe presses are applied to other paper and board grades.

---

[1]Shaded area between the static water pressure curves in Figure 17.

Thermally-Augmented Pressing

Thermally augmented wet pressing ('hot pressing') is defined as pressing of paper at elevated temperatures (but below 100°C). The resulting improved sheet water removal has long been known by papermakers (35). Heating of the sheet between presses, for example, has been practiced on pulp grades for decades. Steam heating in the press section became prevalent beginning in the early 1980's (96), but further extensive use is awaiting implementation of new press roll materials which can safely withstand severe temperature gradients.

It is generally agreed that no new fundamental water removal mechanisms are invoked as the sheet temperature is increased (the basic mechanism is still one of mechanical volume reduction) and that at least part of the dryness improvement is due to the reduced viscosity discussed long ago by Campbell (9). However, the rate of change in viscosity is much lower than the observed change in water removal so it is believed other mechanisms play a role. Back *et al.* (90,94,95,96) have performed a large number of thermally-augmented platen and pilot pressing studies. Their work shows that, while water softens cellulose at all temperatures, its softening effect is increasingly pronounced above 60°C. Back contends that above this temperature the increased fiber softening enhances the water removal considerably beyond that expected from viscosity effects alone and that significant gains in water removal can be made over the elevated temperatures now in use (typically up to about 75°C).

Although water removal is enhanced by elevated temperatures, questions remain concerning effects on sheet properties such as wet tensile strength reduction (91), sheet springback (95) and final paper density, sheet surface condition, and others. For example, Back's (92,93) experimental data suggest that for some paper and board grades, hot pressing may offer an appealing improvement in sheet water removal without increasing the final sheet density. There are other practical and technical questions such as the effect of high temperatures on felt and roll materials, the stability of chemical additives, adhesion to roll surfaces, and the vexing problem of completely eliminating air so that steam can be condensed at temperatures above about 70°C (90). These areas await further investigations.

Pressing and Drying Interactions

There was an intriguing aspect of Szikla and Paulapuro's (69) z-direction density investigations not discussed at length. They found that freeze-drying the freshly pressed sample resulted in almost no density gradient in the final sheet when compared to one that had been evaporatively-dried under restraint. In fact, the outer layers of the freeze-dried sheet were actually less densified than the inner layers no matter which direction the water was pressed[1]. They commented that the densification effect of wet pressing is primarily attributable to the improvement of the fiber bonding conditions.

However, there may be even more to learn. For example, after the press load is released, there is a rapid[2] "springback" of the fiber network to a quasi-equilibrium condition where the network mechanical expansion forces are almost balanced by the surface tension forces. During springback much of the density gradient might be lost, but then partially recovered (or perhaps even enhanced) during the evaporative drying process. The density *gradient* recovery might be partly due to the fiber network having a 'memory' of its condition at the press. Sublimation during the freeze-drying process eliminates the surface tension

---

[1]It was not stated if the sample was freeze-dried under restraint or to what extent the formation of ice crystals might have affected the density distribution.

[2]For example, a high springback occurred during the very short 2 msec expansion (Figure 5) in Burton and Sprague's (73) work.

forces which promote densification and bonding of the fiber network with its original density gradients. If these postulations are true, this means that we probably have never observed a freshly-pressed sheet surface or cross-section accurately enough to directly measure the effect of pressing on the z-direction or surface densities; we have only observed the final dried sheet and inferred how it must have appeared after pressing.

Perhaps even more important, Szikla and Paulapuro's work dramatically demonstrated the possibility of a significant interactive effect between pressing and subsequent evaporative drying--the sheet density condition (and history) arriving at the dryer may have an impact on its density development during drying, not only in the thickness direction but also at very small dimensions in the sheet plane. This interactive effect was suggested recently (83) as the underlying cause of "MD microstriations" observed in the dried paper which correlated strongly with the direction of water removal during pressing. The sheet density and associated moisture distribution leaving the press--*in all three axes and down to very small dimensions*--is believed to be very important to the final properties and more research is needed in this area.

Sheet Surface Densification

There is a wet pressing phenomenon thought to result in a far greater density of the first several fiber layers compared to the sheet interior. This phenomenon has even been observed in sheets normally considered to have high springback. The densified surface is always on the paper side through which most of the water was removed and can easily be seen in SEM surface photomicrographs but not in the cross-sections (e.g., Figure 16). The surface densification phenomenon *may* be the specific reason for the reduced 2-sidedness (67,69) to liquid, oil, or pigment penetration and not the overall z-direction density distribution as suggested earlier (65,66). However, in achieving this reduced 2-sidedness, there is increasing evidence that, under certain conditions, the highly densified surface may lead to topography, porosity, and residual stress problems in the dried paper (83). The exact mechanisms of sheet surface densification are unknown and the possible causes are many, including 'interfacial controlled' pressing, an interfacial deformation phenomenon involving localized load distribution, fiber network 'springback', a sheet dryness gradient, and others. More research is expected in conjunction with the interactive effects mentioned above.

Wet Pressing Studies using Platen and Roll Presses

General. Press simulations have been reasonably successful at predicting sheet dryness for commercial conditions. However, much of this apparent success may be due to the fairly significant changes required of most variables to produce even modest changes in sheet dryness[1]. A vast amount of wet pressing research has utilized platen presses, laboratory roll presses, or pilot roll presses to study dynamic compression or to simulate wet pressing in a commercial nip. Whether evaluating that work or attempting one's own, it is instructive to consider the differences--some obvious and some subtle--between the commercial press, the laboratory roll press, and the platen press.

Time (compression rate) and space (geometric relationships) are not interchangeable between the three situations. Although scaling laws can be used to achieve dynamic similitude (identical pressure-*time* profiles), geometric similitude cannot be achieved amongst the various press types. For example, Figure 18 shows the significantly different vertical stress distributions for various press types, all having the same pressure vs time profile.

------

[1]Relatively large errors in pulse shape and even in press impulse have a small effect on the final dryness for many sheets.

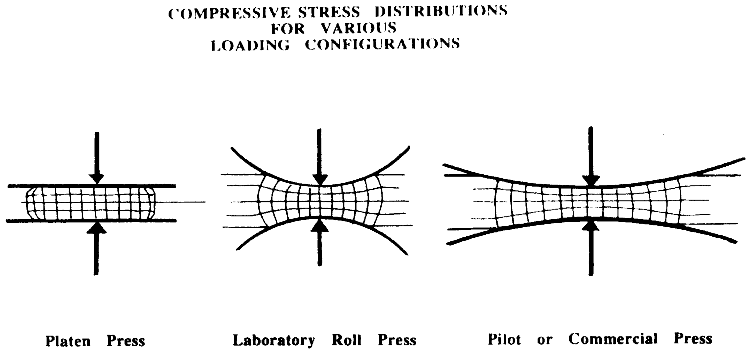


Figure 18. Compressive Stress Distributions for 3 Different Press Loading Surfaces.

Because the nip geometry is not highly sensitive to roll radius[1], geometric similitude between different roll presses probably does not present a major problem if their diameter differences aren't extreme. Therefore, the following section pertains to the fundamental differences between the roll press and platen press.

Characteristics of Platen Presses. Platen presses are convenient to use and easy to instrument compared to a roll press. They have unquestioned value for studying dynamic compression behavior and the relative effects of various parameters on sheet thickness response. However, these deceptively simple devices do present difficult problems, and their value must be carefully considered for studying sheet properties or certain fundamental water removal mechanisms.

------

[1]The difference between two roll press nips in nip width, average nip pressure, and peak pressure is approximately proportional to the square root of their effective roll radius (29) ratio. For example, doubling the press roll size would give only a 40% increase in nip width (or less with soft covers)

The characteristics of platen presses can be summarized as follows:

--A platen press produces a high speed compression event which can be treated as an essentially 1-dimensional compression event, thus simplifying experimental and theoretical considerations;

--Actual sheet dryness cannot be measured during the compression event and some testers do not allow retrieval of the sheet sample for measuring the sheet dryness after the pressing event;

--An accurate and representative measurement of the static water pressure curve is extremely difficult in a platen press;

--The platen press inherently has a varying degree of thickness inaccuracy due to fiber penetration into the water receiver (usually a porous plate or fine wire cloth);

--The sheet and water receiver are in planar contact in a platen press and very little in-plane shear is produced compared to a roll press;

--If a stiff porous plate is used as the water receiver in the platen press, there is a significant difference in the interfacial dynamic conditions compared to a felted rolling nip;

--The compression, expansion, *and* (when relevant) the sheet separation from the water receiver in a platen press is planar. This leads to fundamental differences in water removal, rewetting, and sheet properties;

--Under identical impulse conditions, the platen tester consistently gives a somewhat lower final sheet dryness;

--It is not possible to achieve a mechanically conditioned felt in a platen press.

A more accurate name for an instrumented platen press would be a 'dynamic thickness tester'. These devices do not allow the measurement of actual sheet dryness during the pressing event, although workers have often used the misnomer 'sheet dryness' when reporting their results. To provide more accurate dynamic sheet thickness measurements, an incompressible porous plate is often used in place of the press felt. Compared to a roll press, this gives a large difference in macro-uniformity of pressure application (and lateral water redistribution) as well as in the dynamic response of the interfacial region (e.g., the instantaneous permeability, interfacial volume, and liquid/air/fiber interfaces). While the incompressible porous plate results in a more well defined interface than a felt, there still is an inaccuracy in the thickness measurement resulting from some fiber penetration into the pores of the plate (or the interstices of the wire cloth). This inaccuracy can be of the same order as many estimates of rewetting water film thickness (85) and results in a higher calculated sheet dryness than actually occurs.

There are considerable difficulties in obtaining accurate and representative static water pressure measurements during a high speed pressing event. Although not generally reported in the literature, these problems are well known to most of those who have used platen press testers. Static water pressure is an extremely sensitive indicator of water flow and permeability conditions inside the sheet during pressing. Unfortunately, this measurement is also very sensitive to external conditions. Those who have attempted this measurement undoubtedly experienced times when, early in the pressure pulse, the value of the static water pressure actually far exceeded that of the externally-applied pressure. This 'overshoot' is likely a result of a 'shock wave' propagating through the water and perhaps being reflected several times between the platens. This is produced by the impact loading[1] inherent in the platen press. Several groups also experienced high-frequency pressure oscillations ('ringing') during the pressing event. This is a typical result of mechanical vibrations from the tester which are transmitted into the

------

[1]Unlike a roll press, the platen press creates higher impact loading conditions by uniaxially loading the *entire* sample (often saturated) in an extremely short time.

incompressible water. Vibrations are caused by even slight mechanical misalignments (e.g.,the platens), combined with excess energy from the loading system.[1]

There are several other problems to contend with in measuring static water pressure. A small fluid chamber volume is needed for high response rate of the measuring system but this increases its sensitivity to the vibration problems mentioned earlier. Penetration of paper fiber into the capillary entrance leading to the pressure transducer chamber affects the pressure reading during compression. During the expansion phase, this same penetration, plus the adhesion of the paper to the surrounding platen surface also alters the pressure reading. In the testers used to date, the static water pressure measurement is made within a relatively small area and may not be representative of the entire pressing area, especially if the loading surfaces are not perfectly flat, parallel and stiff, the sheet not reasonably uniform, or if there is radial flow in the sheet. Finally, even the smallest amount of air in the measuring system affects the response rate and the pressure level.

The importance of the platen press separation process has also never been discussed in the literature. Unlike in a roll press, the separation of the paper from the water receiver in the platen press can be greatly affected by their intimate *planar* contact, especially (it is thought) when a nonexpanding porous plate is used in place of the felt. Fiber penetration into the porous plate during the compression (50) creates much larger vacuum forces and greater volume in contact with water during the expansion. Curvilinear separation in a roll press and relative motion between the sheet and expanding felt fibers do not produce the same intimate contact and high vacuum at the time of separation as a platen press. The volume of interfacial water at the time of separation is also thought to be much less for a roll

------

[1]Computer controlled servo-hydraulic loading systems apparently do not suffer from 'ringing' problems (although they are incapable of extremely high speed pressing events).

press. Rewetting is therefore probably much greater for a platen press (discussed later).

In-plane mechanical fluid and shear stress may be significant for a roll press but, in contrast, these are usually assumed to be negligible for the platen press if the water receiver (or the sheet itself[1]) has sufficiently low flow resistance such that no radial flow is produced in the sheet. Interestingly, the assumption of 1-dimensional flow has never been substantiated by measuring the inplane static water pressure profile near the periphery to determine the extent of the 'edge effect'. Despite this assumption, there have been numerous observations of radial crushing and it is possible that some inplane flow occurs long before catastrophic crushing is noticed.

It is well known that the dynamic compression response of a press felt changes rapidly, even after hundreds of compressions. It also changes as a function of time between compressions. In a roll press the felt can be sufficiently mechanically conditioned by passing it through the nip thousands of times immediately before the sheet sample is pressed. This cannot be done with a platen press and makes it impossible to duplicate the pressure-time curve of a roll press (81). Lack of conditioning may also result in rewetting differences due to the long low pressure tail mentioned earlier.

In carefully controlled experiments (81,84), the platen press systematically gave a somewhat lower final sheet dryness than a roll press operated with nearly the same pressure pulse. This could be due to the low shear during compression[2] and/or the planar expansion and separation in a platen press which leads to greater rewetting.

----

[1]'Interfacial Controlled' pressing could cause some radial flow in the sheet.

[2]It has been speculated that simultaneous shear during compression could give a small increase in densification and water removal.

Summary. In summary, properly instrumented platen press testers are useful devices for water removal simulations and studies of dynamic thickness behavior, but they should not be used for studying paper properties or certain water removal mechanisms. In view of the limitations discussed above, perhaps the next generation laboratory press tester for wet pressing research should incorporate curvilinear loading and sheet separation. Today, the most accurate wet pressing studies still require the use of a fully instrumented, reasonably large roll press to obtain both dynamic and geometric similitude, but even this may be inadequate for careful study of paper properties because the interactive effects between pressing, wet straining, and conventional cylinder drying seems extremely difficult to accurately simulate. It is therefore believed that meaningful study of paper properties must, as a minimum, be accompanied by careful evaluations of commercially pressed and dried paper.

Sheet Dryness Calculations by the 'Differencing' Method

Attempts have been made to *calculate* the sheet dryness using a sheet thickness determined from the difference in dynamic compression response with and without the sheet present. Besides obviously demanding highly accurate instrumentation, there are other more fundamental problems with this 'differencing' method, many relating to the ill-defined interfacial region which has dimensions similar to the quantities being "measured". The following attempts to show why this procedure is inherently inaccurate and its further use should be discouraged, no matter how sensitive the press instrumentation is.

Andersson and Gärdh (109) used the 'differencing' method to calculate a surprising 70%D midnip dryness in a roll press operated at commercial speeds. Attributing the low final dryness to rewetting, they understandably concluded that ways must be found to eliminate this large dryness loss. Implying that their figure seemed very unrealistic and that something must have been incorrect, Schiel (100) combined his own experimental data with the earlier data of Heller (31) to estimate it would take press rolls 12km in diameter loaded to 28,000 kN/m to produce 70%D at commercial speeds! Beck (89) perhaps believed that he could overcome Andersson and Gärdh's problems by using much more sensitive instrumentation[1] to accurately measure midnip separation and applied pressure in a roll press. Others have tried to circumvent or minimize the accuracy problems by using platen press testers with flat, incompressible porous plates. This allows a somewhat better definition of the paper/felt interface but some inaccuracy still remains due to fiber penetration into the pores.

To perform sheet thickness calculations for a roll press, one of the first assumptions one must make is that no midnip longitudinal water flow occurs in the paper. Midnip flow has been theoretically and experimentally shown for a press felt (18,19,20,21,23) and, while never substantiated for the paper, is theoretically plausible (for example, Beck's data (59), discussed earlier, implied there was substantial in-plane flow in the sheet for a plain press operating near nip saturation). Another critical assumption involves the location of the point after midnip where either water vapor forms as Carlsson (54) suggested or air begins to enter the expanding paper from the felt and along the interface (97). This point is impossible to determine, and of course nullifies the assumption of paper saturation needed to make the sheet dryness calculation in the expanding nip. Yet another difficulty arises with the differencing technique. When two spring-mass-dashpot systems (paper and felt) connected either in series or parallel undergo a given displacement, the interfacial displacement response can only be deduced if the separate response of each is known first--one cannot

------

[1]The midnip separation instrumentation was accurate to within +-13 microns. This is about +-15% of the midnip sheet thickness he measured and also approaches many estimates of rewetting.

simply be subtracted from the combined response to obtain the other. These fundamental issues seem more than sufficient to invalidate the technique, but there are other serious experimental problems as well.

Norman (7) pointed out that, due to the pressure nonuniformities introduced by the felt, the differencing technique actually yields a calculated sheet thickness value which is *lower* than its true average. This procedure would give an optimistically high calculated sheet dryness and, furthermore, would be affected by the felt UOPA. Another problem is that of paper and felt fibers intermeshing in their shared interfacial region. This also gives a somewhat lower total thickness than the two materials would have produced if pressed separately--an extension of Norman's dilemma to the microscale. As an illustration of this possibility, during calibration of their dynamic compression tester, Ceckler and workers (50) had found evidence of significant fiber penetration even into their flat porous plate (40 micron pore size). They believed that a "small amount of fiber was lost in the plate", causing a 25 micron discrepancy with the mylar calibration gages. This discrepancy by itself is equal to many of the rewetting figures (85) seen in the literature. The same phenomenon surely must be possible in the presence of a felt.

Jaavidaan (88) recently abandoned an attempt at using the differencing technique in the presence of a felt because he could not achieve satisfactory agreement with the dynamic sheet thickness measurements made against a porous plate. Even with his more simple platen press system, Jaavidaan concluded he could find "no other way of measuring the sheet thickness accurately enough" during a dynamic compression event except to use the incompressible porous plate in place of the felt.

With all these problems in mind, it is believed that an accurate dynamic measurement of sheet thickness, either in the presence of a compressible felt or a porous plate, has yet to be achieved. Furthermore, even if this thickness measurement could be made, there is the problem of proving how much of the associated sheet volume increase is due to air, water vapor, or rewetting water. It is therefore still not possible to say with conviction exactly how the sheet dryness varies inside a realistic press nip and then use this 'data' to make definitive conclusions about felt designs, sheet water removal, or rewetting mechanisms.

A Perspective on Rewetting

General. Rewetting water is understood as the water returned to the sheet inside the expanding nip which had once been pressed out during the compression phase. 'Shared water' is that water shared by the felt and paper in the ill-defined interfacial *region* where the fibers and open spaces intermingle. From a theoretical standpoint, it is not clear whether shared water should be included in the definition of rewetting water.

Of all the fascinating aspects of wet pressing, perhaps no other has received greater attention than rewetting--from Wrist's (4) first questions to Jaavidaan *et al.'s* (57) recent work. Ibrahim (85) lists thirty publications on the subject. Most people have accepted that rewetting exists and in fact, laws of physics dictate that some must exist. Estimates of rewetting amounts have ranged from under 10 gsm (32) to over 15 times that amount (86), with most accepting Wahlström's (2) more moderate estimate of up to 35 gsm.

Another Kind of Rewetting? Norman (7) suggests there may be another important kind of rewetting, called 'separation rewetting'. He defines this as either a partitioning and/or a movement of discrete water 'pools' filling interfacial cavities shared by the sheet and felt (author's interpretation). The partitioning occurs at the time of paper and felt separation and the amount partitioned depends on the volume of shared water at the time of separation. This in turn depends mainly on the felt uniformity and perhaps somewhat on its expansion properties.

It is possible that Wrist (4) and others visualized this type of rewetting as part of the 'film splitting mechanism' but they never articulated it as such. Heller and colleagues (97) measured the total area and approximate depth of dyed water in contact with a plastic block loaded against felts having various batt fiber sizes. They found the large diameter fiber resulted in larger 'pools' of water which, if present at the time of separation, presumably had to move or be partitioned in some manner. This seems to support Norman's 'separation rewetting' but they felt that, in the real situation, most of the cavities seen against the plastic plate would be filled with uncompressed, water-enveloped paper fiber. Since they believed this water never actually left the paper, it would be incorrect to classify it as rewetting water. Therefore they chose to characterize those volumes as 'lack of micro-UOPA' rather than rewetting. This illustrates the need for a better definition of the interfacial region.

From a pragmatic standpoint, it probably does not matter to the final sheet dryness whether the water in the interfacial cavities is called rewetting water or lack of micro-UOPA--the end result is still the same and the solution also seems to be the same. That is, methods must be found to provide a more uniform interfacial region, down to paper fiber dimensions, where small uncompressed paper volumes and/or water-filled cavities can be minimized at the time of separation. In this quest, some interesting improvements in sheet properties may also be discovered.

Recent Rewetting Studies. Jaavidaan *et al.* (57) recently modified the University of Maine Dynamic Compression Tester (DCT) to enable *calculations* of rewetting. His data and physical evidence seem to offer compelling proof that rewetting exists in a roll press and that it is substantial. However, there are questions regarding the validity of extrapolating platen press rewetting results to the roll press that should be explored.

First, it was unclear how Jaavidaan dealt with the problem encountered earlier by Ceckler (50) and Carlsson (54) of fibers penetrating into the pores of the porous plate[1]. The amount reported by Ceckler (25 microns) would give lower measured thickness, higher calculated maximum dryness, and thus higher calculated rewetting. The intimate contact caused by fiber penetration would also be expected to have a large effect on the vacuum developed during planar separation of the plate and sheet. In fact, with sufficient fiber conformation and penetration, enough vacuum could momentarily develop (Jaavidaan did not measure the vacuum) to cause sheet rupture during the separation. The intimate planar contact and high momentary vacuum encountered with the wet porous plate very likely gives an unrealistically high 'separation rewetting' that could not occur to this extent in the presence of an expanding press felt undergoing curvilinear separation as in a roll press.

These effects might also offer a better explanation for Jaavidaan's findings regarding the effect of sheet furnish on calculated rewetting (which contradict most of the published literature). More refining would give greater conformation, penetration, and densification of the fiber layers adjacent to the porous plate, thus reducing the number and size of interconnected airflow paths between the porous plate and the sheet. Fewer air pathways would presumably result in much higher vacuum and give the driving force for greater 'separation rewetting'. Jaavidaan's implication[2] of less air permeating laterally from the

------

[1]Jaavidaan's photographs also give independent evidence of fiber penetration. During the separation, many water filaments are seen between the plate and the sheet, each with a paper fiber in them.

[2]A careful reading of his explanation requires the inference that water and air fills the growing 'gap' between the sheet and porous plate and, if the sheet refining played an important role, most of this air must come from the sheet. This could only occur if the air was permeating laterally from the edges of the sheet.

edges of the more highly refined sheet (which then leads to higher vacuum) seems less likely.

After reconciling the potentially significant thickness error from fiber penetration, the remaining calculated rewetting is probably real *for his platen press tester*. This does not mean the results can be extrapolated to a roll press. Nonetheless, the apparent good agreement between the platen and roll press final sheet dryness must be rationalized because if the platen press really gives an inherently higher rewetting due to its planar separation, then equal final dryness would only be coincidental (e.g., UOPA differences just offset by rewetting differences).

Jaavidaan (88) showed the felted platen press to give a somewhat lower net water removal (final dryness) than the porous plate, although this difference was indeed quite small and could be due to the lower UOPA from the felt. The similarity of the final dryness data, coupled with the large calculated rewetting of the porous plate case, seem to imply there is significant rewetting in the platen press *even in the presence of the expanding felt*. It is possible the rewetting for either the felt or the porous plate configuration is due primarily to the planar separation between the sheet and water receiver.

In the case of the roll press comparison, a closer inspection of the apparent good fit of Jaavidaan's DCT data with the earlier roll press data (50,51,88) reveals a large disparity between the two testers in their sensitivity of sheet dryness to impulse (see Figure 19 showing Ceckler *et al.'s* earlier pilot roll press data superimposed over Jaavidaan's new DCT data). The new DCT appeared to remove only about one-third of the water that the roll press did over the same impulse range. This disparity would have been far greater if rewetting from Ceckler *et al.'s* grooved pilot press (110,32) at unrealistically low speeds (7.5 to 23 mpm) is taken into account for the last number of high impulse data points[1]. The surprising difference in press impulse sensitivity seen in this work does not seem consistent if the DCT and pilot roll press are in mechanistic

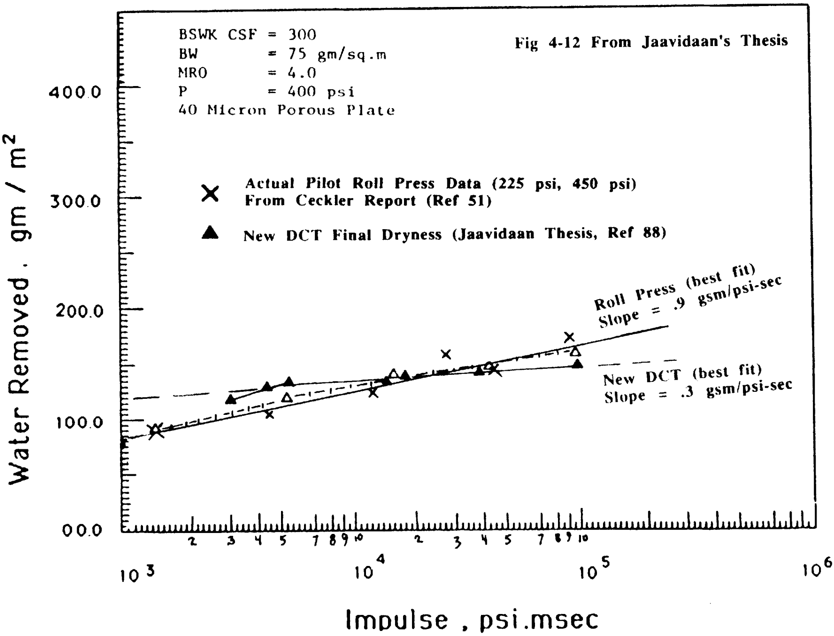


Figure 19. Comparison of Final Sheet Dryness Data.
UOM DCT Tester vs Pilot Roll Press.

agreement. However, it is consistent if a large 'separation rewetting' in the DCT renders its impulse gain much less effective than that of a roll press.

---

[1]In order to obtain the high impulse at the an average applied pressure of 3.2MPa (450psi), the roll press had to be operated at very low speeds to give the long pressing times required (up to 220 msec). Pressing speeds of 23 mpm down to 7 mpm for a grooved press lead to very high rewetting of the sheet from the grooves up through the felt, and cause the final sheet dryness to be unrealistically low for that impulse level. Pressing at the same high impulse, but using higher pressures and speeds, would be expected to increase the sheet dryness significantly over that shown.

Although not done, it would have been interesting to measure the static water pressure during the pulse and at the time of separation, and also to compare the calculated water return during sheet thickness expansion to the calculated rewetting. It is suspected that the sheet volume increase during the expansion would be much less than the calculated rewetting. If so, this would be consistent with the hypothesis of substantial rewetting during planar separation.

The author's views from studying this platen press research can be summarized as follows:

--The work was probably a valid measure of a certain kind of rewetting, but the planar separation between paper and water receiver (felt or porous plate) very likely resulted in an unrealistically high 'separation rewetting' that would not occur in a roll press;

--Compared to this work, the curvilinear separation between paper and felt in a roll press would probably greatly reduce the vacuum (and possibly the amount of water available) for water transfer to occur;

--As in all other rewetting work reported in the literature, sheet dryness was only calculated and not actually measured during the pressure pulse. There also was some undefined error due to paper fiber penetration into the porous plate;

--The amount of rewetting, its mechanisms, or the implications for preventing it in a roll press have not been unequivocally established in this work.

Present View of Rewetting. The following views are based on the author's present understanding of rewetting. Unless it can be irrefutably demonstrated *in a roll press nip* that rewetting is more significant, all evidence supports Busker's (43) apt characterization of rewetting as a 'secondary variable'--that is, it represents less than a 2%D dryness loss for all but the most unusual cases. The large values reported in the literature, while perhaps accurate for their special cases, are unrealistically high for a commercial nip.

It has never been conclusively proven either on a real paper machine or a laboratory roll press that rewetting is significant. It seems unreasonable to extrapolate platen press rewetting data to a rolling nip. Rewetting has never been directly measured--it has only been inferred from indirect calculations (24,55,86,88,89,110,others) or from observations made outside the nip.

Except as a matter of academic interest, rewetting inside the nip is probably discussed and studied out of proportion to its significance in the paper making process. The ultimate sheet dryness out of the press is a much stronger function of the following:

-- The sheet flow resistance

-- The pressing time and/or the maximum applied pressure

-- UOPA by the press felt and vented roll surfaces

-- The rewetting *outside* of the nip (when nip exit conditions are incorrect)

Wet Pressing and the 'Percolation Theory'?

According to Ritala (107), the percolation theory possesses some very useful universal properties but has only recently been applied in our industry (mostly as a first step in understanding the mechanical properties of the inhomogeneous paper fiber network). So far, this theory (well established in theoretical physics) has not been applied to wet pressing. The similarities to other phenomena where the percolation theory has been successfully applied seem sufficient to consider its relevance to wet pressing. The objective here is not to discuss the theory in detail or to judge its applicability, but to help stimulate thinking about the pressing process at the microscopic level and in all dimensions of time and space.

The percolation theory originated as a way of explaining the more or less sudden decrease in filtration rate through a particle bed as smaller particles moved to block capillary passages. The mathematical analysis revealed that this occurred even though the system was far from consolidated and still contained many liquid-filled capillaries having no open connection through the structure to the outside. Percolation theory thus shows that when a component is present in small quantities, its amount is not as important in determining the process as its location. This concept might be relevant to the 'interfacial controlled' pressing or to the fines and filler entrapment problems discussed earlier.

Water removal during the fiber network volume reduction process can be considered as belonging to a class of problems known as 'maze' problems. On the fiber dimension scale, wet pressing presents an exceedingly difficult mass transport problem in that the fiber network forms a 3-dimensional chaotic maze of interconnected pathways which change drastically in size and shape during the consolidation process. This change is brought about by the combined effects of network compressive stress and fluid shear force from water flowing through the maze. These stresses partition themselves throughout the network in a complex, nonuniform manner. The problem is further compounded by some air and water possibly becoming entrapped in the 'dead ends' formed later in the process, thus not finding the flow paths necessary to escape from the system.

Although the integral result of the water transport process--the final sheet dryness--has been well known since the origins of wet pressing, it is obviously impossible to trace the complicated and continuously changing water streamlines in this maze. We only know that the principle of least flow resistance must prevail at each point to determine the water flow pattern in its totality. As pointed out elsewhere, we also have an inadequate understanding of how the maze is deformed during the consolidation process. If correctly applied, however, perhaps theories like 'percolation' can be exploited to achieve a more fundamental understanding of the complex water removal and paper property development processes.

Comments and Suggestions for Future Research.

Research should be a creative interactive process between people and machines. There have been occasions when we could have made more timely use of scientific knowledge, technology and assistance from other areas such as mathematics, physics, mechanics, aerospace, and others. Provided sufficient driving force was available, it seems realistic that a well-directed interdisciplinary team approach, founded on first principles, could yield advances previously not thought possible. For example, such a team could develop a more complete and fundamental mathematical description of the very complex wet pressing and thermomechanical web consolidation[1] processes.

Important in verifying theory, direct observations also serve to pique the imagination and help drive us forward. We should therefore avail ourselves of novel techniques and new instrumentation from other fields to make direct measurements and observations of events inside the press nip and inside the sheet. Pressure sensitive thinfilms, flash x-ray, submillimeter 3-Dimensional x-ray microtomography, scanning tunneling electron microscopy, image analysis, confocal or tandem scanning light microscopy, cryogenic scanning electron microscopy, computational fluid dynamics, and moving interface models are just a few examples of tools and technology that might be imaginatively used in our wet pressing studies.

------

[1]Thermomechanical web consolidation (108) refers to a general class of processes which remove liquid and vapor phase water by simultaneous pressing and drying at temperatures above 100 °C.

Some specific areas of research might include studies of 'separation rewetting'; a more accurate definition of the paper/felt interfacial region; the mechanisms of surface densification; theoretical and experimental studies showing the significance of the compressive and fluid shear stresses; the role of the compressive stress component in determining final sheet density; interactions between pressing and the subsequent processes (drying, coating, calendering, printing,etc.); fiber network springback; and the effect of pressing on residual stresses, paper topography, and 'destructuring'(98).

Summary

Some may consider wet pressing a mature technology with major improvements no longer possible. This paper has hopefully demonstrated the inaccuracy of this characterization. Wet pressing research has traditionally been directed toward ways of achieving high final sheet dryness and we have been reasonably successful in that pursuit. However, we still have inadequate fundamental knowledge about the water removal process itself. While further breakthroughs in final sheet dryness may seem improbable, there is much to learn about how the wet pressing process affects the sheet structure on a microscopic level. We also know too little about how pressing then interacts with subsequent manufacturing processes. Several new methods of investigation are likely to accelerate progress in understanding the fundamentals of water removal and property development. In this research, both water removal and property development are expected to share equal status.

Summarized below are the important points this paper has attempted to address.

--In collecting the background for the 'Historical Perspective' section, it was surprising to learn how long ago many of our present ideas originated and still apply;

--We have made many advances, both qualitative and quantitative, but there is still much fundamental knowledge to learn;

--At times we have been slow to utilize science and technology and to seek assistance from other rapidly advancing fields;

--Understandably, the preponderance of wet pressing research has been devoted to achieving a better understanding of water removal. There have been relatively limited fundamental studies of the effects of wet pressing on paper properties and the interaction of pressing with subsequent processes;

--Vertical flow pressing, 3-dimensional felt structures, uniformity of pressure application, double felting, high impulse pressing, the shoe press, and hot pressing are all viewed as major equipment advances having their basis in wet pressing research over the past 3 decades;

--Optimum combination of pressure and time, extended pressing time, sheet and felt dynamic compression response, fluid pressure measurements, and mathematical modeling are viewed as major research advances;

--There have been relatively limited direct measurements inside the press nip (machine direction applied stress distribution and fluid pressure at the press roll surface, and midnip separation). All these have been at the system boundaries and not *inside* the sheet;

--Sheet dryness and thickness have never been measured inside a roll press nip. Sheet dryness calculations by the 'differencing' method suffer from inherent and unsolvable inaccuracies;

--Platen press testers are excellent devices for studying uniaxial dynamic compression behavior and provide reasonably good simulations of water removal in a commercial nip. They have some fundamental differences with a roll press which make their usefulness for studying sheet properties and rewetting highly questionable;

--'Separation rewetting' deserves further study;

--The importance of fluid shear stress during pressing is not understood;

--Surface densification associated with wet pressing is important for paper properties but is not well understood;

--The interactive effects of pressing and drying on web consolidation is a new field for study. A better understanding is needed of exactly where small-scale x,y, and z-direction density gradients and residual stresses are created;

--Fiber network compression recovery ('springback') deserves more study;

--Wet pressing causes large and small-scale density and bonding variations which affect residual stresses, topography, porosity, 'destructuring', coating, calendering, printing, and optical properties. This area deserves more study as a broader part of the pressing and drying interactions;

--The effect on final sheet density and smoothness of sheet temperature, coupled with pressure pulse shape and length, deserves more study for various paper grades. The role of the compressive stress (mechanical pressure) component in determining final sheet density should be included in this study because it has never been studied;

--The sheet/felt interfacial region has not been adequately characterized.

ACKNOWLEDGEMENTS

This review of wet pressing could not have been done without the kind assistance and support of many, not the least of which was from my wife, Sue (who never dreamed she would be sharing her first 4 months in Sweden with this paper):

Prof. Emeritus Börje Steenberg for suggesting the applicability of the 'percolation theory' to wet pressing, for countless hours of critical discussions, for his invaluable editing and organizational suggestions, and for being such a strict intellectual disciplinarian.

Prof. Bosse Norman for his contributions on technical aspects, for his moral support, and for helping me pick up the pieces every time Steenberg was through.

My colleague **Dr. Terry Conners** edited this manuscript and contributed numerous valuable suggestions on technical points.

I appreciate all the helpful comments, suggestions, and corrections (especially on the historical perspective) made by the following: J. Bergström, B. Wahlström, E. Back, L. Busker, T. Lindström, G. Carlsson, C. Schiel, P. Kolseth, K. Jewett, C. Sprague, H. Paulapuro, B. Lebeau.

Literature Cited[1]

1. Wahlström, P.B., "Our Present Understanding of the Fundamentals of Pressing", *Pulp Pap. Mag. Can.*, Vol.70, T349, 1969.
2. Wahlström, P.B., "New Developments and New Insights In Water Removal By Pressing", EUCEPA Conference Proceedings, London, England, 1979.
3. Wahlström, P.B., "An Overview of Web Consolidation", Pira Int'l. Conf. Proceedings, Brighton, England, May 1986.
4. Wrist, P.E., "The Present State of Our Knowledge of the Fundamentals of Wet Pressing", *Pulp Pap. Mag. Can.*, Vol.65, T-284, July 1964.
5. Rance, H.F (Ed.), *Handbook of Paper Science* , Amsterdam, pp.219-256, 1980.
6. Bergström, J., "Studies on the Mechanism of Wet Pressing", presentation (unpublished) at S.P.C.I. Conference, Stockholm, Sweden, April 1959.
7. Norman, B., "On the Mechanisms of Dewatering in the Twin-Wire and Press Sections", *Nordic Pulp Pap. Res. Jrnl.*, Special Steenberg Issue, p.39, Aug. 1987.
8. Paulapuro, H., "Pressing and Drying--A Revolution Ahead?", EUCEPA Conf. Proceedings, Harrogate, England, June 1988.
9. Campbell, W.B., "The Physics of Water Removal", *Pulp Pap. Can.*, Vol.48, No.3, p.103, Mar. 1947.
10. Bergström, J., *Sv.Pap.*,Vol.62, No.10, p.367, May 1959.
11. Wahlström, B., "A Long Term Study of Water Removal and Moisture Distribution on a Newsprint Machine Press Section--Part I", *Pulp Pap. Can.*, Vol.60, T-379, Aug. 1960.
12. Wahlström, B., "A Long Term...--Part II", *Pulp Pap. Can.*, Vol.60,T-418, Sept.1960.
13. Brauns, O., and Jordansson, L., Can. pat. 624,831, Filed July 15, 1958.
14. Justus, E.J., and Cronin, D., "The Vented-Nip Press", *Tappi* , Vol.47, No.8, p.493, Aug. 1964.
15. Asklöf, C., Larsson K., and Wahlström, B., "Studies of Compressibility and Drainage Resistance of Wet Paper Webs", *Pulp Pap. Can.*, Vol.65, No.8, T-339, Aug. 1964.
16. Asklöf, C., Larsson, K., Linderoth, J., and Wahlström, B., "Flow Conditions in a Felt in a Plain Press Nip", *Pulp Pap. Can.*, Vol.65, No.6, T-246, June 1964.
17. Lyall, J. D., "Observed Crushing in Press Roll Nips", *Tappi*, Vol.47, No.2, p.119, Feb. 1964.
18. Westra, H. A., "A New Contribution to Press Nip Analysis", 1975 Int'l. Water Removal Symposium Proceedings, London, England, Mar. 1975.
19. Roux, J. C., and Vincent, J. P., "Mathematical Model of a Press Section", *Revue Assoc. Technique du l'Industrie Pap.*, Vol.39, No.10, p.543, Dec. 1985.

---

[1]The original list of 300 Wet Pressing references from which these citations were taken is available upon request.

20. Ershov, V. A., "Investigation of the Resistance of Paper Webs to Crushing in the Process of Wet Pressing", Trans. from: *Sb. Tr. VNII Tsellyul.-Bumazhnaya Promyshlennost.*, no. 59, p.113, 1971.
21. Beck, D. A., "Fluid Pressures in a Press Nip", TAPPI Engrg. Conf. Proceedings, Sept. 1983.
22. Hamilton, H.D., and Wrist, P.E., "The S.P.F.I.--Mead Fabric Press: A Novel Approach to Wet Pressing", *Pulp Pap. Can.*, Vol.64, No.5, T-219, May 1963.
23. Nilsson, P., and Larsson, K., "Paper Web Performance in a Press Nip", *Pulp Pap. Can.*, T-438, Dec. 1968.
24. Sweet, J.S., "A Basic Study of Water Removal at the Press", *Pulp Pap. Can.*, Vol.62, No.7, T-367, July 1961.
25. Heller, H.H., MacGregor, M.A., and Bliesner, W.C., "Back to the Basics in Wet Pressing", 1975 Int'l Water Removal Symposium Proceedings, London, England, Mar. 1975.
26. Busker, L.H., "Effects of Extended Nips on Wet Pressing", *Tappi*, Vol.54, No.3, p.373, Mar. 1971.
27. Justus, E.J., and Cronin, D.C., "Development of the Extended Nip Press", *Tappi*, Vol.64, No.12, p.35, Dec. 1981.
28. Asklöf, C., Larsson, K., and Wahlström, B., "Studies of Compressibility and Drainage Resistance of Wet Paper Webs", *Pulp Pap. Can.*, Vol.65, No.8, T-339, Aug. 1964.
29. Schiel, C., "Optimizing the Nip Geometry of Transversal-Flow Presses", *Pulp Pap. Can.*, T-71, Mar. 1969.
30. Schiel, C., "Pressing and Paper Quality", *Tappi*, Vol 56, No.12, p.112, Dec. 1973.
31. Heller, H.H., and Tewksbury, C.G., "What Are the Limits of Paper Dryness Obtainable in a Wet Press?", *Tappi*, Vol.55, No.6, p.893, June 1972.
32. Bliesner,W.C., and MacGregor, M.A., "How Important is Rewetting in Wet Pressing?", *Tappi*, Vol.59, No.6, p.114, June 1976.
33. **Reserved for Rolling Shear Stress Reference.**
34. Baughman, S.E., and Mattila, L.J., "Opening The Draw Between Second and Third Presses", *Tappi*, Vol.62, No.1, p.27, Jan. 1979.
35. Cutshall, K., "Hot Pressing Systems", Conference Proceedings, Pira Int'l Conference--New Technologies in Web Consolidation and Drying, Brighton, England, May 1986.
36. MacGregor, M.A., "Duplication of Pilot Pressing Studies Using a Laboratory Web Former", *Tappi*, Vol.58, No.6, p.116, June 1975.
37. Fekete, E., "Water Removal on a Grooved Second Press--Part II", 1975 Int'l. Water Removal Symposium Proceedings, London, England, Mar. 1975.
38. Smart, F., "Water Removal on a Grooved Second Press--Part I", 1975 Int'l Water Removal Symposium, London, England, Mar. 1975.
39. Fekete, E.Z., 'Stratified Felt' Patent, U.S. Patent 3,928,699, Filed Aug. 9, 1973, Issued Dec. 23, 1975.
40. Oliver, J.F. and Wiseman, N., "Water Removal in Wet Pressing: The Effect of Felt Roughness", *Pulp Pap. Can.*, Vol.77, No.9, T-149, Sept. 1976.
41. Yamamoto, H., "Effect of Uniformity of Pressure Application on the Moisture Content of a Wet Paper Sheet in Pressing", OFE Annual Award 1978, The Hague, Netherlands.

20. Ershov, V. A., "Investigation of the Resistance of Paper Webs to Crushing in the Process of Wet Pressing", Trans. from: *Sb. Tr. VNII Tsellyul.-Bumazhnaya Promyshlennost.*, no. 59, p.113, 1971.
21. Beck, D. A., "Fluid Pressures in a Press Nip", TAPPI Engrg. Conf. Proceedings, Sept. 1983.
22. Hamilton, H.D., and Wrist, P.E., "The S.P.F.I.--Mead Fabric Press: A Novel Approach to Wet Pressing", *Pulp Pap. Can.*, Vol.64, No.5, T-219, May 1963.
23. Nilsson, P., and Larsson, K., "Paper Web Performance in a Press Nip", *Pulp Pap. Can.*, T-438, Dec. 1968.
24. Sweet, J.S., "A Basic Study of Water Removal at the Press", *Pulp Pap. Can.*, Vol.62, No.7, T-367, July 1961.
25. Heller, H.H., MacGregor, M.A., and Bliesner, W.C., "Back to the Basics in Wet Pressing", 1975 Int'l Water Removal Symposium Proceedings, London, England, Mar. 1975.
26. Busker, L.H., "Effects of Extended Nips on Wet Pressing", *Tappi*, Vol.54, No.3, p.373, Mar. 1971.
27. Justus, E.J., and Cronin, D.C., "Development of the Extended Nip Press", *Tappi*, Vol.64, No.12, p.35, Dec. 1981.
28. Asklöf, C., Larsson, K., and Wahlström, B., "Studies of Compressibility and Drainage Resistance of Wet Paper Webs", *Pulp Pap. Can.*, Vol.65, No.8, T-339, Aug. 1964.
29. Schiel, C., "Optimizing the Nip Geometry of Transversal-Flow Presses", *Pulp Pap. Can.*, T-71, Mar. 1969.
30. Schiel, C., "Pressing and Paper Quality", *Tappi*, Vol 56, No.12, p.112, Dec. 1973.
31. Heller, H.H., and Tewksbury, C.G., "What Are the Limits of Paper Dryness Obtainable in a Wet Press?", *Tappi*, Vol.55, No.6, p.893, June 1972.
32. Bliesner,W.C., and MacGregor, M.A., "How Important is Rewetting in Wet Pressing?", *Tappi*, Vol.59, No.6, p.114, June 1976.
34. Baughman, S.E., and Mattila, L.J., "Opening The Draw Between Second and Third Presses", *Tappi*, Vol.62, No.1, p.27, Jan. 1979.
35. Cutshall, K., "Hot Pressing Systems", Conference Proceedings, Pira Int'l Conference--New Technologies in Web Consolidation and Drying, Brighton, England, May 1986.
36. MacGregor, M.A., "Duplication of Pilot Pressing Studies Using a Laboratory Web Former", *Tappi*, Vol.58, No.6, p.116, June 1975.
37. Fekete, E., "Water Removal on a Grooved Second Press--Part II", 1975 Int'l. Water Removal Symposium Proceedings, London, England, Mar. 1975.
38. Smart, F., "Water Removal on a Grooved Second Press--Part I", 1975 Int'l Water Removal Symposium, London, England, Mar. 1975.
39. Fekete, E.Z., 'Stratified Felt' Patent, U.S. Patent 3,928,699, Filed Aug. 9, 1973, Issued Dec. 23, 1975.
40. Oliver, J.F. and Wiseman, N., "Water Removal in Wet Pressing: The Effect of Felt Roughness", *Pulp Pap. Can.*, Vol.77, No.9, T-149, Sept. 1976.
41. Yamamoto, H., "Effect of Uniformity of Pressure Application on the Moisture Content of a Wet Paper Sheet in Pressing", OFE Annual Award 1978, The Hague, Netherlands.
42. MacGregor, M.A., TAPPI Pressing and Drying Seminar Lectures(unpublished).

43. Busker, L.H., and Çronin, D.Ç., "The Relative Importance of Wet Press Variables in Water Removal", Int'l Water Removal Symposium, Vancouver, B.C., Oct. 1982.
44. Beck, D.A., "The Dynamic Properties of Paper Machine Wet Felts in a Press Nip", TAPPI Engineering Conf. Proceedings, Sept. 1980.
45. Ballard, J., "Press Felt Characterization", TAPPI Engineering Conf. Proceedings, Sept. 1986.
46. Sze, D.H., "Measuring Wet Press Felt Pressure Uniformity and its Effects on Sheet Solids", *Tappi Jrnl.*,Vol.69, No.4, p.120, April 1986.
47. Carlsson, G., Lindström, T., and Söremark, C., "Expression of Water From Cellulosic Fibres Under Compressive Loading", BPBIF Transactions from the 6th Fundamental Research Symposium--Fiber-Water Interactions (2 vols), Oxford, England, Sept. 1977.
48. Stone, J.E., and Scallan, A.M., see refs 1-6 in Carlsson *et al.*(47).
49. Chang, N.L., "Dynamic Compression of Handsheets", TAPPI Engineering Conf. Proceedings, Sept. 1978.
50. Ceckler, W.,and Thompson, E., The University of Maine at Orono Wet Pressing Project--Final Report", DOE/CS/40064-3(DE83009342), Aug 24, 1982.
51. Ceckler, W., Thompson, E., and Jewett, K., "Wet Pressing Behavior of Newsprint and Linerboard--Final Report(Phase II)", DOE/CS/40064-4, May 1984.
52. Ceckler, W., "Progress Report--DOE Wet Pressing Project (Oct '79-Oct.'80)", COO-40064-1, Nov. 1980.
53. Thorne, J.T., "The Effect of Capillary Rewet on Wet Pressing Operations", Master's Thesis, Univ. of Maine at Orono, May 1981.
54. Carlsson, G., "Some Fundamental Aspects of the Wet Pressing of Paper", PhD Thesis, The Royal Institute of Technology--Dept. of Paper Tech., Stockholm, Sweden, Aug. 1983.
55. Carlsson, G., and Lindström, T., "An Apparatus for Dynamic Compression Studies of Wet Paper Sheets", BPBIF Tansaction of the Fundamental Research Symposium--The Role of Fundamental Research in Paper Making(2vols), Cambridge, Sept. 1981.
56. Carlsson, G., Lindström, T., and Norman, B., "Some Basic Aspects on Wet Pressing of Paper", *JPPS*, Vol.9, No.4, TR-101, Sept. 1983.
57. Jaavidaan, Y., Ceckler, W., and Thompson, E., "Rewetting in the Expansion Side of Press Nips", *Tappi Jrnl.*, Vol.71, No.3, p.151, March 1988.
58. Egelhof, D., "Possibilities to Tailor Paper Quality by the Forming System and Press Configuration", *Das Papier*, Vol.34(, No.10A9, p.143, Nov. 1980.
59. Beck, D., "Re-Examining Wet Pressing Fundamentals Inside the Nip Using Dynamic Measurement", Tappi Engineering Conf.Proceedings, Sept.1986.
60. Bliesner, W., "Sheet Water Removal in a Press: The Role of the Wet Felt Properties", *Pulp & Paper*, Vol.52, No.11, p.76, Oct. 1978.
61. Busker, L., and Gordon, A., "A Performance Comparison of Plain and Various Transverse Flow Presses", *Tappi*, Vol.64, No.2, p.103, Feb. 1981.
62. Royo, M., "Effect of Felt Equilibrium Moisture on Sheet Dryness", TAPPI Committee Assignment, Sept. 1982.
63. Eriksson, S., and Thunberg, M., "Permeability Measurements in the Plane of the Sheet", Graduate Examination--Dept of Pap Tech., Royal Institute of Technology, Stockholm, 1981(in Swedish).

64. Schiel, C., "Influence of the Wire and Press Sections on the Two-Sidedness of Graphic Papers", *Das Papier*,Vol.26, No.5, p.223, May 1972.
65. MacGregor, M.A., "A Description of Sheet Stratification Caused by Wet Pressing", *Tappi*, Vol.66, No.6, p.53, June 1983
66. MacGregor, M.A., "Practical Effects of Sheet Stratification Caused by Wet Pressing", *Tappi*, Vol.66, No.7, p.65, July 1983.
67. Wicks, L., "The Influence of Pressing on Sheet Two-Sidedness",*Tappi Jrnl.*, Vol.65, No.9, p.73, Sept. 1982.
68. Szikla, Z., and Paulapuro, H., "Z-Directional Distribution of Fines and Filler Material in the Paper Web Under Wet Pressing Conditions", *Paperi ja Puu,* Vol.68, No.9, p.654, Sept. 1986.
69. Szikla, Z., and Paulapuro, H., "Changes in Z-Direction Density Distribution of Paper in Wet Pressing", *JPPS*, Vol. 15, No. 1, J11, Jan. 1989.
70. Brooks, J.W., "Migration of Fines in a Thick Fiber Mat Under Dynamic Compression", Inst. of Pap. Chem. Report, A-291 Independent Study, May 1982.
71. Busker, L.H., "Effects of Wet Pressing on Paper Quality", *Southern Pulp Pap.*, Vol.49, Nos.2 & 3, p.23 and 34, Feb., Mar. 1986.
72. Andersson, H., "Technique for Determining Density Distribution in the Thickness Direction by Automatic Image Analysis", SCAN Forsk-rapport nr 392., 1983.
73. Burton, S., and Sprague, C., "The Instantaneous Measurement of Density Profile Development During Web Consolidation", *JPPS*, Vol.13, No.5, J145, Sept. 1987.
74. MacGregor, M.A., "Paper Defects Caused by Fluid Shear Force During Pressing", TAPPI Eng.Conf. Proceedings, Sept. 1984.
75. Jewett, K., "Application of a Model for Two-Phase flow Through a Compressible Porous Media to the Wet Pressing of Paper", PhD Thesis, Univ. of Maine at Orono , Sept. 1984.
76. Jantunen, J., "Visco-Elastic Properties of Wet Webs under Dynamic Conditions", BPBIF Transactions of the Fund. Res. Symp.--Papermaking Raw Materials, Oxford, England, Vol 1, p.133, Sept. 1985.
77. MacGregor, M.A., "Pressure Profiles in a Press Nip: The Role of the Wet Felt", *Tappi*, Vol.60, No.7, p.86, July 1977.
78. MacGregor, M., "What Happens During Shell and Groove Marking", *Tappi Jrnl.*, Vol.68, No.9, p.84, Sept. 1985.
79. Redfern, A., and Gavelin G., "The Causes of Shadowmarking in Paper", *Pap. Tech.*, Vol 3, No.5, p.463, Oct. 1962.
80. Ingmanson, W.L., and Andrews, B.D., "Internal Pressure Distributions in Compressible Mats Under Fluid Stress", *Tappi*, Vol.42, No.10, p.840, Oct. 1969.
81. Chang, N., and Beck, D., "Comparison of a Wahren-Zotterman Press Simulator and a Pilot Press Nip", *JPPS*, Vol. 12, No. 2, J39, Mar. 1986.
82. Wicks, L., "Continued Development and Experience with the Extended Nip Press", *Tappi Jrnl*, Vol.66, No.4, p.61, April 1983.
83. MacGregor, M.A., and Conners, T.E., "MD Microstriations in Paper: A Two Sided Shrinkage Phenomenon?", *Tappi Jrnl.*, Vol.72, No.4, April 1989.
84. MacGregor, M.A., unpublished internal work.

85. Ibrahim, A., "Survey: Understanding Rewetting Phenomenon in the Pressing Operation", *Pulp Pap. Can.*, Vol.82, No.2, T-46, Feb. 1981.
86. Wheeldon, B., "Practical Developments in Pressing", 1975 Int'l. Water Removal Symposium Proceedings, London, England, Mar. 1975.
87. Wahlström, B., "Opportunities in Pressing--Part II", *Tappi*, Vol.64, No.2, p.57, Feb. 1981.
88. Jaavidaan, Y., "Experimental and Theoretical Study of two-Phase Flow Through Compressible Porous Media With Application to Sheet Rewetting in Wet Pressing of Paper", PhD. Thesis, University of Maine at Orono, May 1987.
89. Beck, D., "Re-examining Wet Pressing Fundamentals: a Look Inside the Nip Using Dynamic Measurement", *Tappi Jrnl*, Vol.70, No.4, p.129, April 1987.
90. Back, E., "Steam Boxes in Press Sections--Possibilities and Limitations", *Appita*, Vol.41, No.3, p.217, May 1988.
91. Andersson, L., and Back, E., "The Effect of Temperature on the Initial Wet Strength Between 30 and 50 Per Cent Dryness", STFI-meddelande series B No. 620, May 1983 (in Swedish).
92. Back, E., "Using the Wet Press to Optimise Paper Properties", *Pap. Tech. Ind.*, Vol.28, No.3, p.454, 1987.
93. Back, E., "Press Drying Compared to other Means of Densifying Paper", *Tappi Jrnl.*, Vol.68, No.3, p.93, Mar. 1985.
94. Back, E., and Ekblad, M.,"The Effect of Wet Web Temperature in Press Nips on Paper Properties", STFI-meddelande series D, No. 223, Nov. 1984 (in Swedish).
95. Back , E., and Norberg, K., "Effect of Temperature on the Compressibility of Wet Pulp Pads", BPBIF Transactions of the Fund. Res. Symp, Cambridge--Consolidation of the Paper Web, England, Sept. 1965.
96. Back, E., "Improvements in Dewatering at Increased Pressing Temperatures--a Press Simulator Evaluation", *Tappi*, Vol.65, No.7, p.75, July 1982.
97. Heller, H., and Bliesner,W., "A Photographic Study of Wet Pressing Phenomena", TAPPI Engrg. Conf. Proceedings, Sept. 1977.
98. LePoutre, P., Bichard, W., and Skowronski, J.,"Effect of Pretreatment of LWC Basestock on Coated Paper Properties", *Tappi Jrnl.*, Vol.69, No.12, p.66, Dec. 1986.
99. Schiel, C., "Optimizing Pressing Conditions", *Das Papier*, No.9, p.548, Sept. 1969.
100. Schiel, C., "Presses, Felts, Paper Quality", *Das Papier*, Vol 26, No.4, p.137, April 1975.
102. Paulapuro, H., "Wet Pressing--History and Future Trends", CPPA Annual Tech. Mtg. Proceedings, Jan. 1989.
103. Jewett, K.B., "A Two-Phase Flow Model of a Transversal Flow Press Nip", M.S. Thesis, University of Maine at Orono, May 1980.
104. Reiner, M., *Physics Today*, 17:62 (1964).
105. Jewett, K., Ceckler, W., and Busker, L., A.I.Ch.E Symposium Series, Vol.76, p.59, 1980.

106. Ceckler, W., Thompson, E., Ellis, E., Jewett, K., Hoering, J., and Thorne, J., "The University of Maine Wet Pressing Project and the Application of the Results to Optimization of Press Performance", TAPPI Engrg. Conf. Proceedings, Sept. 1982.

107. Ritala, R.,"Comment on Percolation Theory of Fibrous Networks", *Tappi Jrnl*, Vol.72, No. 2, p.179, Feb. 1989.

108. Sprague, C., "An Integrated View of Web Consolidation Processes", BPBIF Transactions of the Fund. Res. Symp--The Fundamentals of Papermaking, Cambridge, England, Sept. 1989

109. Andersson, N., and Gärdh, H., "The Compression and Recovery of a Paper Web in a Felted Press", *Sv. Pap.*, Vol.73, No.13/14, p.425, July 1970.

110. Busker, L.H., "Wet-Press Water Removal Over a Wide Parameter Range", *Pap. Tech. and Ind.*, Vol.21, No.3, p.91, April 1980.

Transcription of Discussion

SOME THOUGHTS ABOUT WET PRESSING IN 1989

Preface from address at the
Fundamental Research Symposium
Cambridge, England
Sept. 20, 1989

by

Michael A. MacGregor[1]
Visiting Research Professor
The Royal Institute of Technology
Stockholm, Sweden

The following is an excerpt from the author's symposium address and is presented here because it contains several additional ideas which developed after the review paper was published.

the editors

Thank you Mr. Chairman, ladies and gentlemen. It certainly is a pleasure for me to be at this important gathering today. Before I begin my formal talk, I would like to explain to you how I today visualize wet pressing.

[1]Manager Science and Technology, Voith, Inc., Appleton, WI

WET PRESSING RESEARCH IN 1989— AN HISTORIC PERSPECTIVE, ANALYSIS AND COMMENTARY

Prof. M. A. MacGregor

Several additional ideas were presented in MacGregor's verbal presentation which were not present in his original paper. At his suggestion they are reproduced here. Ed.

Introduction

Wet pressing can be viewed from several perspectives.

In the realm of producing saleable paper, we worry mostly about things like nuts and bolts, smiles and frowns, tilts and crowns.

In this realm, a per cent in press solids one way or the other doesn't matter as much (for example) as having it uniform across and along the paper machine.

Today, I would like to take you into another realm where some fascinating action takes place--a microscopic world where the water removal occurs and where the paper qualities are created.

Mechanical Effects on the Paper.

In a roll press, the energy which collapses the fiber network and expells water originates from the driven press roll--the **only** place where energy is put into the system. Even if both rolls are driven, there is always some transfer of force through the sheet in the form of **mechanical shear**.

The wet sheet has almost no ability to transfer shear unless it has first been highly compressed. Thus, in a roll press, the press load not only drives out water but it allows the paper to resist shear forces.

In contrast, the energy transferred to the sheet in a platen press tester comes from the volume work of moving a piston directly against the fibers and water. A platen press therefore produces virtually **no mechanical shear** on the paper.

Many laboratory studies of the wet pressing process have been carried out on platen presses. Because of the fundamentally different means of applying and transferring the loads, the results cannot be indiscriminately extrapolated to the roll press nip, especially where paper properties are concerned.

The combined effects on the paper of compression, shear, and stretching by a roll press are well known to papermakers but not necessarily understood by either them or by those of us who do the research.

And so, the <u>1st major point</u> I want to make is that, in addition to its traditional role of removing water, a roll press has some very important mechanical effects on paper structure at the microscopic level

<u>Mechanics of Fiber Networks.</u>

My next major point is, **that in wet pressing, not only must we deal with a system containing water, we must deal with the complex mechanics of interconnected, discrete elements which form the fiber network.**

Some portion of the energy transfered thru the rotating press rolls which is not used for expelling water will be used to compress the fiber network. However, this compression behavior cannot be dealt with by classical elasticity models.

The paper fibers are distributed in various sizes, shapes, and orientations, forming a particulate body where not all parts are load bearing.

Thus, the assumption of uniform stress distribution is quite incorrect when viewed at the scale of fiber dimensions.

The press load is in fact partitioned through the network in a complex and unknown fashion. So even the concept of pressure--i.e., load over an area--becomes an abstraction which poorly approximates reality.

An important part of the fiber network mechanics arises from the viscoelastic behaviour of the water-swollen fibers. The extent of this contribution has not been appreciated until relatively recently, and no mathematical models are yet adequately treating this.

Water Removal.

As far as flow of free water out of the fiber network is concerned, life would be much simpler if we could treat it as a continuous flow process through a simple filter.

In fact, water removal by wet pressing is **not** a continuous flow process as many have imagined--it is a **liquid displacement process** which begins as soon as the liquid continuum is established. Interestingly, this is not necessarily at saturation conditions.

What makes this displacement process so complicated (and at the same time fascinating) is that it also happens to occur through a network of fibers which forms a 3-dimensional, rapidly-collapsing, interconnected maze.

In roll pressing, the **local** water movement in the sheet is not straight downwards, but takes whatever convenient path it finds--**or creates for itself**--at any instant in the collapsing network.

It is therefore conceivable that local water movement can even occur **upwards** in places, that it can occur **against** the incoming fiber network, and that (under certain conditions) some can even be **forced through** the middle of the nip **inside the sheet**.

It is also conceivable that there are chambers of entrapped air and water which cannot be displaced out of the fiber network.

When water moves substantially faster than the fiber, the fiber surfaces experience a **fluid shear stress** which can be so strong that the network is densified very nonuniformly, that particles are transported from one place to another, or that the paper structure is even rearranged.

I believe it is inaccurate to assume that a continuous water pressure gradient exists from the top surface of the paper down to the felt during wet pressing.

It is probably far closer to the truth that the major pressure drop inside the sheet occurs **mainly across the collapsed fiber layers next to the felt** and **not through the entire network** as so many of us have previously maintained.

Even in cases where water is turned and forced against the incoming fiber network--traveling along the sheet plane until it can escape the system--there is probably very little z-direction pressure drop.

Even though we have known for decades that wet pressing causes sheet 2-sidedness, I believe we still cannot accurately predict the static water pressure and resulting density distributions through the sheet during and after pressing.

And so, my final major point is that we still have a certainly incomplete--perhaps even a mistaken--view of exactly what happens to the water and the fiber inside the sheet during wet pressing.

Wrapup.

My paper will tell a reader that we really have only begun to study water removal at its more fundamental level and that we have not delved far enough into the mechanisms of property development associated with wet pressing.

Actually, I think this is a very exciting situation in which to find ourselves because it means we still have many interesting and satisfying things left to accomplish, even in an area which some had characterized as a 'mature technology'.

J.R. Parker, BTS

At the ingoing side of the nip, because of the high proportion of water in the stock near the surface of the smooth roll, you have said that the major part of the nip pressure will be carried by the stock as a hydraulic pressure rather than as a load on the fibres. I think this implies that the shear stress that can be sustained by static friction between the fibres and roll face will be small and at times insufficient to prevent slip. This would account for the disruption of the surface of the sheet, if I have understood you correctly.

Prof. M.A. MacGregor

I feel that in the case you are referring to, there is a lot more freedom for the fibres to move around. All the fluid shear defects that I have seen have firstly been of the in plane type, and secondly, they are more prominent at the smooth roll surface.

J. C. Roux, Ecole Francais de Papetrie, Grenoble

Prof. MacGregor, I would like to ask you a question about fluid shear stresses. I have calculated in a mathematical model of wet pressing, that you have mentioned in your text, the relative velocity of water to the solid matrix. I have found very low velocities of the order of some centimetres per second or so similar to those given previously by De Crosta and Plaisted with experiments carried out using the constant listed. So how can we explain the fluid shear resistance in wet pressing, if relative velocities are so small?

Prof. M.A. MacGregor

As I said in my talk (but not in my paper) I believe that velocities are very low in most of the sheet, except in the collapsed network. There is another interesting case I have been thinking of: when the fibre network has collapsed at the exiting surface water can be turned upstream. (Incidentally I do not think your model takes this into account.) When the water is turned upstream with respect to the fibre, there can be a very large relative velocity with respect to the fibres even though the pressure drop across the sheet in the vertical direction may be small. However the pressure drop and relative velocity can be quite high in the sheet plane for some distance until that water can escape the system up stream. I may have been incorrect in saying that no-one had tried to calculate these velocities, because you presumably have. I am just saying we have to consider more accurate determinations of the stress and strain distributions in a rolling nip. In other words, velocities under some conditions can be a lot higher than you calculated, but in another part of the sheet, they are very low. I think that these are the reasons why we do not see the kind of vertical density gradients which I talked about in my 1983 paper.

Dr. D. Wahren Stora Technology Prepared Contribution

Rewetting Inside the Wet Press Nip

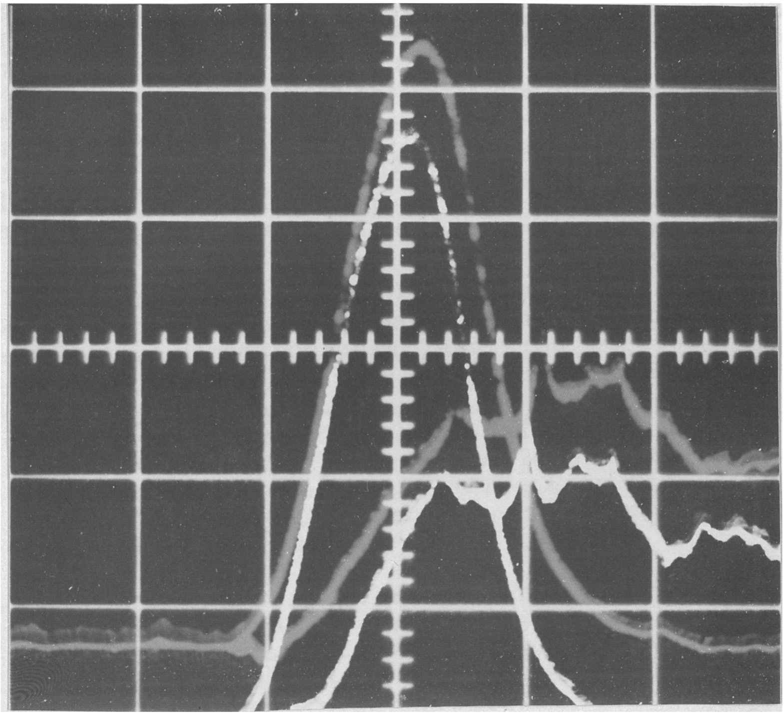
The anvil in a Wahren-Zotterman "Hammer and anvil" type press simulator was constructed out of two 45° glass prisms pressed together to form a cube onto which the wet paper to be pressed was placed. The underside of the paper could thus be illuminated and observed. Its reflectance could be measured by means of a photomultiplier and lens arrangement.

The press force transducer was fastened on the underside of the falling hammer and the press felt directly on the underside of the force transducer. The press felt was died black permanently.

Sheets were formed from highly bleached, lightly beaten(25°SR) softwood kraft fibres suspended in water which had been died black with a dye which had very little affinity to the fibres. Thus when the sheet was viewed through the glass anvil, virtually all the light reflected from the sample could be seen to be reflected off the fibres, and the reflectance increased strongly when the water was pressed out of the sample.

When making an experiment the wet sheet was couched onto the prism and inspected through the lens arrangement to ascertain that no air was trapped. The sheet was then statically pressed to the desired initial dryness, inspected again, and the experiment performed.

The diagram shows recordings from two measurements made on two separately processed 100g/m^2 sheets having an initial dryness of 19$\pm$0.5% and a final dryness of 35$\pm$1%. The two sets of curves were displaced vertically relatively to one another. The horizontal timescale is 1 msec/cm. The smooth bell-shaped curve is the press force and the somewhat jagged curve is the sheet reflectance, i.e. the indicator of the sheet dryness.



It is seen that the sheet dryness reaches a maximum a short time after the press force does. This agrees with the concept of a somewhat "flow-controlled" pressing case. The dryness then falls off to its final value as the press force decreases further. The hammer finally bounces back so that the felt separates from the sheet.

Although the diagram proves that considerable rewetting occurs inside a press nip, the method has several shortcomings. The dryness scale is difficult to calibrate and, certainly, need not be linear. Because of air intrusion before pressing, the method is not suitable for sheets having an initial dryness appreciably above 20%. It is possible that the irregular shape of the reflectance curve was caused to some extent by cavitation. An idea to use the reflectance of trapped air bubbles in an otherwise black system as an indicator of local hydrostatic pressure was not properly tested.

COMMENTS ON WAHREN'S REWETTING EXPERIMENT

by
Michael A. MacGregor[1]
Visiting Research Professor
The Royal Institute of Technology
Stockholm, Sweden

At the Fundamental Research Symposium, Dr. Wahren presented the novel approach he used to support his feeling that "considerable rewetting occurs *inside a press nip*" (emphasis mine). His technique utilized a modified platen press to measure the reflectance of light from the interfacial region formed by the top side of the sheet against the solid pressing surface. Although Wahren stated this reflectance "is a measure of sheet dryness" during the press pulse, I think he actually meant that it was an *indicator*.

While I believe that Wahren's intriguing experiment creates interfacial conditions which are very different than exist in a commercial roll press nip, I also feel his results provide further evidence for the significant 'separation rewetting' which I have postulated occurs in a platen press. I discussed this belief at some length on pp. 50-55 and pp. 58-64 of my review paper in an attempt to explain Jaavidaan's surprisingly high rewetting results. In that discussion, I stated that Jaavidaan probably measured the rewetting which occured in *his* platen press, but felt that these numbers were unrealistically high when compared to a commercial roll press nip.

I feel the same reasoning applies for Wahren's work. I think Wahren's results must be showing the combined effect of reduced fiber contact and the sudden water and air movement which occurs at the time of planar separation between the felt and the sheet.

---

[1]Manager of Science and Technology, Voith, Inc., Appleton, WI

Using the compression half of Wahren's pressure pulse as a guide for estimating the end of the pressure pulse (see his oscilloscope trace reproduced elsewhere in this volume), I interpretate the very steep drop in reflectance to indicate the separation process. This separation occurs in the last **.4 to .6 msec** of the press pulse--a very short time indeed. Up to the actual separation, I believe (just as Carlsson's(54) work suggested) that very little bulk rewetting occurs in either the platen press tester or the roll press[1]. Indeed, Wahren's data also suggest the same thing to me--his reflectance measurement actually *increases* slightly after midnip until the point I have called 'separation'.

Therefore, my interpretation of Wahren's data is that, instead of proving that significant rewetting exists in a commercial press, it supports the idea that a platen press is not representative of a commercial roll press nip when it comes to rewetting.

I did not go into this detail in my paper and I am not ready to offer yet another theory of rewetting mechanisms, but it is my view that (compared to a roll press) air cannot as easily penetrate the saturated interfacial region since this is more easily resupplied with water and less easily with air in a platen press[2]. I visualize that air intrusion plays a crucial role in disrupting the liquid continuum and

---

[1]Even for unrefined sheets, Carlsson (54) measured only about 1 % sheet expansion from the maximum pressure (midnip) down to a very low pressure (.04 MPa) and *prior to separation*. Nobody has ever reported measuring the complete expansion history from minimum thickness, through separation, to well outside of the nip. It is conceiveable that most of the expansion, even for sheets with so-called high springback, might occur at separation or even outside of the nip. Both Burton's data (73) and Burn's recent data (1989 TAPPI Engrg. Conf. Proceedings) suggest this distinct possibility. Thus, it is not difficult to imagine that the increased volume in the expanded sheet is filled mostly with air rather than rewetting water. In a roll press, I propose that this air enters *inside* the nip and penetrates the interfacial region.

[2]Our photographic evidence indicates (97) that air easily penetrated well back inside the nip along the interfacial region formed by the plexiglass roll and the expanding felt. The penetration distance required to break the liquid continuum prior to the actual separation is substantially less for a roll press than a platen press. In Jaavidaan's case, where he used an incompressible porous plate instead of a felt, there may have been almost no air intrusion until the time of separation.

allowing water to be drawn away from the interfacial region *prior to the actual separation.*

It is also possible that the strong momentary vacuum which I think develops in the interfacial region of the platen press[1] opposes forces from the expanding felt which would otherwise tend to deplete the interfacial region of rewetting water[2].

In any case, as Jaavidaan's photos and the figure below suggest, the large amount of interfacial water remaining at the end of the platen press pressure pulse is then probably partitioned by a formation and fracture of discrete water filaments.

I believe the roll press cannot develop as high a vacuum as a platen press, nor does it allow large amounts of water to be retained in the interfacial region. I think the basic reason is because the line contact of a roll press allows large air intrusion to occur prior to separation.

---

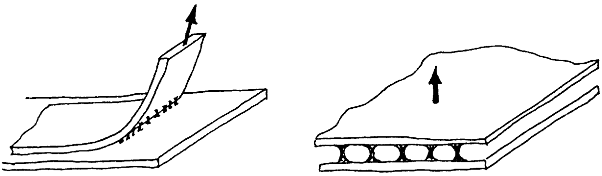
[1]As evidence of this, it is known that sheet samples are sometimes ruptured during separation when a porous metal plate is used in place of the expanding felt.

[2]Because of its annecdotal nature we have not published the following observation, but it may be worth noting in the present context: In our small grooved press (150 mm dia.), operating with a *damp* felt at fairly high speeds (380 m/min) for that diameter (36), we consistently observed a small dryness *increase* (ax. .5%) as the felt moisture ratio was raised to a certain level (beyond which further dryness increase ceased). We felt at the time that the extra water could have helped establish a liquid continuum between the grooves and the felt in the rapidly diverging nip, slightly increasing the vacuum created by the expanding felt and somehow affecting the interfacial region. I now think it possible that the vacuum created in the felt might have augmented the interfacial air intrusion. Incidentally, if these ideas are correct, a vacuum-augmented platen press tester (especially one with a porous plate) should show a significant improved final sheet dryness due to reduced separation rewetting, but it would be predicted that vacuum-augmentation in a roll press should not improve the final sheet dryness significantly.

In addition to the speculative and annecdotal nature of the above observations and discussions, it should be noted that the laboratory press had a divergence rate 2-3 times higher than a commercial press and therefore would be expected to produce a higher vacuum. Consequently, it may not be possible to observe this same effect on a commercial papermachine.

'Separation' Rewetting

Curvilinear Separation — **Planar Separation**



High air intrusion
Low vacuum and adhesion
Low rewetting

Low air intrusion
High vacuum and adhesion
High rewetting

To reiterate my present beliefs about rewetting: I believe that *some* rewetting must exist in a commercial roll press, but that it is very small for most pressing conditions of interest. Further, because of what I think are significantly different interfacial conditions, I believe that it is imprudent to exptrapolate platen press rewetting data to a commercial press nip.

Having said all this, I must conclude by emphasizing that my opinions (like all others before me), while based on many experiments and observations from *outside* the real press nip, nonetheless *remain unproven*. I also firmly believe that we should not abandon our efforts at trying to understand rewetting, and I would be more than happy to eventually be shown the truth--even if it differs from my version of it.

B. Wahlstrom (Written Contribution)

I appreciate the opportunity to comment in writing on this paper as I was unable to do so at the Conference.

I like to congratulate Mike for an interesting and thought provoking paper putting special emphasis on the effect of pressing on paper properties and the interaction between pressing and drying, and raising the question of the effect of mechanical and fluid shear in the plans of the paper on water removal and paper properties.

My comments are restricted to a few areas that I feel are of special importance to our understanding of pressing, where I might disagree with the author or feel that my comments will add understanding.

A theory to be valid must be able to explain all known, well proven facts. New information must always be viewed against what is already known. While direct observations of phenomena is preferable and adds to our understanding we cannot abstain from learning through the observation of the effects of events and use that to further understand what is happening in the context of known science. Nobody has seen electrons or subatomic particles, but we know their characteristics through the way they behave. We have to apply the same principles in studying pressing.

WATER IN THE FIBRE WALL

I would have liked to see you deal with the effect of water in the fibre wall on the water removal process as well as its effect on paper properties. As you correctly state Carlsson, G et al were the first to show experimentally that water is pressed out of the fibre wall during pressing. However, already in 1976 Wahlstrom presented a paper at the Tappi Papermakers Conference, pre-printed, that dealt with this aspect in some depth.

Flow out of the fibre wall limits the compaction of the fibrous structure and makes it a "flow controlled process". That the pure structural compression resistance is of minor importance below about 45% dry was already stated in 1968(1) and clearly documented by Szikla et al in this conference. Szikla also clearly showed the large compression resistance caused by flow out of the fibre wall by compressing unsaturated sheets at high rates.

Because flow out of the fibre wall controls dryness in pressure controlled pressing and the density gradients in the densified layer at the exit surface it is also mostly controlling in flow controlled pressing. Thus it also controls the wet density distribution in the sheet. A better understanding of this phenomena is thus a key in pressing research. It is the missing link in all mathematical modelling of pressing.

UNIFORMITY OF PRESSURE APPLICATION OR UOPA

This concept was coined in 1968(1) to account for the effect of felts on the MR intercept in the Sweet plots based on work on the KMW pilot machine. Another important reference is K F Hansson "The Periformer Tissue Machine", Paper Technology, June 1972(Presented March 1972), which showed the enormous influence of felt structure on the dryness of light weight sheets. The use of Sweet plots made it possible to distinguish between UOPA effects and interface effects, rewetting. The ability to separate UOPA and rewetting is of great value for pressing research and especially helpful in felt development work.

The Sweet plots have been discarded and discredited and the explanation of them called conjecture based on Heller et al(31). However Heller(31) cannot be used as the tests were run at very low speeds using grooved rolls, which as is well known causes rewetting from grooves greatly effecting the results. This was not taken into account in Heller's analysis of the results. I think it is time to revive the Sweet plots for the following reasons.

That the Sweet plots are real has been clearly established not only by Sweet himself, but by KMW on a pilot machine running under well controlled conditions using fabric presses over a very wide range of basis weights, speeds and furnishes. Others such as Billerud running sheets through a press nip have confirmed it. Based on this pressure controlled and flow controlled pressing concepts are now well established.

Independently of this work the platen press work shows clearly that in pressure controlled pressing the maximum dryness, which corresponds to mid nip moisture is independent of basis weight and constant(50) for a given furnish and pressing conditions.

The fact is that the moisture content leaving the press nip in a pressure controlled pressing situation can be expressed by a constant term, which is independent of basis weight, and a second term which contribution to outgoing moisture ratio is a constant, named rewetting, which varies with furnish and the surface properties of the felt, divided by the basis weight. The present explanation for these results are, that the intercept corresponds to the midnip moisture while the slope is the result of an interfacial transfer of water from felt to paper called rewetting.

The intercept has been shown to be influenced mainly by the UOPA, and corresponds well with the non-uniformities seen in pressing the felt against a pressure sensitive film basically showing the impact of the base weave and the underlying structure, such as holes and grooves. These non-uniformities are in the millimetre range, and also in severe cases match felt marking of the sheet. They can be picked up as pressure variations in a roll nip.

The slope of the moisture ratio curve or rewetting on the other hand is controlled mainly by the surface structure of the felt and the elastic expansion of the sheet. It is independent of basis weight. The coarser the felt and the more the paper expands the larger the rewetting.

Micrographs of felts and paper together show how much more open the felt structure is and how nonuniform the contact is between paper and felt. This non-uniformity is in the micron scale and thus small with regards to the thickness of the sheet, which in this scale must be exceedingly stiff. If micro UOPA is the reason for rewetting we should see felt marking in the batt scale and we could not expect it to be independent of basis weight or increase with the expansion of the sheet.

However the open felt structure contains water in contact with the paper in the interfacial region. This water is obviously very accessible to an expanding sheet, which explains why the coarseness of the felt and the expandability of the sheet control rewetting. It also explains why an elastic felt is needed to minimise rewetting. The felt expansion before the expansion of the sheet unsaturates the felt and redistributes the water as well as allowing air to flow through groves and felt into the sheet.

The developments of felts towards finer base structures and finer surface batts has in a practical way utilised our understanding of UOPA and rewetting.

A better understanding of these phenomena is still needed and I believe, that using the Sweet plots would be very beneficial in our further studies.

I agree that rewetting in the nip today is of minor importance in most cases, except for very light weight sheets and in double felted nips due to our understanding of the importance of fine surface batt. However for our understanding of pressing it is still very important to have a correct physical model.

IN PLANE FLOW

The development of the transversal flow nip was to reduce the limiting factor of in plane flow in the felt, that in plain presses and even suction presses severely limited pressing. The basic limitation to pressing was crushing, which is caused by in plane flow in the sheet disrupting the sheet, when the hydraulic pressure gradient exceeds the wet web strength. All our experience suggests that in plan flow only occurs in rare cases and then marginally as it has such a devastating effect on sheet properties. MacGregor's examples all deal with situations when localised in plane flow has caused some surface defects. Shadow marking and groove marking are obvious cases of in plane flow.

The existence of large hydraulic pressure gradients in the plane is well known. These have dramatically increased with higher speed and nip pressures. Looking at the flow distances and velocities in the plane and through the thickness the effect of in plan flow on water removal must be negligible, except when combined with a dramatic disruption of the sheet, which is unacceptable.

The absence of in plane flow under normal conditions is further supported by the fact that there is very good agreement between platen press work and nip press work with regards to MR vs. press impulse. Under severe pressing conditions high impulse, short time, heavy basis weight and low dryness in a platen press we see disruption of the edges and crushing in a nip press. With incipient crushing we see a drastic improvement in water removal and a loss in strength and bulk.

Even if in plane flow is not present in normal pressing a better understanding is valuable in dealing with special cases of sheet structural changes.

PLATEN PRESS WORK AND ITS APPLICATION

If in plane flow is not normally a factor in pressing, then platen presses are an excellent tool to study the compression phase of pressing eliminating the impact of UOPA and rewetting. This is not only of fundamental importance for our understanding of pressing but also shows the potential from improving UOPA and rewetting.

Szikla seems to have eliminated the interaction with the sintered plate and the sheet almost completely. Thus the determination of sheet dryness from thickness measurements should be valid. Experimental techniques for valid hydraulic pressure measurements also seem to available, making platen presses a very valuable tool for studying the compression phase.

The fact that the hydraulic pressure maximum occurs normally after the total pressure maximum is consistent with minimal flow in the plane. In a wet felt running though a plain press nip all the flow is in plane accounting for the fact that the hydraulic pressure maximum is ahead of the total pressure maximum. This is a minor modification to the press nip model.

Platen presses are not very suitable for rewetting work. The sintered disc does not expand as the felt, which effects both the water available for rewetting and the ability of air to enter the felt and the sheet. The felt and the sheet separate at the end of the nip, which was eg not the case with Carlsson et al. work.

FLUID STRESS

I would like to know more about the fluid stress added to the hydraulic pressure gradient. My understanding is that at the low flow velocities in a press nip, cm/sec, where thus the inertial forces are negligible, the drag forces, fluid shear the hydraulic pressure gradients are the same.

What is the size of the mechanical shear and what effect could it have on water removal and sheet properties. The good agreement between platen press testing and roll nip testing would suggest that it is small.

Z-DIRECTION RESEARCH, SURFACE DENSIFICATION AND INTERACTION PRESSING DRYING

A comment on fines and filler movements during pressing.

There is obviously some movement of fines and fillers as shown by Szikla and Busker and by the fact that there is some fines and fillers in the water from the press section. However the effect on water removal and sheet properties seem minimal. This is understandable as the flow velocities in pressing are at a maximum .5 m/s, but normally only .01 to .05 m/s, which is less than 1/10th of those during forming. Thus, it is very unlikely that fines and fillers held by the structure after forming will move during pressing.

I agree that we need to know more about the impact of pressing on the sheet properties and especially the density gradients in the sheet. There is a lot of basic knowledge about the interaction between wet sheet density, press dryness and dry sheet density for different furnishes at relatively static conditions. It is reasonable to believe that these basic relationships also hold reasonable well for wet density gradients and the dry sheet gradients after drying. This has been shown by a number of investigators.

We know that pressing causes hydraulic pressure gradients through the sheet, which in turn cause wet density gradients at the end of the compression phase part of which will remain after the expansion phase and cause dry density variations in the drying phase. This is the reason for two-sidedness.

Without taking into account flow out of the fibre wall we cannot model the density distribution in the compaction phase, nor the relaxation in the expanding phase. These areas need much work. However there is no compelling evidence that suggests that this model cannot explain the differences observed in Fig 16 between the top and bottom side of a pulp sheet pressed in three single felted nips all with the felt on the bottom side.

Because of the importance of surface densification, building I-beams, etc this is obviously an area of the greatest importance.

RESPONSE TO B. WAHLSTRÖM'S COMMENTS

by
Michael A. MacGregor[1]
Visiting Research Professor
The Royal Institute of Technology
Stockholm, Sweden

I appreciate your generally positive response to my paper and address. As I said in this address, if I helped to provoke further thinking about wet pressing on a microscopic scale, then one of my important goals would have been accomplished.

As you know, I have been unable to share your enthusiasm for the 'Sweet Plot Technique' which you discussed at length in your reponse. I have always viewed this as an interesting, but empirical mathematical method for presenting data. Statistical methods can only describe correlations between variables for a specific set of circumstances. As we said in our carefully worded analysis back in 1975 (25), we believed the Sweet Plot results could be explained by other equally valid postulations than the ones used by Sweet and later by you. Our data were collected only *after* we first derived our views from a critical review of the existing literature and by trying to apply logical reasoning. Finally, with repect to your comment on rewetting from the grooves, I would like to note that we did **not** (p. 157, 25) use a grooved press in the particular work you cite. Therefore, this issue should have no bearing here.

I am delighted to see what I consider a very significant statement from the "father" of rewetting concerning the relative importance of this topic. We only seem to differ in the exact mechanisms, and even here we are in agreement about the importance of air intrusion. Further, both of us acknowledge a vast

---

[1]Manager of Science and Technology, Voith, Inc., Appleton, WI

difference in rewetting between a roll press and a platen press.

Ironically, it is not rewetting where we now seem to disagree. I believe there are some fundamental *(and important)* differences between roll presses and platen press testers while you don't. Your strongly-held belief in vertical flow pressing makes it understandable why you feel platen press testers are excellent simulators for roll pressing and that inplane stresses play little role for "normal" roll pressing conditions (your words). However, I believe that inplane mechanical and fluid shear stress must be considered in any realistic model of roll pressing.

If inplane stresses are unimportant, then what else is causing the MD-oriented disruptions we have shown on numerous occasions (66, 74, 78) such as fines/fillers movement, shadow marking, groove marking, checkmarking, surface density marking, shear fault planes, and others? Do you also classify these real-life occurances as 'crushing' which therefore fall outside of the 'normal' pressing regime? My experiences on real paper machines make me wonder how a model which does not recognize or explain the existance of these inplane phenomena can be considered truly realistic. Further, I feel uncomfortable in dismissing the existance of inplane stresses solely because we are unable at this time to measure them or specifically relate them to problems in the final product (we are currently trying to think of ways to do this).

Like you, I have also questioned the true significance of fluid shear stress in wet pressing. This is why I tentatively depicted it as being fairly small in Figure 13 and also why I called for more serious study in my recommendations. Again, one must ask what other forces would cause movement of material inside the sheet (without disruptive crushing I might add) if fluid shear stress was not involved? I also would like to learn whether fluid shear stress is playing a role in the 'surface densification' I speak of, or if the latter is simply caused by high static water pressure on the interior side of the flow-exiting surface layers, counteracted by mechanical compression from the felt on the exterior side. Incidentally, this is what recently led me to believe there may be a very low relative water velocity (and pressure drop) inside most of the paper--that when significant static water pressure is measured at the upper platen (e.g., 54, Szikla, Vol I), most of the pressure drop, water velocity, and density development occurs across a relatively few exiting-side layers and not uniformly throughout the paper structure.

Even this is speculation on my part as I said in my speech. For example, we have long known that wet pressing causes a density 2-sidedness, but most of us have only **theorized** various shapes of *smooth and continuous* density curves connecting the two surfaces--we have never accurately measured the true density distribution for various pressing conditions. Further, we don't know how these density distributions change from the midnip to the reel.

I do not think we can use either Burton's (73) or Burn's (1989 TAPPI Engrg Proceedings) data from platen press testers to study all we need to know about density gradients. The platen press tester may be useful for measuring dynamic compression effects, but *only until the point of separation*--after that, the vacuum and adhesion forces (especially for the porous plate tester used by these people) must certainly have a major disruptive effect on the density distribution. This is yet another reason for being careful with data platen press tests.

I feel that most of your remaining points you have raised are addressed in various parts of my paper. I am very appreciative of your comments and am also grateful to the Committee for allowing us this opportunity to have an open dialogue.