

THE INSTITUTE OF PAPER CHEMISTRY, APPLETON, WISCONSIN

NEW CONCEPTS IN WET PRESSING

FINAL REPORT

BY

DR. CLYDE H. SPRAGUE

✓ PROJECT 3584

DOE CONTRACT NO. DE-AC02-84CE40685

February 28, 1986

TABLE OF CONTENTS

	PAGE
SUMMARY	1
Displacement Pressing	1
Pressing Process Models and Nip Efficiency	3
INTRODUCTION	5
Water Removal on the Paper Machine	5
Wet Pressing	7
Flow Controlled Pressing	7
Compression Controlled Pressing	8
New Pressing Concepts - Displacement Pressing	8
Displacement Pressing for High Dryness	8
Displacement Pressing for Property Development	10
DISPLACEMENT PRESSING	12
Exploratory Experiments - First Generation	13
Simplified Analysis of Displacement Pressing	20
Exploratory Experiments - Second Generation	24
Displacement Pressing for Bulk Control	34
Exploratory Experiments - Third Generation	37
Third Generation Pressing Head	37
Results	42
Blowthrough Dewatering of Paper Webs - A Review	45

TABLE OF CONTENTS - Continued

	PAGE
PRESSING MODELS AND NIP EFFICIENCY	52
Introduction	52
UMO Wet Pressing Project Results	53
Porous Plates and Nip Efficiency	58
Results	60
Other Factors in Nip Efficiency	65
New Modeling Objectives	68
Approach and Experimental Equipment	69
Modeling Steps and Exploratory Experiments	75
Compression-expansion Behavior of Wet Sheets	75
Transport in the Expansion Zone	78
Nip Opening	80
Post-nip Zone	80

SUMMARY

This is the final report in a small, year-long project to investigate two subjects; the technical feasibility of displacement pressing and the factors causing the differences in water removal between a laboratory compression tester and a pilot press, both used in the recently completed wet pressing study conducted by the Department of Chemical Engineering at the University of Maine at Orono (UMO). Because of the broad scope of the subject areas and the time and budget constraints on this contract, only limited investigations of these subjects have been carried out.

DISPLACEMENT PRESSING

Displacement pressing, a new concept for wet pressing, replaces or supplements the normal hydraulic pressure gradient in a pressed sheet with an externally imposed pressure gradient, generated by compressed air or steam. This concept has been explored through three generations of laboratory pressing heads in two pressing regimes; moisture levels in the 50% range, typical of third press or early dryer levels, and in the 25-45% range, typical of first or second presses. At low moisture levels, hydraulic pressures are difficult to generate, thus limiting the maximum dryness achievable in a conventional press. In this regime, displacement pressing has been shown to be effective in increasing dryness levels to at least 65%. For lightweight, relatively free sheets, this has been achieved with normal compression pressures, displacement air pressures of 50-100 psi and times in the 10-40 ms range. Heavier or lower freeness sheets are more difficult to dewater.

For wetter sheets where hydraulic pressure gradients can be developed readily, displacement pressing is used for bulk retention (control). Low compression pressure, combined with an external air pressure gradient, are used

to remove water from the sheet without significantly increasing density. In this way, a dry, bulky sheet can be produced, something which cannot be achieved in a conventional press. As an example, a 65 g/m² sheet of bleached northern softwood kraft at a freeness of 690 ml was displacement-pressed at compression levels of 100, 400, and 1500 psi and for an ingoing solids range from 25-50%. For an ingoing solids level of 35%, the outgoing solids levels were all near 48%, but the density levels corresponding to the three compression pressures were about 0.43, 0.47, and 0.51, respectively. These data, and others, have shown that displacement pressing can be used to decouple the normal density-dryness relationship obtained in conventional pressing so dry, bulky sheets can be produced.

A simple model of the displacement pressing process, based on a two-zone description, shows that liquid permeability and thickness of the sheet (basis weight), and air pressure differential are the key variables. Thickness and permeability are both dependent on compression pressure in ways which oppositely affect water removal. Hence, there may be a need to schedule pressure during the displacement pressing event for optimum performance. This can be readily accomplished with some types of pressing systems now in commercial use.

When used for achieving high dryness levels, displacement pressing will offer improved paper machine productivity, better runnability through improved wet web properties in the open draw, and substantially reduced drying energy. Increasing the solids level into the dryer from 50 to 65% will reduce drying energy by 1/3 to 1/2, a large improvement. Using a displacement press in the first or second press position may afford a significant opportunity to achieve both high dryness and high bulk, a real advantage for a number of grades.

The third generation displacement pressing head includes provisions for measuring the flow through the sheet of displacement air. Measurements made with this system show that relative water removal increases directly with air flow superficial velocity. Typical superficial velocities are of the order of a few feet per second. Higher compressive pressures result in more effective use of the air flow. Air supply energy consumption will probably be less than one horsepower day per ton, a small level compared to refining, for example.

With these experiments, the technical feasibility work is nearly completed. One more definitive experiment is required to provide the basis for assessing economic feasibility.

PRESSING PROCESS MODELS AND NIP EFFICIENCY

In their recently completed wet pressing study, the UMO showed that a laboratory compression tester was much more effective in removing water than a pilot press of conventional design. A correction factor, called the "nip efficiency", was defined to correct the model data to agree with data from the pilot press. A number of experiments conducted in this follow-up study have shown that the difference is not attributable to the use of a porous plate as a water receiver in the compression tester. In fact, for every condition investigated and for several porous plate designs, felts have given better performance. Initially, the major thrust of this part of the study was the comparative evaluation of porous plates and felts as water receivers, prompted by the UMO interpretation of its findings. With the discovery that porous plates could not account for the extraordinary performance of the UMO compression tester, attention was diverted to other differences between the tester, the model for it, and real presses. This turn of events did, of course, considerably broaden the overall scope of this project.

There is now mounting evidence that the compression tester showed better water removal because the sheets were compressed from a presaturated state and because the expansion part of the process, with its attendant reabsorption of water, was ignored in water removal determinations and in modeling. Proper accounting of the deleterious effect of porous plates and of these two testing artifacts should permit estimation of the nip efficiency factor used by the UMO to correct the laboratory data to agree with pilot press data. More importantly, a mathematical description of the factors omitted in the UMO model will make it unnecessary to use a nip efficiency factor, thus providing a much more complete description of the pressing process. The late stages of this contract period were devoted to the initial steps in developing a model for the complete wet pressing process. Modeling is interpreted here to cover description of density development and other quality issues that are so important to papermaking and paper performance, but have heretofore been omitted in modeling considerations.

The initial steps in modeling are experimental in nature and are based on two unique platen-type press nip simulators. One is of the falling weight type and the other is an electrohydraulic unit. Both are equipped for making instantaneous measurements of the density profile development through the sheet as it is being pressed and of the hydraulic pressure developed during pressing. A rolling nip pilot press with full instrumentation, now under design, will join this laboratory equipment collection shortly. Several experimental series have already been completed exploring the areas of saturated compression and expansion, adhesion during the nip opening process, and hydraulic pressure development. Modeling per se is just getting underway with equations developed for the constituent mass balances. This work is being continued beyond the limits of the current contract.

INTRODUCTION

WATER REMOVAL ON THE PAPER MACHINE

Figure 1 shows a schematic illustration of the water distribution in a typical papermaking process. Processing starts at the headbox with perhaps 200 parts of water for each part of fiber. Most of this water is removed before the presses through such forces as gravity, vacuum, centrifugal, and wire tension. In the presses, additional water is removed so the exiting web has about equal parts of water and fiber. The last bit of water is removed in the dryer, usually by direct evaporation. Although the relative amount of water removed in pressing and drying is small, it is profoundly important in terms of operating costs and energy consumption, machine runnability, and paper properties.

In wet pressing, the moist sheet, along with one or two felts, is passed through a press nip to mechanically compress the combination. Figure 2 shows an example of a two roll press with a single felt working against a vented roll. Within the sheet, part of the water is carried in the network pores ("free" water) and the remainder is carried in the fiber pores ("bound" water). For a relatively wet sheet (moisture ratio >2.0) much of the water is free and readily accessible for removal by this compression process. For dryer sheets, much of the water is bound making it more difficult to remove. As a consequence, two or three presses are needed to increase the solids content from 20% or so to the 40-50% range. In drying all of the water is evaporated requiring about 1.5 pounds of steam for each pound of water removed.

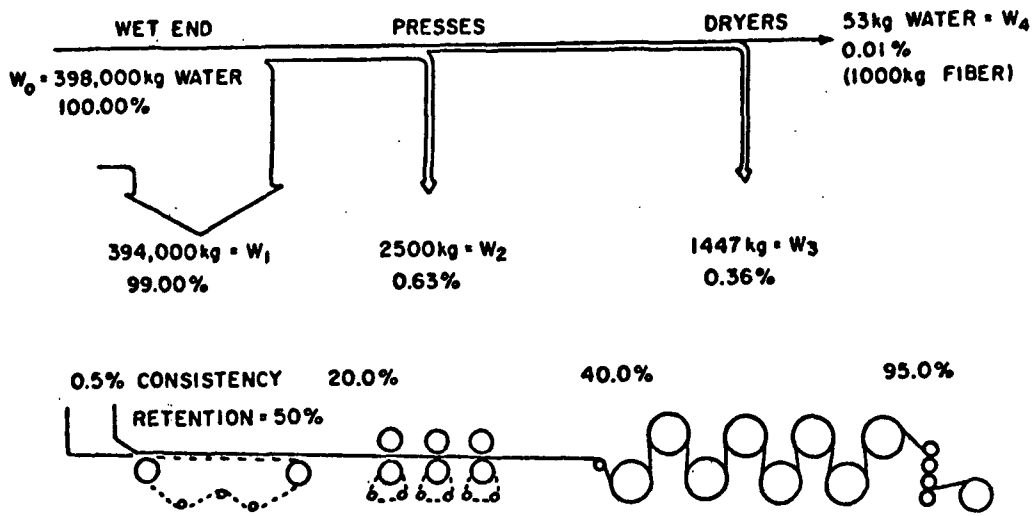


Figure 1. Water distribution on paper machine.

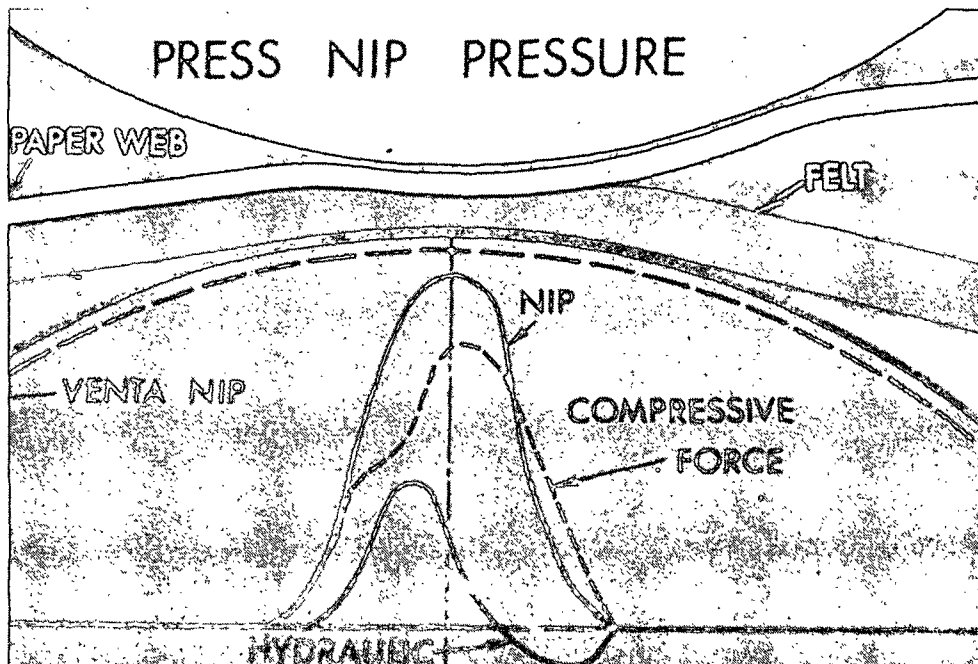


Figure 2. Roll press and pressure diagrams.

WET PRESSING

As the wet sheet passes into the nip, the pressing forces compress the fiber structure, thus reducing the pore volume available to hold water. At some level of compression, the pore volume and water volume become equal, creating a condition known as saturation. Additional compression beyond the saturation level causes a hydraulic pressure gradient to form, forcing water to flow from the sheet. Under these conditions, the total pressure applied by the roll is borne partly by the fiber network and partly by the hydraulic pressure or, in equation form,

$$P_t = P_h + P_s \quad (1)$$

where P_t = total applied pressure

P_h = hydraulic pressure

P_s = structural pressure
(fiber network pressure)

As the sheet continues through the nip, the hydraulic pressure rises to a maximum, usually around mid-nip, and then declines through zero as the sheet expands on the exit side of the nip. Beyond this point, the hydraulic pressure gradient reverses and some water may flow from the felt back to the expanding paper web. Representative nip pressure profiles are shown in Fig. 2.

Flow Controlled Pressing

For sheets having high moisture, high basis weight, or low freeness, the primary impediment to water removal is the flow resistance of the fiber network. This regime is called "flow controlled". For flow controlled pressing, the amount of water removed depends on the hydraulic pressure available to force water from the sheet and the time available for flow. Under these conditions, the hydraulic pressure depends directly on the total applied pressure. Thus, in this regime, water removal depends almost totally on the area under the pressure-time curve, called the "impulse" of the press.

$$I = \int_0^{\text{NRT}} P_t dt. \quad (2)$$

NRT = nip residence time

Time and pressure may be freely interchanged to achieve equivalent water removal in the flow controlled region. This flow controlled behavior, typical of most first presses in a multi-press system, is illustrated by the left portion of the impulse diagram in Fig. 3. Water removal is independent of basis weight in this region.

Compression Controlled Pressing

As the free water leaves the sheet, removal of the bound water starts to dominate the pressing process. Considerable compression is necessary to free sufficient water from the fibers to saturate the sheet, even though the pore volume of the highly compressed sheet is small. Only a modest amount of water remains to be removed. This regime, called compression controlled pressing, is typical of third presses and is characterized by relatively dry sheets, low basis weights and high freeness furnishes. Press impulse remains an important driving force in the compression controlled regime, but here maximum pressure has an important independent effect, as shown in the righthand part of Fig. 3. Water removal is directly proportional to basis weight in the compression controlled zone. The transition between these zones is not sharply defined and certainly depends upon such situational factors as furnish, basis weight, freeness, and certain press design factors. Nevertheless, the concepts are well founded and very useful in understanding or describing pressing behavior.

NEW PRESSING CONCEPTS - DISPLACEMENT PRESSING

Displacement Pressing for High Dryness

As a foregoing discussion suggests, one of the primary measures of press effectiveness is the dryness of the sheet going to the dryers. All of the

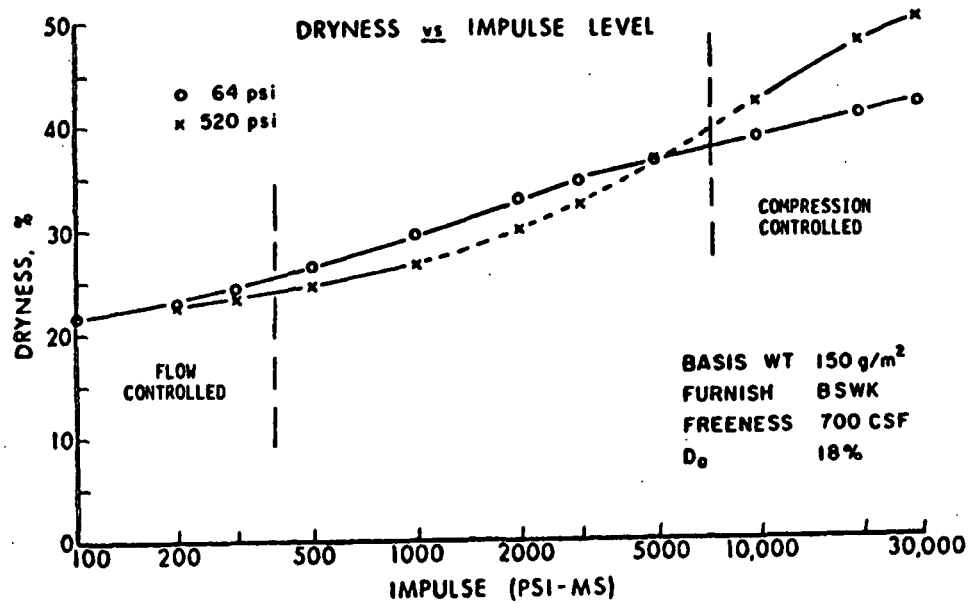


Figure 3. Pressing impulse diagram.

water not removed by the press must be evaporated in the dryer. About 36% of the gross energy consumption in an integrated kraft mill occurs in the paper mill with most of this going to paper drying. As a consequence, each percentage point increase in solids content out of the presses reduces dryer energy consumption by about 4.5%. Hence, there is a big energy cost incentive for improving press exit dryness.

On many machines, the first (or only) open draw occurs between the last press and the first dryer can. Many web breaks occur in this zone because of the poor mechanical properties of the wet web. These breaks cause a significant loss of productivity. Improved pressing usually increases the dryness of the web and, correspondingly, the mechanical properties of the web in the open draw, thus reducing the frequency of breaks. Hence, runnability, as well as dryer energy cost, is well related to press exit dryness.

In first presses, and in some second presses, double felting, extended or high impact nips, and increased loading are all examples of actions that are effective in increasing water removal. Third presses are normally compression controlled so that high pressures as well as long nips (time) are needed to effect significant additional water removal. Both have been improved by recent press developments, but the additional incremental improvements expected in these technologies seem unlikely to produce substantial increases in dryness. It is this combination of factors which lead to the concept of displacement as another pressing dimension to be used in improving the performance of presses, especially third presses.

For relatively dry sheets ($MR \leq 1.0$) it is still possible to press water from the fibers, but difficult to create a hydraulic pressure gradient to drive the water out of the sheet. In displacement pressing, the sheet is mechanically compressed as usual, but the water removal force is supplied as an externally imposed pressure gradient using compressed air, for example. With this approach, significant additional water can be removed, pushing sheet dryness levels 10-15 percentage points above those normally achieved. One of the principal objectives of this project is to investigate the feasibility of the displacement pressing concept in achieving high press exit dryness levels and the benefits derived therefrom.

Displacement Pressing for Property Development

As a moist sheet passes through a pressing nip, it is first compressed to some minimum thickness, beyond which it expands, but not to its original thickness. If the sheet is dried promptly after pressing, much of the densification that occurs during pressing is permanently captured in the sheet. Because sheet density is at the root of many strength properties and some optical properties, densification in the presses has an important influence on paper

properties. Generally, if strength is the end-use property of most concern, more densification is desired in the wet presses.

For most presses of current design, density is very nearly a linear function of press exit dryness. Hence, any action taken to increase dryness will correspondingly increase density. Displacement pressing may also lead to much higher dryness levels but, because the water removal mechanism is different from that in more conventional pressing, the degree of incremental increase in density may be less. Some increase in density is expected, however.

For some paper grades, bulk is the property of interest and densification in the wet presses is undesirable. Absorbent grades, boxboard, and some printing papers, are all examples where part or all of the sheet should be bulky to effect the desired end-use properties. Bulk and high dryness are inconsistent in current pressing operations, but can be achieved by starting the displacement pressing process at solids levels of 25-35%. In this regime, low mechanical pressures are used to avoid densifying the sheet. The water is displaced with an external pressure source such as compressed air. A second major objective of this project is to determine the feasibility of displacement pressing as a means of decoupling the usual density-dryness relationship and producing a sheet that is both bulky and dry, something that cannot be achieved with current presses.

DISPLACEMENT PRESSING

The data in Fig. 3 show that increases in press impulse yield only small increases in sheet dryness when the sheet is in the compression controlled zone. The exact level of dryness at which the transition to compression control occurs depends somewhat on basis weight, freeness, and so on. But the point is clear; increasing impulse levels beyond those achievable with extended nip presses will have little impact on water removal/dryness for dryness levels above the 45-50% range. Pressing pressure has a small positive impact in this zone, but structural design considerations will preclude significant advances via this route. Based on all of these factors, it appears that major gains in sheet dryness out of the press will require a different pressing mechanism.

At high dryness levels, practical pressing pressures squeeze some water out of the fibers into the interfiber pores, but not enough to saturate the sheet. For this unsaturated condition, there is no hydraulic pressure gradient to drive the water from the sheet. In impulse drying, a similar state of sheet compression and saturation is achieved (1). There, however, appreciable liquid water removal is induced by the bulk flow of the vapor generated at the hot surface. In pressing at high dryness levels, the same mechanism can be invoked by driving air or steam through the sheet from an external source. As the gas stream flows through the compressed sheet, a portion of the available water is removed by displacement or entrainment. This mechanism, illustrated in Fig. 6., can be used to raise sheet dryness levels well above those achievable with conventional or extended nip presses without using any thermal energy. This concept is called "displacement pressing".

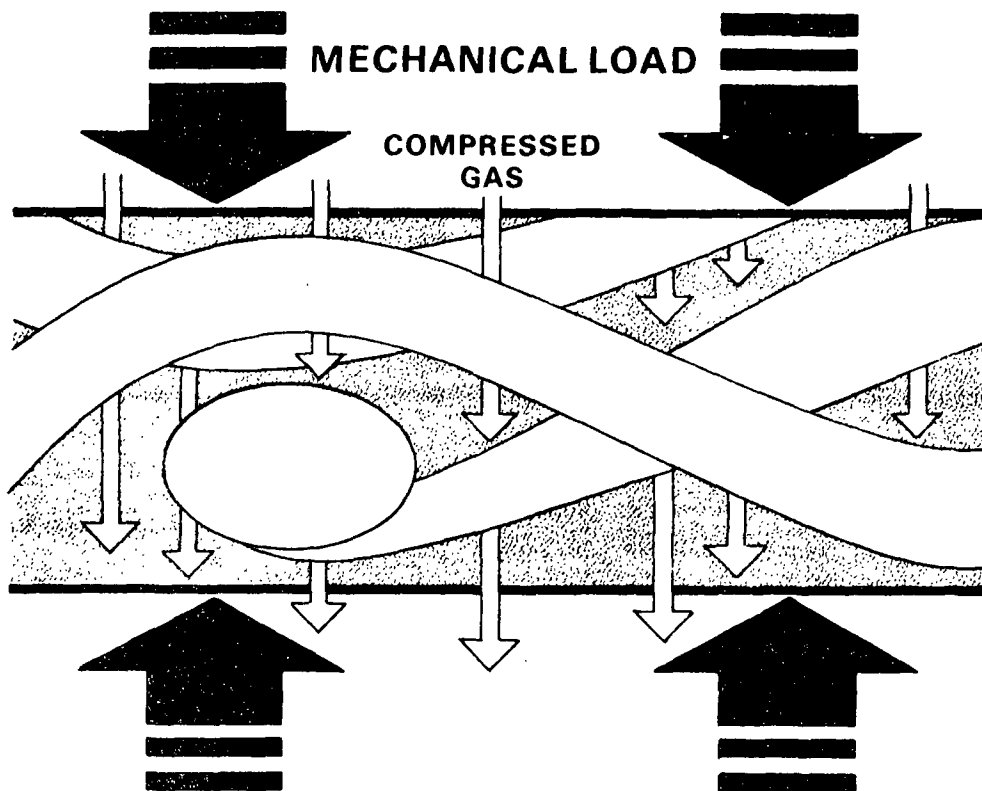


Figure 6. Illustration of displacement pressing concept.

EXPLORATORY EXPERIMENTS - FIRST GENERATION

A simple displacement press chamber (Fig. 7) was constructed for obtaining preliminary data on the dryness levels attainable by displacement pressing. In this simple chamber, the wet sheet is sandwiched between two drilled plates which act as load spreaders while allowing air and water to pass. Various combinations of screens, felts, and porous plates are placed between the sheet and the load spreaders. For the initial experiments, the chamber assembly was placed in a static press to provide compression of the sheet. Compressed air was then passed through the sheet for a predetermined period of time to displace the water. A picture of the static press is shown in Fig. 8.

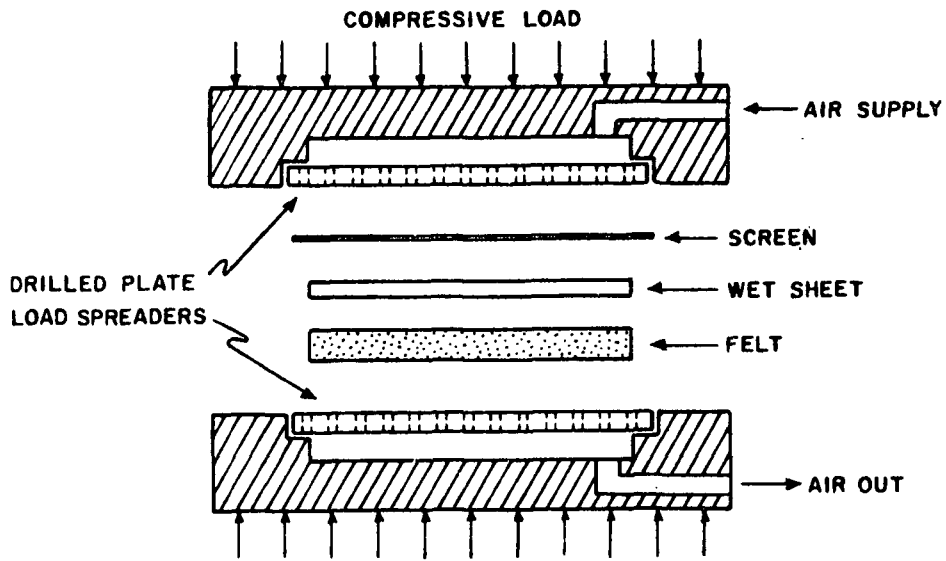


Figure 7. Displacement press chamber.

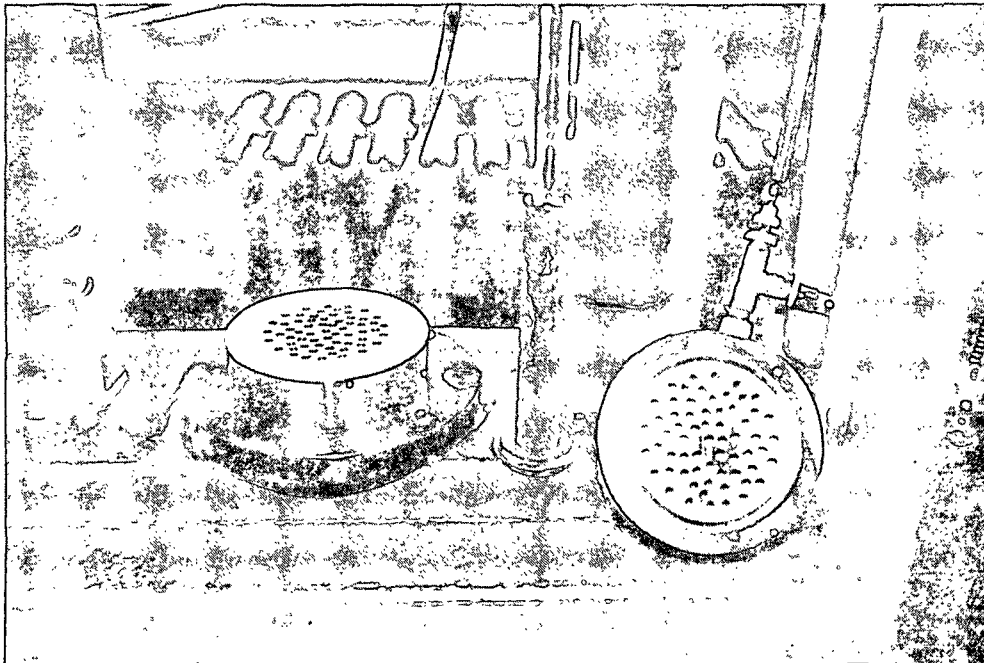


Figure 8A. Press chamber.

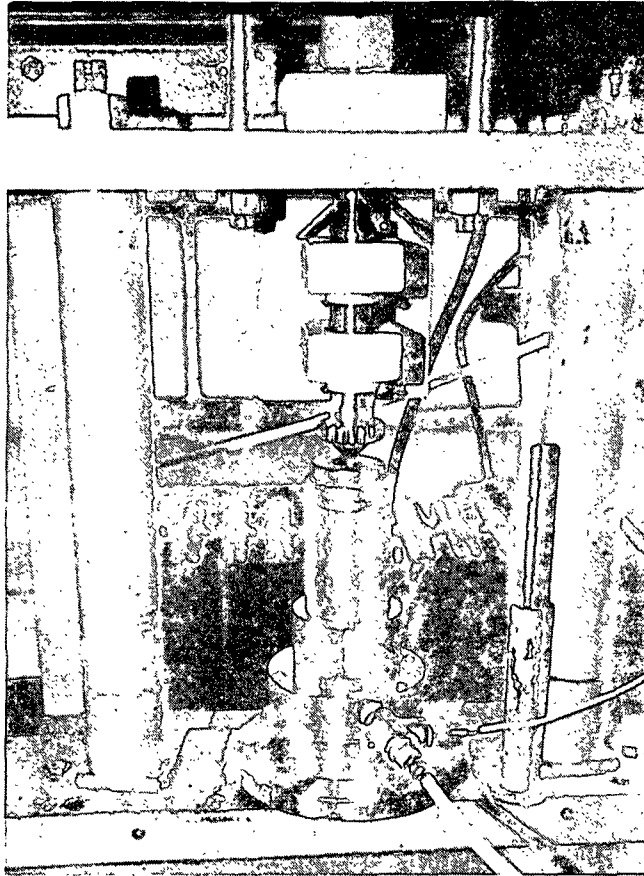


Figure 88. Static press.

For each test, the wet sheet was pressed by conventional means to the desired initial solids content, usually near 50%, and weighed. It was then placed in the test chamber shown in Fig. 7, with the appropriate water receiver, usually a dry felt, and supplemental load spreader, such as a screen. This assembly was then placed in the static hydraulic press and loaded to a predetermined and constant pressure. At a controlled time after compression of the sheet, the air supply valve was opened and left open for a predetermined time. All timing operations were controlled as closely as possible by manual means. After pressing, the sheet was removed from the press and weighed to determine water removal. Care was taken to keep the post-pressing contact time between the sheet and felt constant and minimum, but still there was significant opportunity for rewet so the data presented later underestimate the true water removal.

The purpose of these initial tests was to determine if attractive sheet dryness levels could be reached with displacement pressing and to identify the parameters important to further study. A high freeness bleached softwood kraft furnish was selected and tested at two basis weights, 63 g/m² and 125 g/m². Representative test results are shown in Fig. 9 as sheet dryness versus the displacement pressure P_d , for the two basis weights.

From the data in Fig. 9, one can make the following observations:

1. Sheet dryness levels of 60-65% are readily achievable, despite the limitations of the apparatus used for these tests.
2. Displacement pressure and displacement time are important variables, but they appear to be somewhat interchangeable, so the product of the two may be the key quantity.
3. The external compression pressure, P_t , is a less important variable, especially for the lower basis weight. High compression pressures tend to make more water available for removal but, at the same time, reduce sheet permeability. These counteracting effects seem to balance in the lower basis weight sheet and to favor water removal in the heavier sheet.
4. Higher basis weight sheets are more difficult to dewater by displacement pressing. For Darcy's law flow, assumed to apply here, both the permeability and the pressure gradient decrease with increasing basis weight, giving an inverse square law effect.

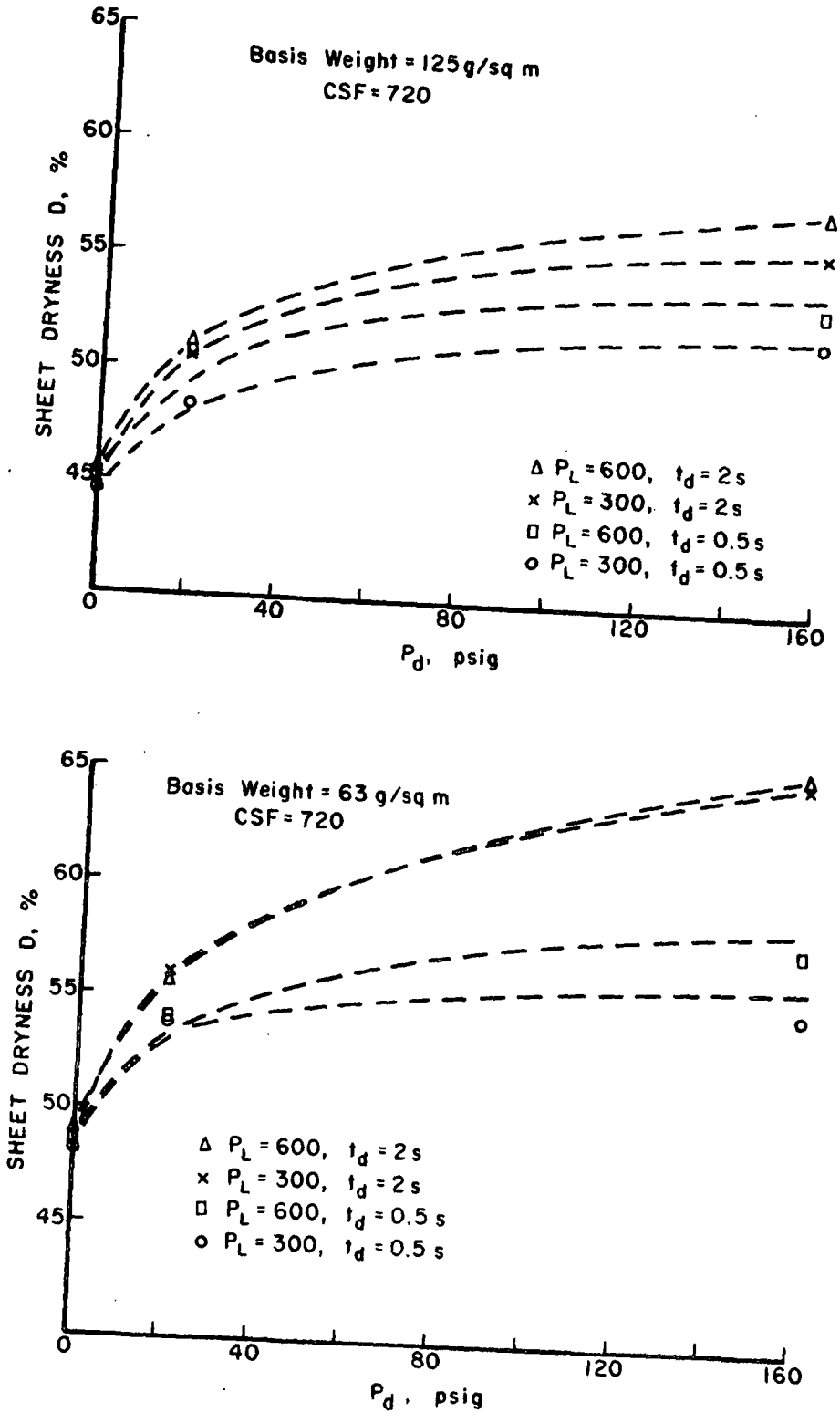


Figure 9. Sheet dryness resulting from displacement pressing at various displacement pressures.

5. Although it is not evident from these data, other results show that almost all of the water was removed by displacement and only very little by pressing alone. This is consistent with the small effectiveness of impulse in dewatering high solids sheets.

Several additional tests were conducted, primarily to explore the effect of press head configuration on displacement pressing performance. These data are shown in Table 1. From these data, one may make the following observations:

1. Replacing the felt with a screen substantially reduced water removal (tests 1 & 2). The data do not provide a valid comparison between use of a felt and porous plates above and below the sheets, but it appears that felts are better. These plates may introduce appreciable pressure drop, thus reducing the gradient across the sheet.
2. Increasing displacement pressure is shown to have a large positive effect by tests 2 and 3.
3. Displacement pressing should remove more water from a wet sheet than from a dryer one. This is supported - but certainly not proven - by the data from tests 4 and 5.
4. Applied pressure has only a minor effect as shown by tests 5 and 6.
5. Displacement time is an important variable, as shown by tests 7 through 10.

Table 1. Displacement pressing data for various press configurations.

	P_t	P_d	T	D_i	D_o	L ₁	L ₂	L ₃	L ₄	L ₅	BW	ΔMR
1.	530	160	2	48.7	56.6	DP	SCR	SHT	SCR	DP	125	0.287
2.	530	160	2	48.7	61.1	DP	SCR	SHT	FLT	DP	125	0.417
3.	530	20	2	48.7	56.1	DP	SCR	SHT	FLT	DP	125	0.271
4.	530	40	10	50.3	64.1	DP	SCR	SHT	FLT	DP	125	0.428
5.	530	40	10	48.7	62.8	DP	SCR	SHT	FLT	DP	125	0.461
6.	300	40	10	48.7	62.5	DP	SCR	SHT	FLT	DP	125	0.453
7.	530	50	1	46.0	52.3	SSS	SHT	SSS	---	---	125	0.262
8.	530	50	5	46.0	55.4	SSS	SHT	SSS	---	---	125	0.369
9.	530	50	10	46.0	59.8	SSS	SHT	SSS	---	---	125	0.502
10.	530	50	20	46.0	66.6	SSS	SHT	SSS	---	---	125	0.672
11.	530	0	5	46.0	48.0	SSS	SHT	SSS	---	---	125	0.091
12.	530	50	5	43.4	57.7	SSS	SHT	SSS	---	---	60	0.571
13.	530	50	10	43.2	67.7	SSS	SHT	SSS	---	---	60	0.838

P_t = total applied pressure - psi

DP = drilled plate

P_d = displacement air pressure - psig

SCR = screen

T = displacement time - sec.

SHT = sheet

D_i = ingoing dryness - %

SSS = sintered stainless steel plate - 40 pore size

D_o = outgoing dryness - %

L₁-L₅ = layers of pressing system - top-to-bottom

FLT = felt

BW = basis weight - g/m²

ΔMR = change in moisture ratio through press

6. The pure pressing effect - i.e., without displacement - is small as shown by tests 8 and 11.
7. Finally, basis weight has a large negative effect as indicated by tests 8 and 12 and by tests 9 and 13.

These observations are consistent with, but expand upon, those made earlier.

While freeness has not been considered as a variable in these tests, decreasing freeness would be expected to have a significant negative impact on displacement pressing performance.

These results show favorable sheet dryness levels for displacement pressing, even though the times involved were excessive for commercial machines. With the simple, manually controlled equipment, it was not possible to effectively test at shorter time intervals. There were several other deficiencies in this first generation system, as well. These included poor distribution of the compression load, extensive rewet because of the long post-pressing contact time, compression of the web well before and after the displacement pulse, severe radial leakage of air, thus reducing and disguising the true displacement pressure, and manual control. Given these qualifications, the results were regarded as sufficiently encouraging to warrant further work.

SIMPLIFIED ANALYSIS OF DISPLACEMENT PRESSING

In order to gain understanding of the primary effects of web and operating parameters, a highly simplified analysis of displacement pressing has been performed. Because of the success of zonal models in describing high intensity drying, a two-zone model has been adopted (see Fig. 10). In this model, the water available for displacement by an air pressure gradient is considered to be displaced from the web as a unit (wet zone), leaving behind (in

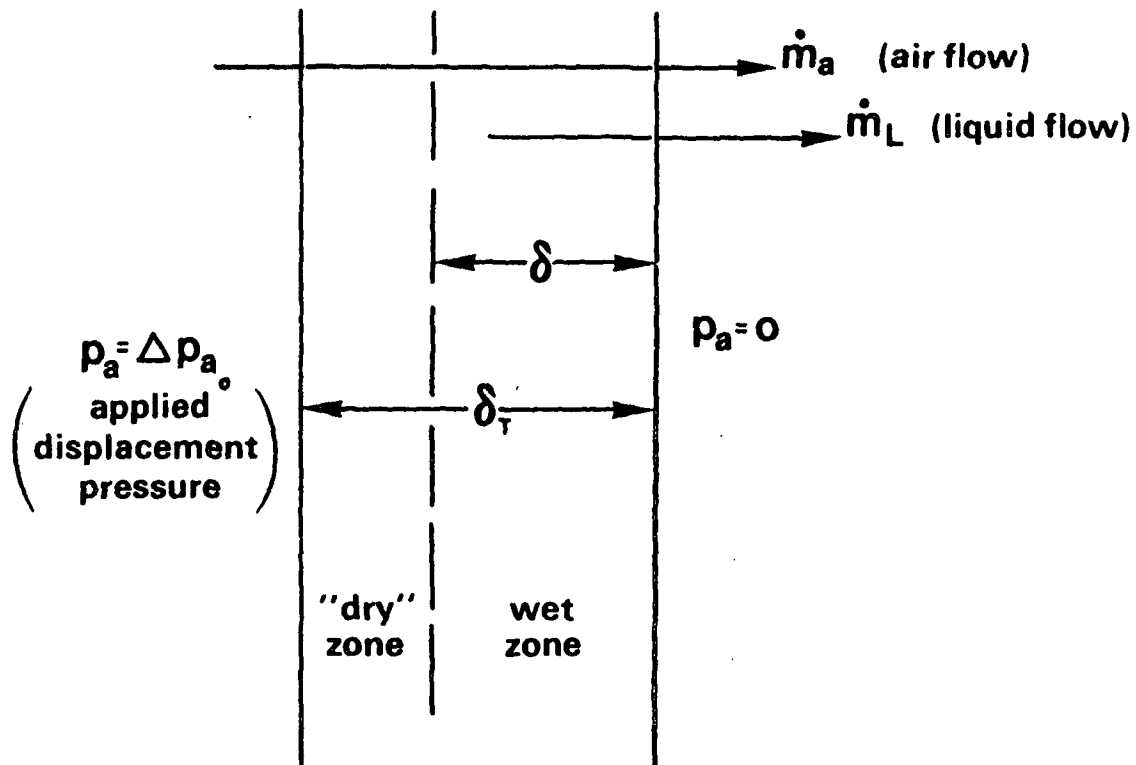


Figure 10. Two-zone model of displacement pressing.

the "dry" zone) that water which is unavailable for displacement. The analysis was performed for the general case in which air flows through the entire web removing water by viscous entrainment. However, the special case of a saturated wet zone, with water removal by a "push-through" mechanism, is readily handled in the model by setting the air permeability of the wet zone to zero.

A brief outline of the analysis is as follows. As a result of mechanical compression, the web has a thickness (δ_T), an effective density of water available for displacement ($\bar{\rho}_L$), air permeabilities for the wet and "dry" zones

(k_{a_w} , k_{a_d}), and a liquid permeability in the wet zone (k_L). The above quantities, as well as the applied air pressure difference (Δp_{a_0}), are considered constant. For simplicity, the compressibility of the air is neglected [i.e., the air density (ρ_a) is treated as constant].

It is assumed that Darcy's law adequately describes both the air and water flows. Although the wet zone thickness will decrease with time, a quasi-steady-state analysis is employed. Thus, the air flow rates (\dot{m}_a) through the "dry" and wet zones must be equal at every instant, yielding:

$$\dot{m}_a = \frac{\rho_a k_{a_d}}{\mu_a} \frac{\Delta p_{a_d}}{(\delta_T - \delta)} = \frac{\rho_a k_{a_w}}{\mu_a} \frac{\Delta p_{a_w}}{\delta} \quad (3)$$

where μ_a = air viscosity

Δp_{a_d} = air pressure drop across "dry" zone

Δp_{a_w} = air pressure drop across wet zone

Of course, the total pressure drop is fixed:

$$\Delta p_{a_d} + \Delta p_{a_w} = \Delta p_{a_0} \quad (4)$$

If capillary pressure effects are neglected, it is Δp_{a_w} that drives the liquid flow. Thus, the liquid flow rate (\dot{m}_L) is given by:

$$\dot{m}_L = \frac{\rho_L k_L}{\mu_L} \frac{\Delta p_{a_w}}{\delta} \quad (5)$$

where ρ_L = density of water

μ_L = viscosity of water

Finally, the rate of change of the wet zone thickness (δ) can be obtained from a mass balance on the wet zone:

$$-\rho_L \frac{d\delta}{dt} = -\dot{m}_L \quad (6)$$

with $\delta(0) = \delta_T$.

All of these equations are based on unit area.

The above equations have been solved, yielding the following expression for the wet zone thickness as a fraction of the total thickness:

$$\frac{\delta}{\delta_T} = \frac{-\bar{k} + \sqrt{1 - (1-\bar{k}^2)\bar{t}}}{1 - \bar{k}}, \quad 0 \leq \bar{t} \leq 1 \quad (6)$$

where $\bar{k} = k_{aw}/k_{ad}$

$\bar{t} = t/t_D$

$$t_D = \text{"pressing time"} = \frac{(1+\bar{k})\mu_L m_L'' \delta_T}{2 \rho_L k_L \Delta p_{a_0}} = \frac{(1+\bar{k})\mu_L \rho_L \delta_T^2}{2 \rho_L k_L \Delta p_{a_0}} = \frac{(1+\bar{k})\mu_L \delta_T^2}{2 k_L \Delta p_{a_0}} \quad (7)$$

$m_L'' = \bar{\rho}_L \delta_T = \text{mass of water available for displacement per unit area}$

Of course, for $\bar{t} > 1$, no further water removal occurs, since $\delta = 0$. The relative water removal (cumulative) is easily derived from the above result as:

$$\bar{M}_{out} = 1 - \delta/\delta_T. \quad (8)$$

Figure 11 shows the predicted behavior for the physically meaningful range, $0 \leq \bar{k} \leq 1$.

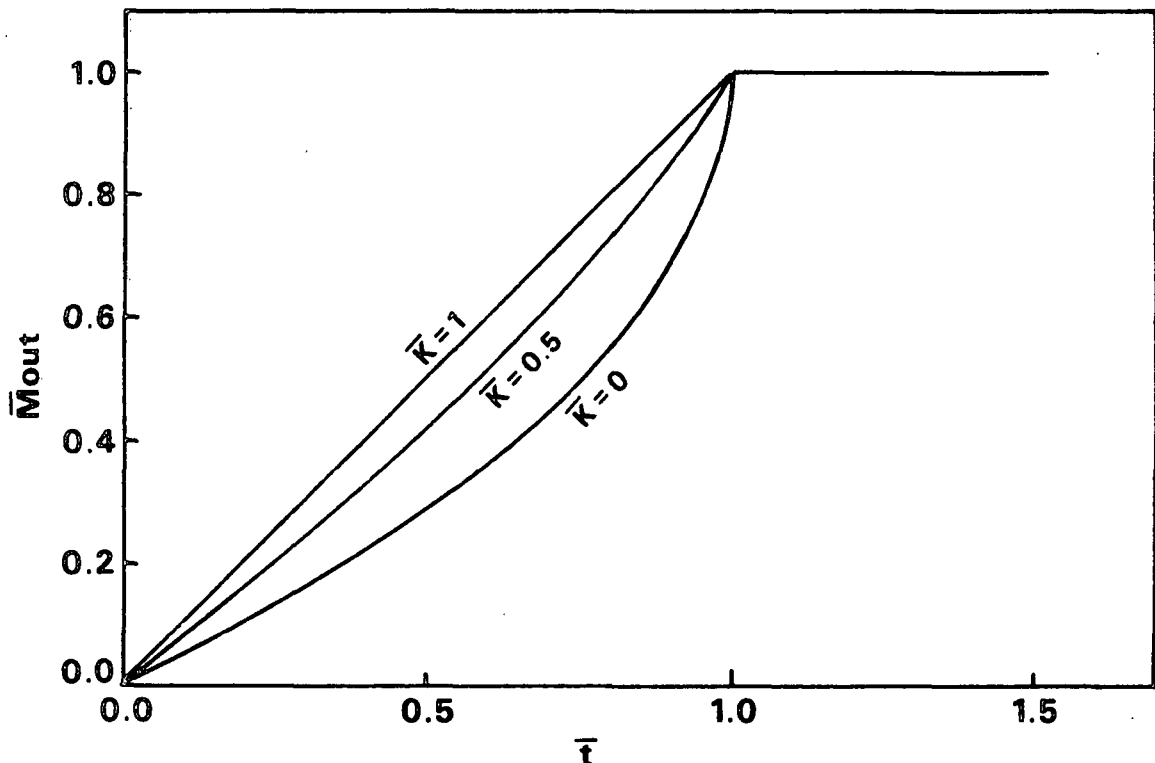


Figure 11. Dimensionless cumulative water removal (\bar{M}_{out}) as a function of dimensionless displacement time (\bar{t}).

Perhaps the most important result of the analysis is the expression for "pressing time" (t_D) listed above. It, in conjunction with the expression for m_L'' , indicates that pressing time is proportional to the square of the web thickness (basis weight) and inversely proportional to applied air pressure and web liquid permeability (a strong function of compression level, moisture ratio, and freeness for a given pulp).

According to the model, there is no incentive to perform displacement pressing for times longer than t_D . The real challenges, then, are to minimize t_D , while maximizing m_L'' (the water available for displacement). This will require understanding and use of optimal operating strategies.

EXPLORATORY EXPERIMENTS - SECOND GENERATION

The initial exploration of displacement pressing reported in an earlier section involved tests performed in a static press device. That is, the sheets were precompressed for several seconds, after which displacement (air) pressure was applied. Although the dryness levels attained (up to about 65%) were very encouraging, the compression and displacement times (>0.5 sec. used) were long compared to residence times typical of commercial pressing equipment.

To learn whether these high dryness levels could be attained or exceeded within a time period more typical of currently practical pressing operations, a second generation of displacement pressing equipment was developed. A new test head, shown in Fig. 12, included a sheet/felt edge seal, improved load distributors, a pressure transducer for measuring the actual displacement pressure on the sheet, and an improved air supply distribution system.

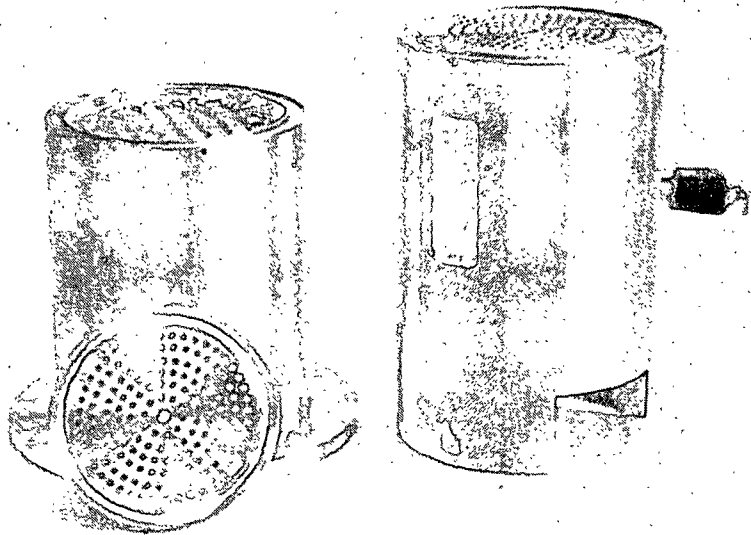


Figure 12. Displacement pressing head.

To permit short duration, dynamic testing, this test head was installed in a falling-weight press nip simulator, shown schematically in Fig. 13 and described more fully in ref. (2). In this device, peak pressure, nip residence time, and impulse are set by selecting appropriate values for the falling weight, the height from which the weight is dropped and the amount of elastic material in the system. While short, hard nips proved easy to simulate, great difficulty was encountered in going to nip residence times beyond a few milliseconds, an area of particular interest for displacement pressing. For this reason, testing of the displacement pressing concept was shifted to an electrohydraulic press.

The electrohydraulic press uses a hydraulic cylinder, servovalve and position and force transducers to form a closed loop, load and position control

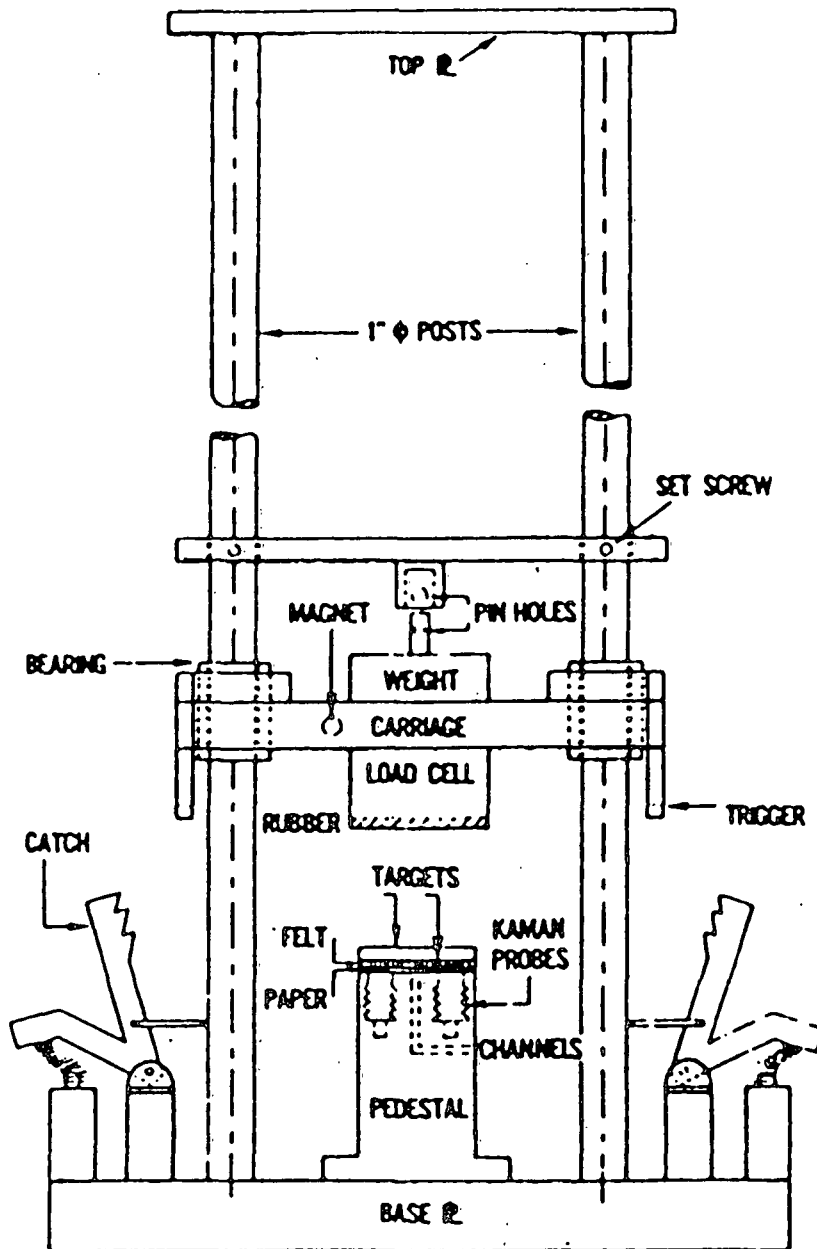


Figure 13. Falling weight press nip simulator.

system. A special electronic control package was developed to allow simulation of a single pressing event. Pressure-time pulses of a wide variety of shapes and sizes may be commanded electrically to simulate various types of nips. This device is extremely well suited to simulating any press configuration with a nip residence time of 10 ms or more. Figure 14 shows the press servo with the displacement pressing head installed.

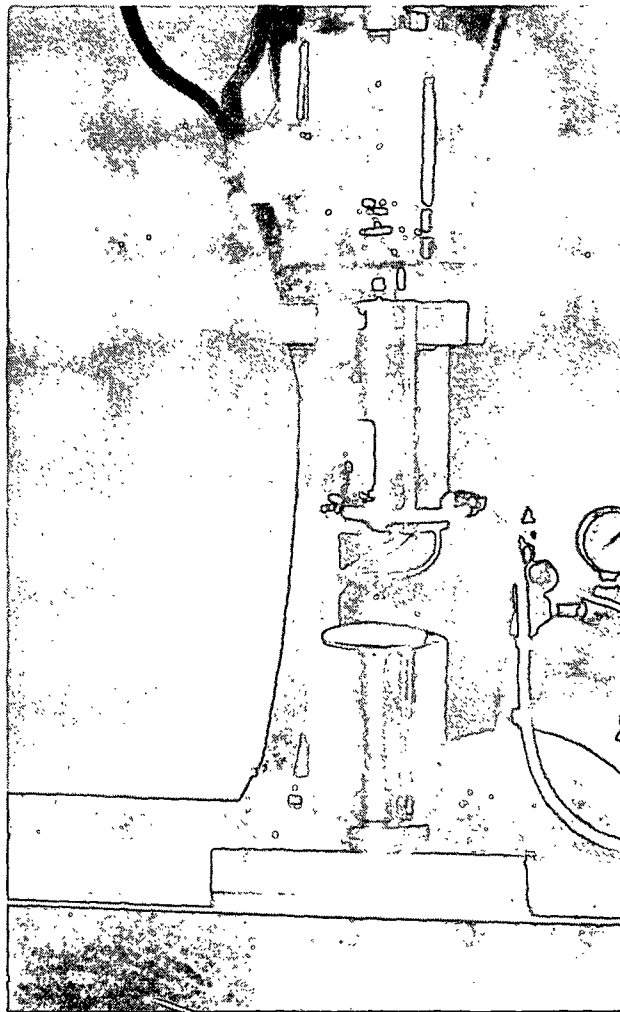


Figure 14. Electrohydraulic displacement pressing system.

Initially, scoping experiments were performed to examine the effects of certain operating variables on displacement pressing performance. For these experiments, 63 g/m² handsheets formed from 720 CSF bleached softwood kraft (once-dried) pulp were utilized.

In one series, the peak mechanical pressure and nip residence time (displacement time) were varied. The tests were performed using sheets at 43-45% initial dryness. The pressing configuration used comprised a bronze wire/handsheet/felt sandwich pressed between the drilled plates of the two test heads with the wire at the air supply side. A soft rubber gasket surrounded the sandwich to minimize air leakage. A haversine-shaped mechanical pressure pulse was applied and the air supply was triggered just prior to initiation of the mechanical pulse. Example mechanical pressure and air pressure responses for this operating mode are given in Fig. 15.

The results of this test series are presented in Fig. 16. It is seen that nearly 50% of the water initially in the sheet (corresponding to final dryness levels of 60% or more) was removed under the maximum time and pressure conditions. For the range of conditions represented in Fig. 16, the peak air pressures ranged from 40 to 80 psi, increasing with mechanical pressure and with displacement time. Air pressure levels were very erratic, however, because of poor sealing. Some of the factors contributing to the beneficial effect of higher mechanical pressures may be: larger quantities of water squeezed from the fibers and available for displacement, increased air pressure differential across the web due to its increased saturation (air flow resistance), and decreased web thickness. The potentially impeding effect of increased liquid

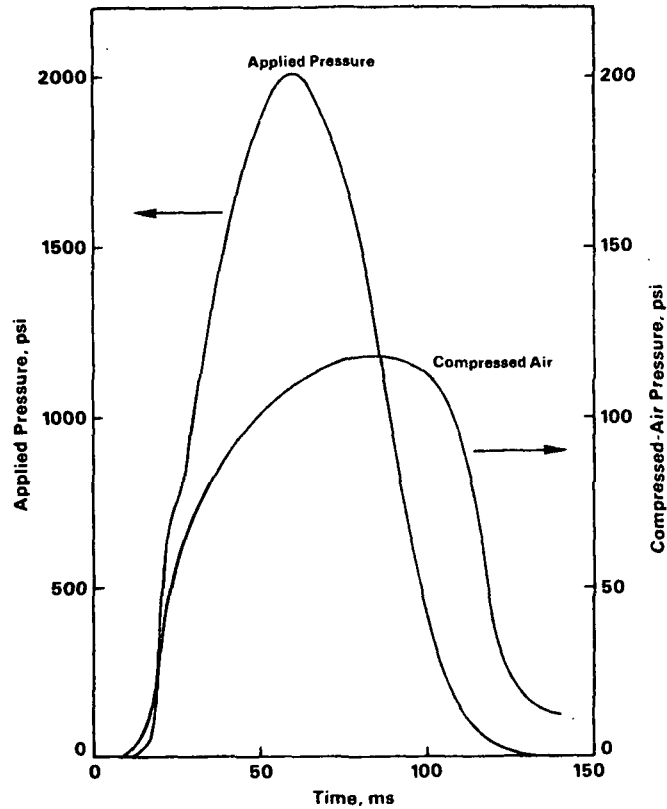


Figure 15. Example applied mechanical pressure and air pressure responses for the harversine mechanical pulse mode.

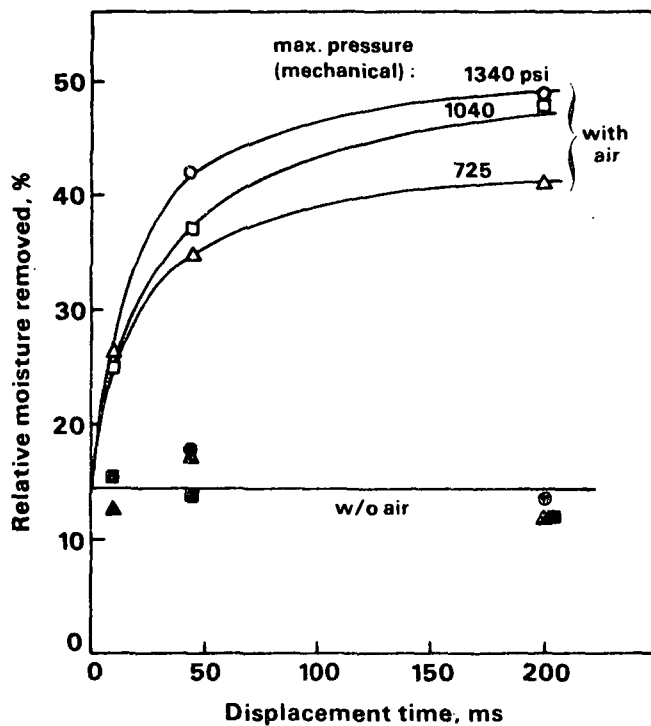


Figure 16. Results of displacement pressing of 63 g/m² handsheets of once-dried bleached softwood kraft pulp at 720 CSF. Initial dryness = 43-45%.

flow resistance at higher compression levels is apparently insufficient to overcome these beneficial effects. These displacement pressing results are particularly encouraging because they indicate that significant dewatering occurs in times approaching those for available pressing equipment (e.g., up to 50 ms).

Because the bronze wire/drilled plate combination yielded marked (dimpled) sheets after pressing, other load spreader/air distributor materials were tried. These included plastic wires and porous metal plates. The use of porous plates tended to result in somewhat reduced water removal. The plastic wire was stiffer than the bronze wire and reduced dimpling without significantly changing water removal. Therefore, it was adopted for use in subsequent experiments.

Although not studied thoroughly, several tests using "square," rather than haversine, mechanical pulse shapes were performed. In some cases, the displacement air application was delayed by ~50 ms, as shown in Fig. 17, to determine the effect of precompression. No appreciable differences in water removal were observed with these pressing modes, as compared to the use of haversine pulses with mechanical precompression, for similar displacement times. These results support the notion that displacement time is a critical variable rather than compression time, consistent with the results obtained in the static press.

Increases in peak mechanical pressure (to 2000 psi), air supply pressure (to 200 psi) and sheet initial dryness (to ~49-51%) were also explored. The combined effect of these changes was an increase of several percentage points in final sheet dryness (up to the 64-65% range) within the same time range as shown in Fig. 16. These higher air supply pressure and initial dryness levels were then retained in subsequent tests.

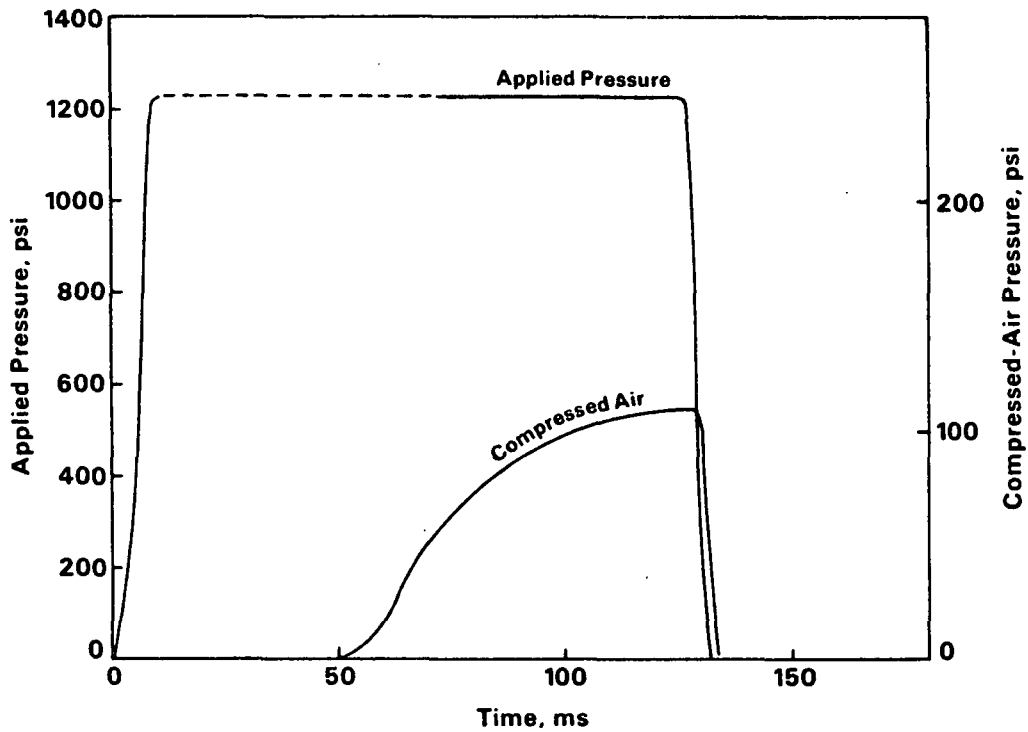


Figure 17. Mechanical and air pressure responses for "square" pulse with air supply "triggered" after 50 ms of sheet compression.

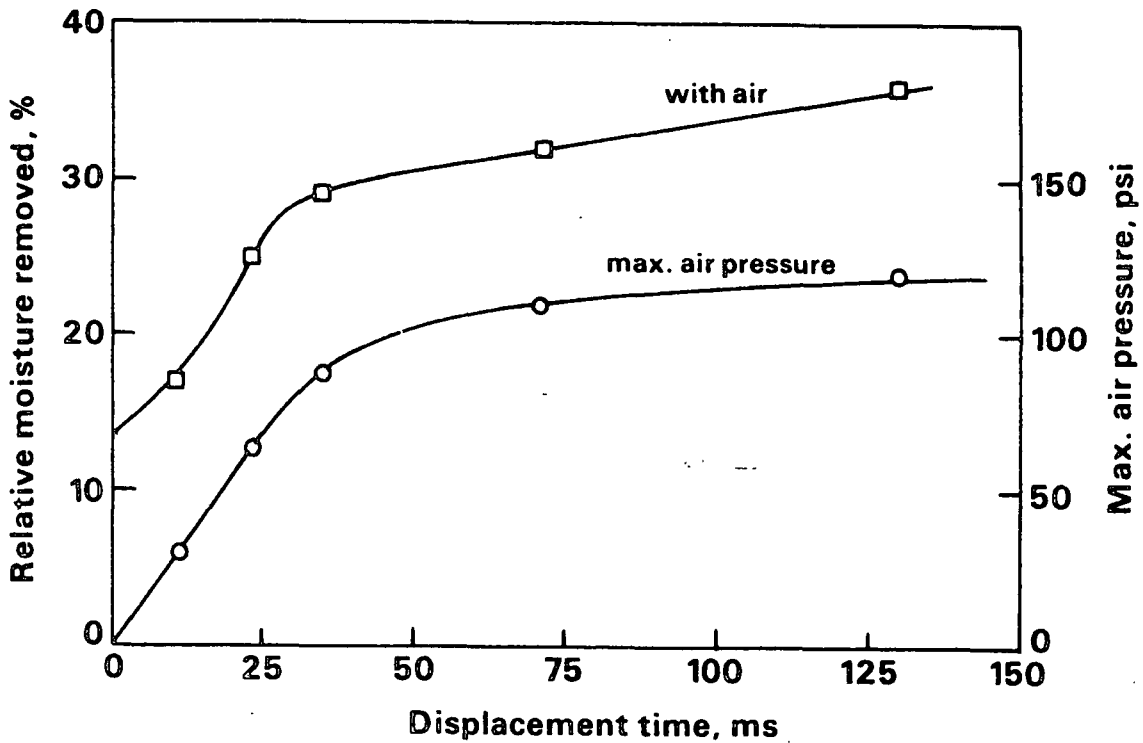


Figure 18. Results of displacement pressing of 63 g/m² handsheets of never-dried bleached northern softwood kraft pulp at 690 CSF. Initial dryness -50%.

The next phase of experimentation involved comparing the displacement pressing behavior of never-dried pulp (bleached northern softwood kraft), at two freeness levels (690 and 300 CSF), with that of the previously discussed once-dried pulp. One of the operating conditions used a "square" mechanical pulse, with ~50 ms precompression time and 130 ms displacement time, at a level of 1200 psi. For 63 g/m² handsheets at about 49% initial dryness, the water removal amounts for the 720 CSF once-dried, the 690 CSF never-dried, and the 300 CSF never-dried pulp handsheets were 47%, 33%, and 20%, respectively. Rather similar results were found using other pulse shapes and somewhat shorter displacement times. For all three sheet types, pressing without displacement air yielded about 15% water removal.

The effects of displacement time and pulp freeness have been investigated in one of the most definitive portions of the displacement pressing study so far. Handsheet samples of 63 g/m² basis weight, formed from never-dried, bleached northern softwood kraft pulp at freeness levels of 300 and 690 CSF and having an initial dryness of about 50%, were employed. Mechanical pressure pulses of "square" shape, at a level of about 1200 psi, were used. The compressed air supply was "triggered" after 50 ms of sheet compression. Typical mechanical and air pressure responses are shown in Fig. 17. The water removal curves resulting from these tests are shown in Fig. 18 and 19. In the case of the 690 CSF pulp, the displacement times needed to achieve significant dryness increases were on the order of 25 ms and, thus, comparable to the response time of the air supply system (i.e., about 40 ms). As a consequence, the maximum air pressure applied to the sheet increased with displacement time (see Fig. 18). Instantaneously applying a given air pressure would probably increase water removal for short displacement times and flatten the curve for longer times.

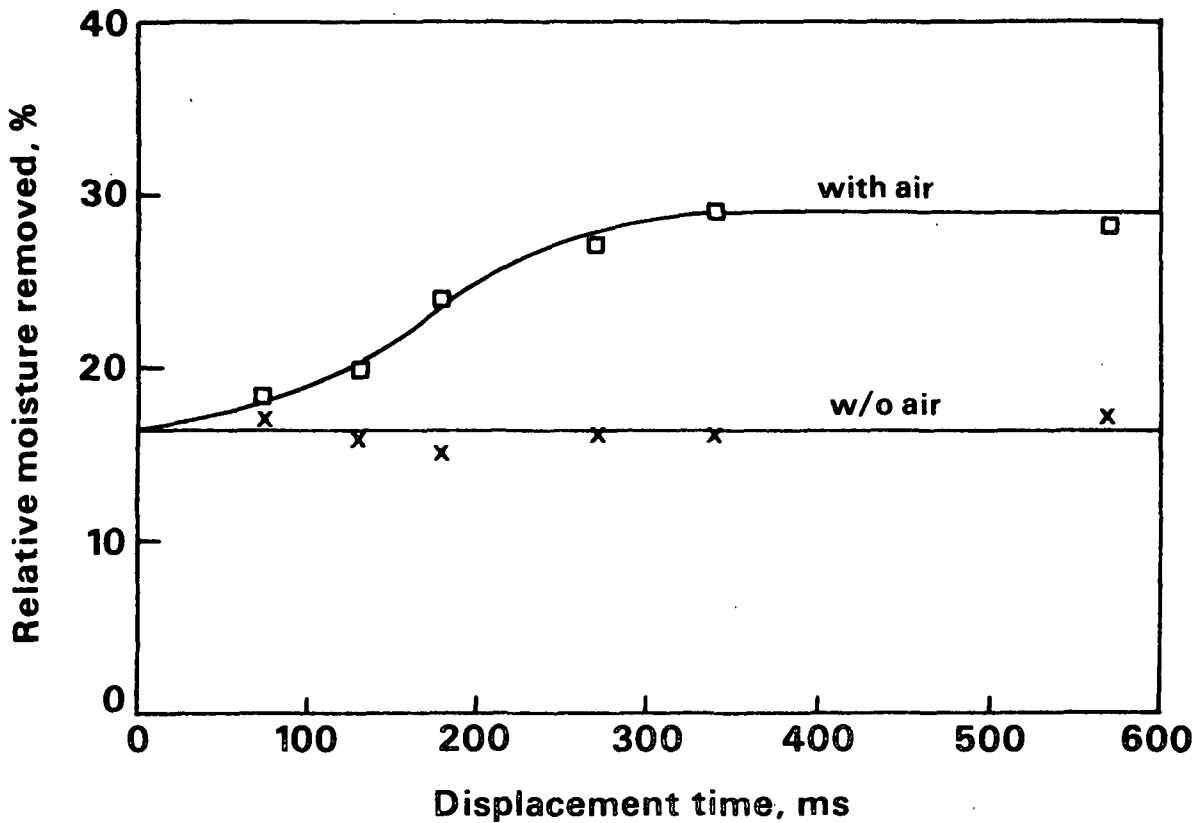


Figure 19. Results of displacement pressing of 63 g/m² handsheets of never-dried bleached northern softwood kraft pulp and 300 CSF. Initial dryness - 50%.

In the case of the 300 CSF pulp, the time required for significant water removal was well beyond the response time of the air system, so the peak air pressures were about the same for all tests. Interestingly, the peak air pressure was greatest for the low freeness pulp (180 psi vs. 120 psi), probably due to differences in sheet flow resistance.

The data presented in Fig. 18 and 19 indicate that significant increments of water removal via displacement pressing are achievable at high ingoing dryness levels. The amount of water available for displacement appears to be somewhat greater for the high freeness case. Importantly, the majority of the water removal occurred in a time period (<35 ms) comparable to the residence time in an extended nip press in the 690 CSF case. For the 300 CSF pulp, the dewatering time was nearly an order of magnitude longer (~300 ms).

The shapes of the displacement pressing curves in Fig. 18 and 19 are in good agreement with that predicted by the simplified model presented earlier in the report. Furthermore, the experimental dewatering times are in reasonable quantitative agreement with those calculated (using estimated parameter values where necessary) from the "pressing time" equation resulting from the simplified analysis.

A few very preliminary experiments were conducted to test the effects of preheating the web and of blinding the back side of the felt to prevent air flow-through. The results are too limited to permit definite conclusions, but suggest that preheating will increase water removal and that blinding the nip has little effect. If the latter observation holds up under more complete testing, it may be significant in reducing air flow and, therefore, power consumption for supplying the displacement air.

DISPLACEMENT PRESSING FOR BULK CONTROL

As stated previously, pressing usually increases final sheet density in direct proportion to the increase in dryness. For some grades, higher densities are undesirable. Examples include absorbent grades, boxboard and some printing paper. For all grades, high dryness out of the press is desirable for good runnability, productivity and low drying energy costs. To achieve both low density and high dryness, it is necessary to decouple the density-dryness relationship common to conventional wet pressing.

Density is developed by compressing the sheet to remove water from the fiber. This density is at least partially retained in the final product if the water remaining in the sheet after pressing is removed before the sheet can reswell. Because conventional pressing relies on strong compression of the sheet for water removal, dryness and density are closely linked. In displace-

ment pressing, however, the sheet can be compressed slightly to make water available for removal. The water is then displaced (removed) by air flowing into the sheet from an external pressure source. In this fashion, sheet dryness can be increased without significantly densifying the sheet. The degree of bulk retention depends on the moisture level at which displacement pressing is started.

Displacement pressing (DP) for high bulk uses the same equipment and procedures previously described for pressing to high dryness levels. Here, however, the DP process is started at a low solids content and much lower compression levels are used. For this type of operation, a displacement press would replace a conventional first or second press rather than a third or fourth press, as in the high dryness case.

To evaluate this concept, a number of tests have been carried out using 63 g/m² sheets made from a never-dried bleached northern softwood kraft furnish with a Canadian standard freeness of 690 ml. These sheets were displacement pressed with air and compression schedules like those shown in Fig. 17, i.e., 60 ms of precompression followed by 60 ms of displacement for a total time of 120 ms. Compression levels of 100, 400 and 1500 psi and ingoing dryness levels of about 25, 35, and 50% were used. Displacement pressed sheets were dried on a hot plate to determine final density. Outgoing dryness levels and density levels are shown in Figs. 20 and 21, respectively. Figure 20 also shows outgoing dryness levels without displacement, i.e., the conventional pressing component alone.

From the data in Fig. 20, one can make the following observations:

1. Displacement pressing is very effective in removing water, especially for low ingoing dryness levels.

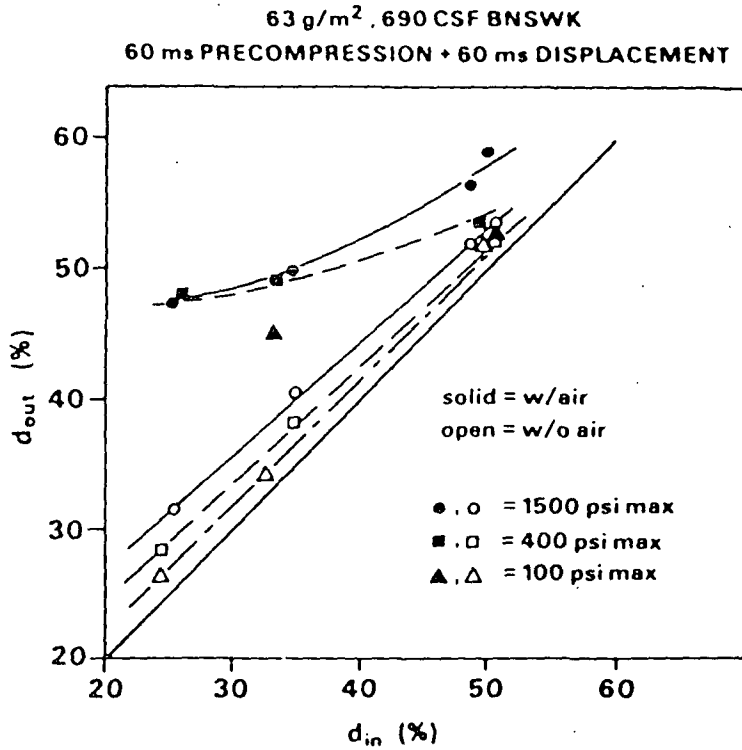


Figure 20. Dryness gains in displacement pressing.

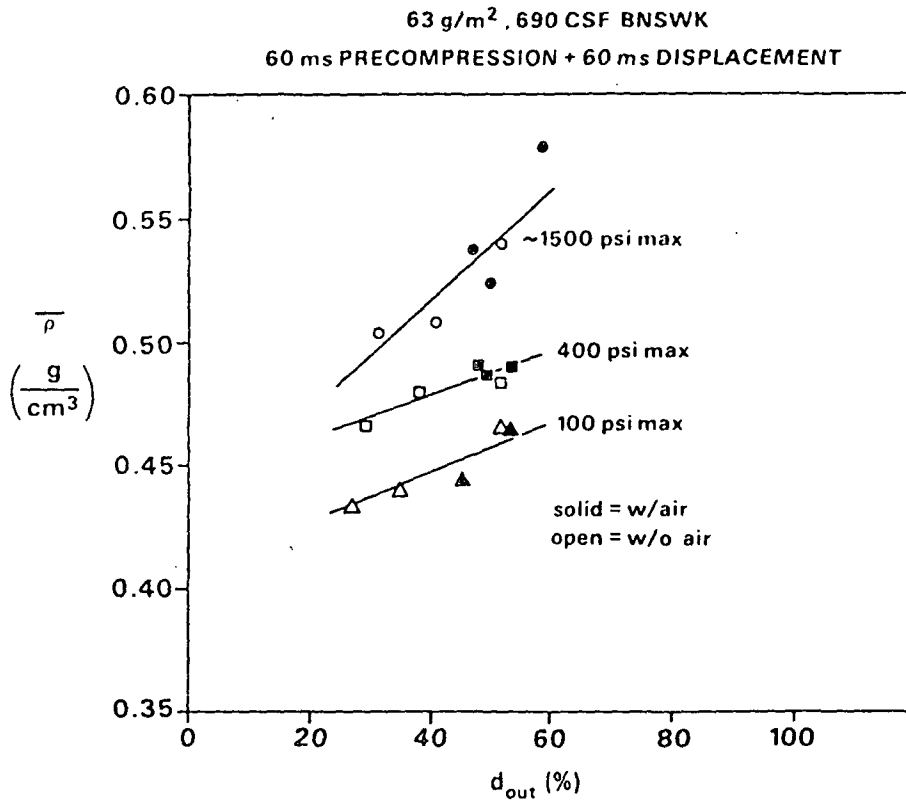


Figure 21. Density development in displacement pressing.

2. Very little of the water is removed by pressing only.
Hence, most must be removed by displacement.
3. Outgoing dryness changes are about 1/3 of ingoing dryness changes. This is equivalent to the rule-of-thumb applied to conventional presses.
4. Water removal is quite insensitive to compression level, especially for low ingoing dryness levels. It is quite remarkable that the solids level can be increased from 25 to 48% in a press operating at a load of 100 psi.

From the data in Fig. 21, it is clear that displacement pressing at low ingoing solids levels can be used to decouple the normal density-dryness relationships. At an outgoing dryness level of 50%, for example, the density ranges from about 0.45 g/cc for pressing at 100 psi, to about 0.54 g/cc for pressing at 1500 psi. For conventional pressing to 50% solids, the density would be fixed, almost totally independent of the specific pressing configuration.

EXPLORATORY EXPERIMENTS - THIRD GENERATION

Third Generation Pressing Head

In an attempt to improve upon the second generation head and add to the measurement system, a third generation head was fabricated. This new head, shown in a cross section drawing in Fig. 22, has a number of important new features highlighted below. These include:

1. An onboard air storage tank, short-coupled directly through a high speed solenoid valve to the test chamber, to supply displacement air. This system avoids the long delay and slow rise of displacement air pressure common to the previous systems. Oscilloscope traces of

typical applied mechanical and air pressure pulses, shown in Fig. 23, illustrated this point. Figure 17 shows corresponding traces for the previous system. The air pressure rise time for this system is about 5 ms.

2. A closed chamber below the sheet, equipped with a pressure transducer to measure the pressure rise caused by air flow through the sheet. This measurement and an appropriate assumption about the thermodynamics of the filling process can be used to calculate the superficial air velocity through the sheet and the displacement power consumption. Figure 24 shows typical load and lower chamber pressure pulses. Back pressure on the sheet is kept low by using a large receiver volume.
3. Improved sealing of the test chamber to preclude leakage to bypass paths.
4. An improved air distributor for faster air pressures rises and more uniform application of pressure.

The resulting head and several of its details are illustrated in Figs. 25-28.

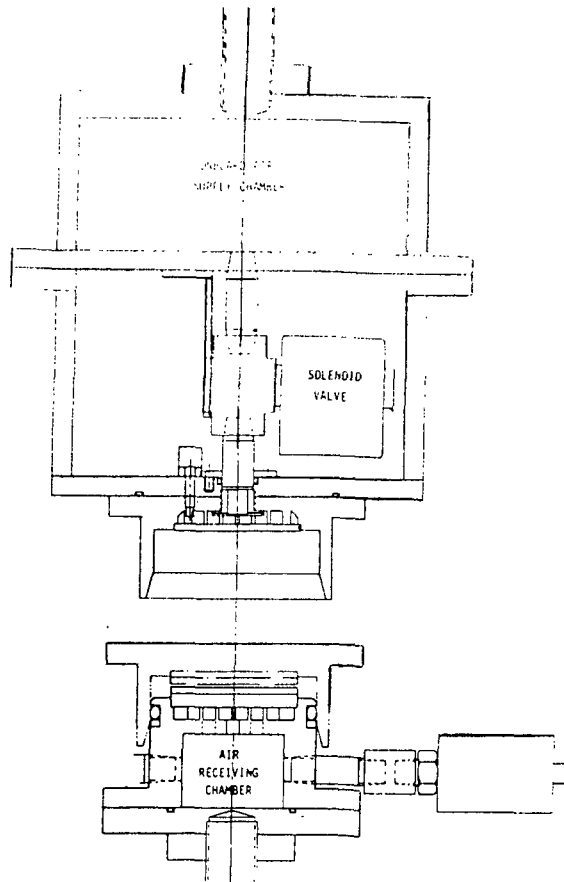


Figure 22. Schematic of displacement pressing head.

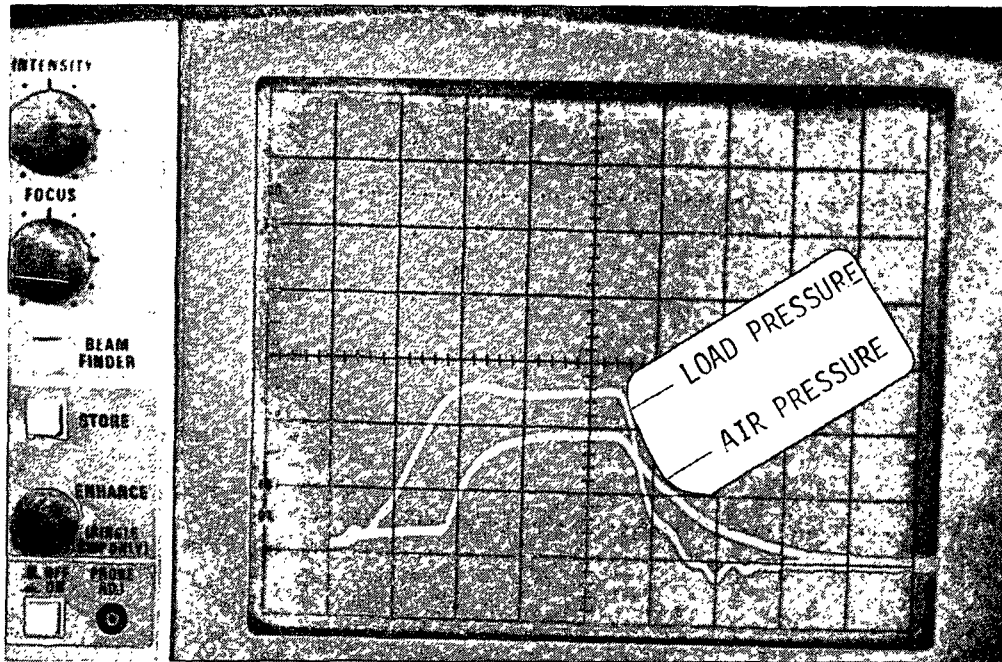


Figure 23. Load and air pressure traces.

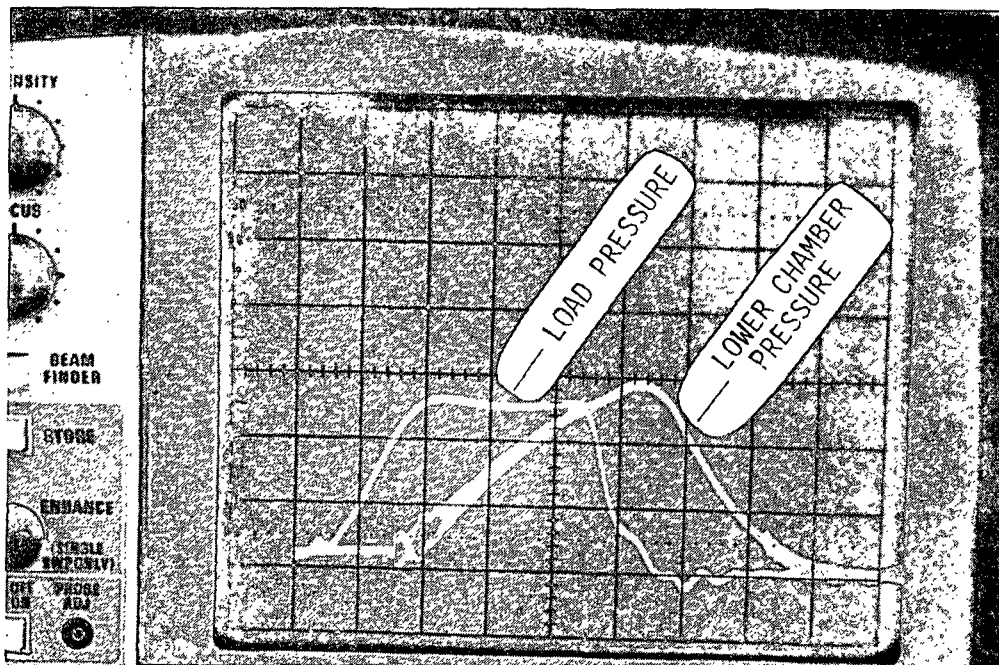


Figure 24. Load and receiving chamber pressure pulses.

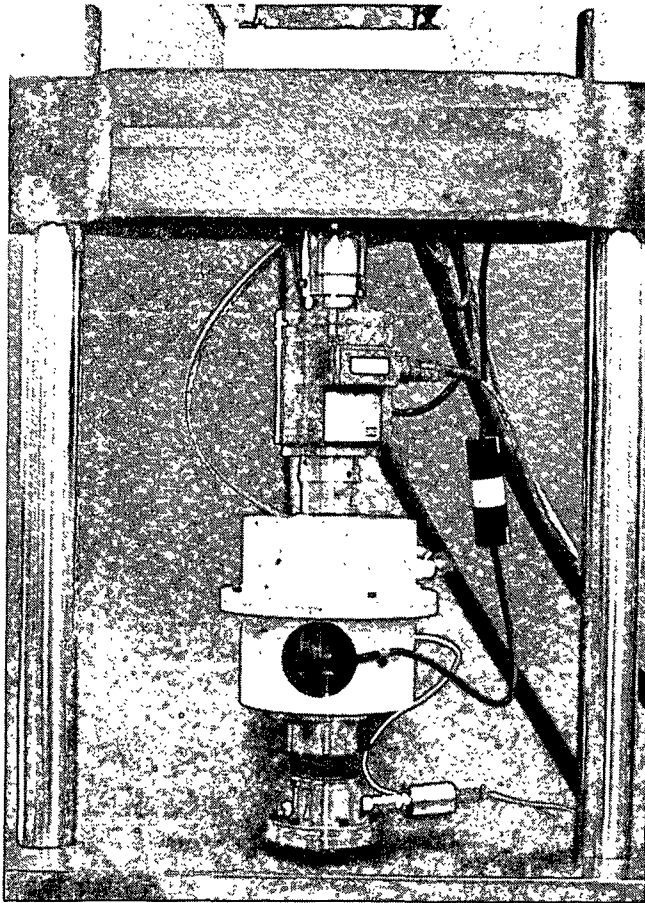


Figure 25. DP head installed in electrohydraulic press.

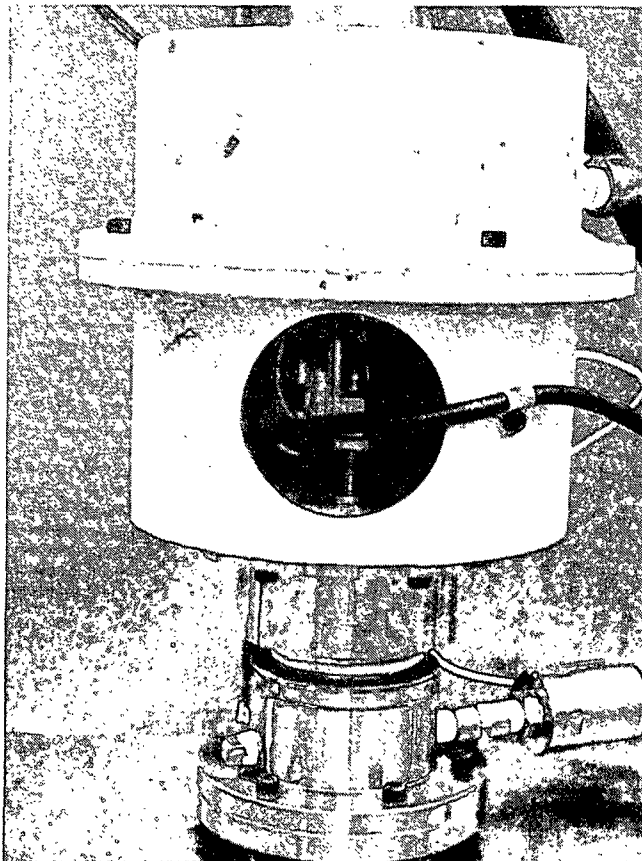


Figure 26. Close up view of head in a slightly open position.

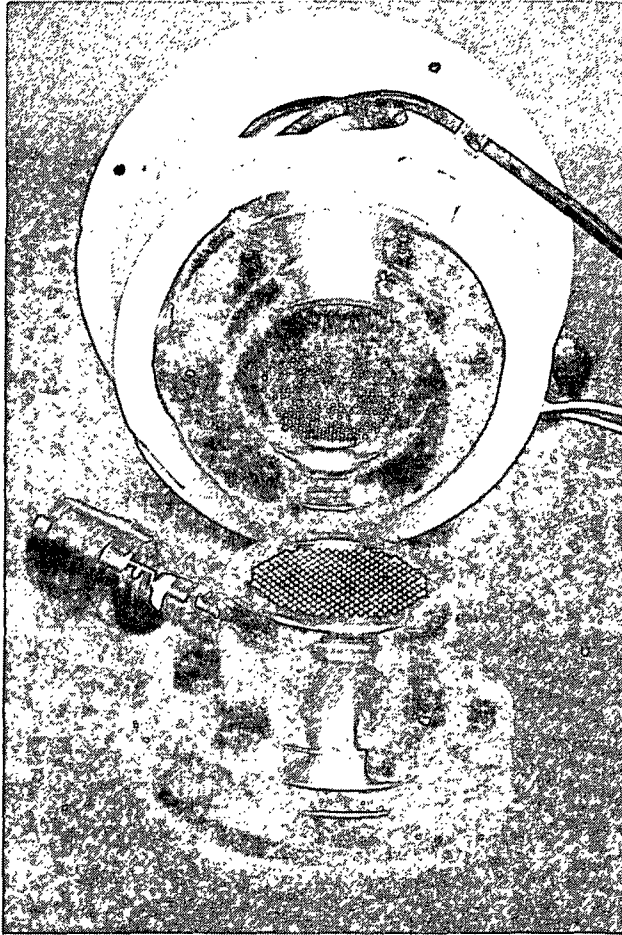


Figure 27. Upper and lower halves of head.

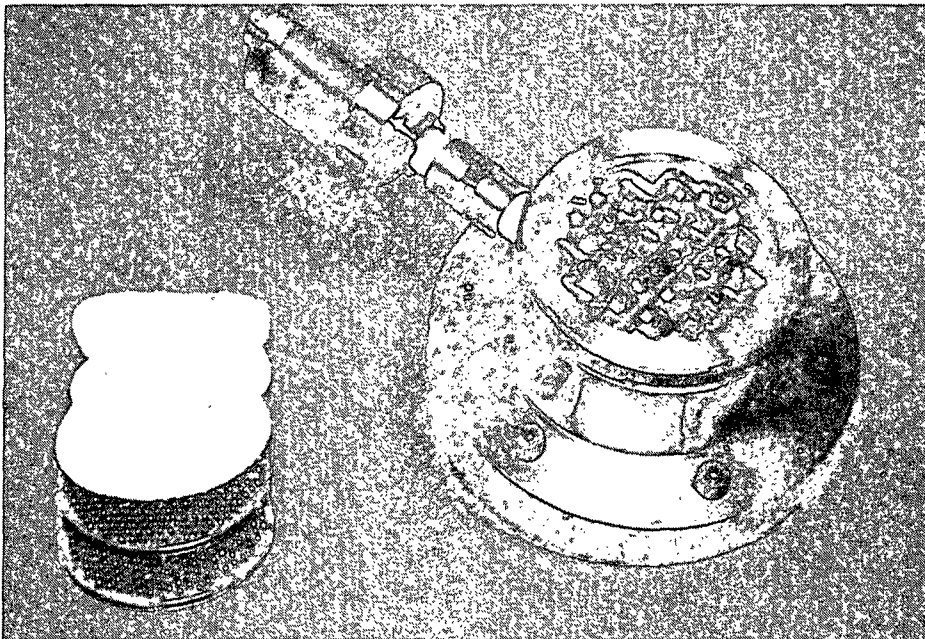


Figure 28. Lower chamber with various layers of load spreaders and water receivers.

Initial tests with the new head proved very satisfactory in all mechanical aspects, but the corresponding water removal values showed wide scatter, precluding effective testing of the displacement pressing process. Although very illusive, the source of the scatter has now been traced to the outer zones of the hole patterns in the lower drilled vent plate. Most recent data show coefficients of variations of 3-5%, regarded as quite satisfactory for a multiple step experiment such as wet pressing. Unfortunately the variability source was found too late to allow completion of the definitive feasibility experiment within the project time frame, but a few of the early data on air consumption and water removal are presented in the next section.

Results

The most important new feature of the third generation head is the air flow measurement system. A few of the early data from this system are shown in Fig. 29 as relative moisture removed (RMR) versus superficial air velocity. Two air pressure levels, two compression levels and three different load/air distributor elements were used in obtaining these data. These same data are replotted in Fig. 30 as RMR versus air horsepower days per ton (HPD/T), where air horsepower was calculated from the superficial air velocity, air pressure and a production speed of 3000 fpm on a 50 g/m² sheet.

For these test conditions air velocities are in the 1-2 ft/sec range and HPD/T varies from about 0.1 to 0.3. Higher compressive pressures clearly lead to greater water removal at a given air flow velocity. Air velocity increases with air pressure with an exponent of 0.5-0.6 or so, thus suggesting that the flow does not obey Darcy's law. The porous plate seems to be more effective than either the plastic or metal screens. Air horsepower requirements

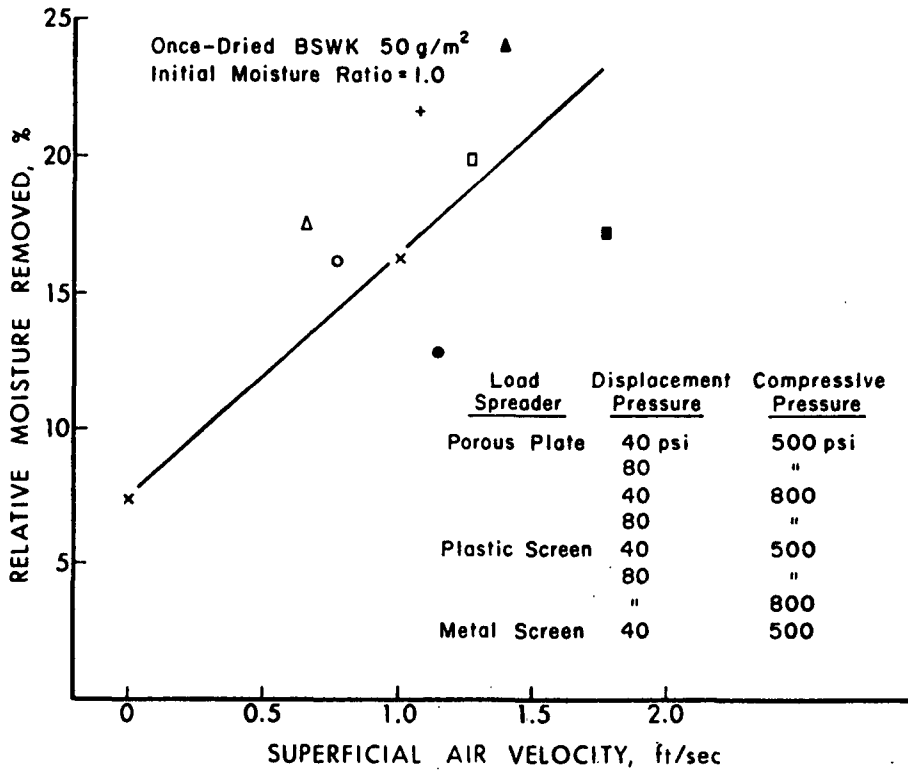


Figure 29. The effect of superficial air velocity on water removal.

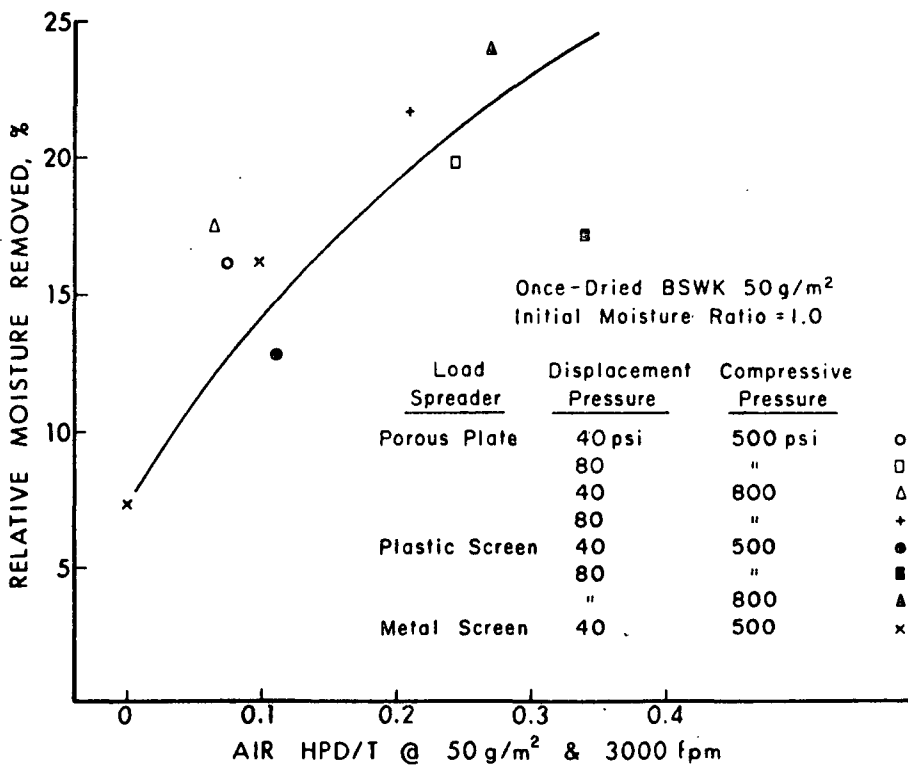


Figure 30. Air horsepower requirements for displacement pressing.

for these conditions are low compared to those for some other papermaking processes, such as refining. All of these data are for a once-dried BSWK pulp.

The air flow experiments described above were all subject to the wide scatter mentioned earlier. A few additional experiments, conducted after the scatter was largely eliminated have confirmed earlier results on both once-dried and never-dried pulps. A design change in the pressing head, now being made, is expected to permanently reduce the scatter to an acceptable level and allow completion of the next large experiment, aimed at providing the data needed to assess the engineering and economic feasibility of displacement pressing.

The intent of the next large experiment is to provide a performance map of the type shown in Fig. 31. Initial moisture content, compression pressure, displacement pressure, displacement time, basis weight and furnish are the key test condition variables. Performance will be assessed in terms of outgoing solids, density, tensile strength and air consumption. This experiment is just now getting underway.

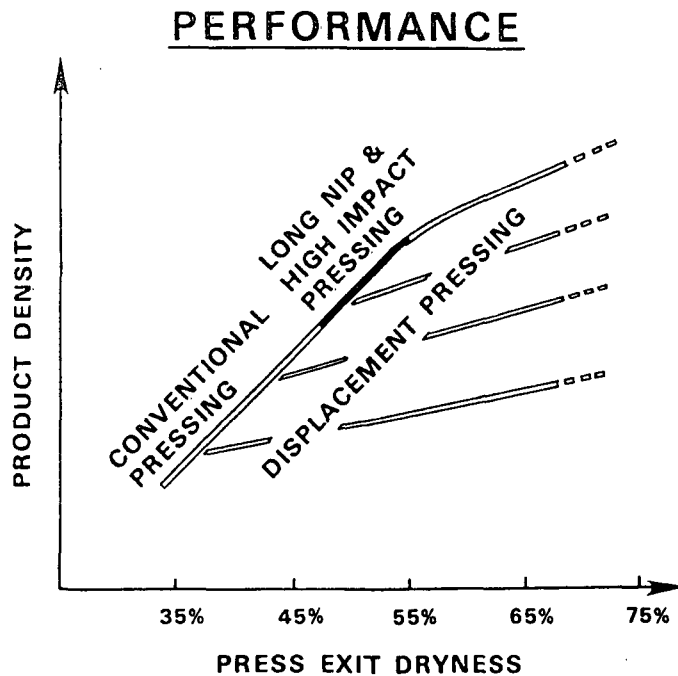


Figure 31. Displacement pressing.

BLOWTHROUGH DEWATERING OF PAPER WEBS - A REVIEW

Drainage or pressing of paper by passing (blowing) air through the wet web is not a new concept. Several devices for this purpose are described in a patent by Holden (3), filed for in March, 1963, and granted November 8, 1966. His work and that of Brundrett and Baines (4) were extended by Kawka and co-workers in Lodz, Poland. Several articles (5-12) have been published since.

Most of the work in Poland has been aimed at the use of the blow-through principle to raise the solids content of the sheet from values in the 10-30% range up to 40-45%. Two representative devices due to Holden (3), used by Kawka, are shown in Fig. 32. An additional device, developed in Poland and called an air press, is shown in Fig. 33. Several other similar devices have been proposed or used (5-12). All have the following characteristics:

- a. low mechanical compression forces on the wet fiber network
- b. long exposure times (0.1-several seconds)
- c. a porous fabric or structure backing the wet web
- d. modest pressure differentials through the wet web (1-30 psi)
- e. low load levels (50-100 pli) on the pressing components, where they were used
- f. low operating speeds (up to 300 m/min)
- g. unheated blowthrough air, in most cases.

Blowthrough dewatering has been applied primarily to lightweight grades where bulk, absorbency, and porosity are important, such as tissue, toweling, and bag papers. There is mention of application to heavyweight board pulp dewatering (11), but no data are given.

Some typical results for a 70 g/m² bag paper are presented in Figs. 34-36. These data were obtained by subjecting sheets with initial solids contents of 18.8, 25.3, and 31.4% to one, two, or three passes through an air press (Fig. 33). Corresponding exposure times were 0.2, 0.4, and 0.6 seconds. Press loads were about 50-100 pli.

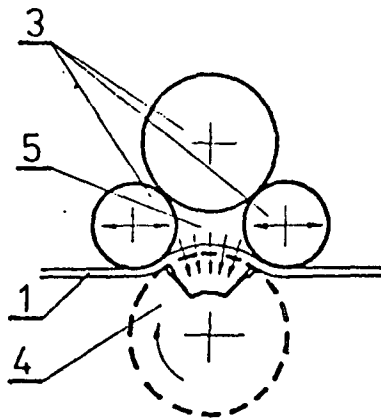


Figure 33. Polish "air press".

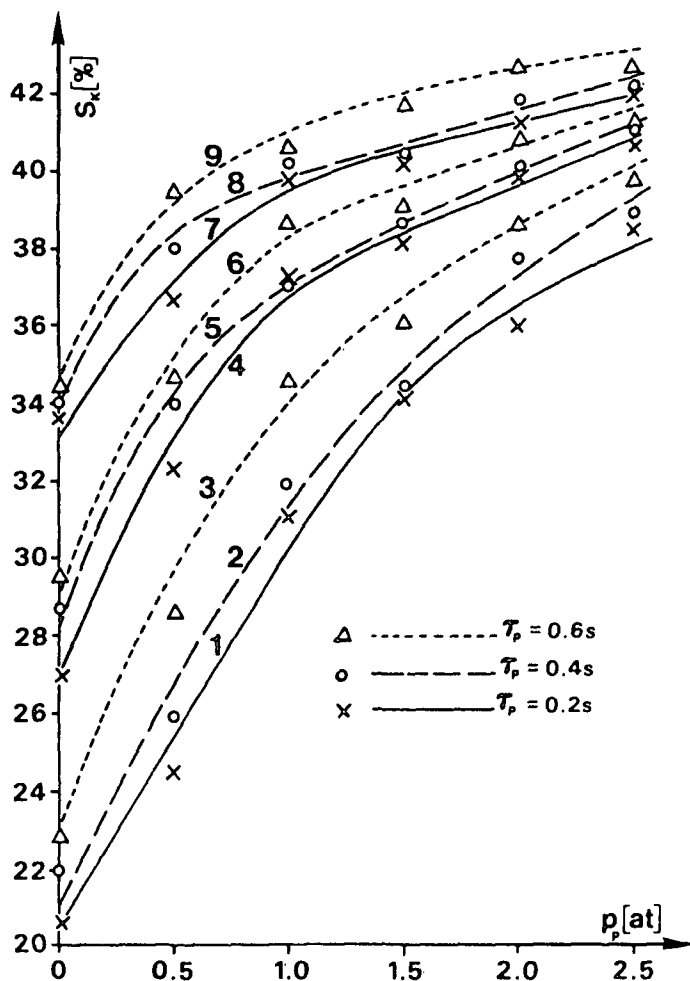


Figure 34. Final dryness (S_k) as a function of blowthrough air pressure differences (p_p) and blowthrough time (τ_p), initial dryness as a parameter. Initial dryness: 18.8% for 1-3, 25.3% for 4-6, 31.4% for 7-9.

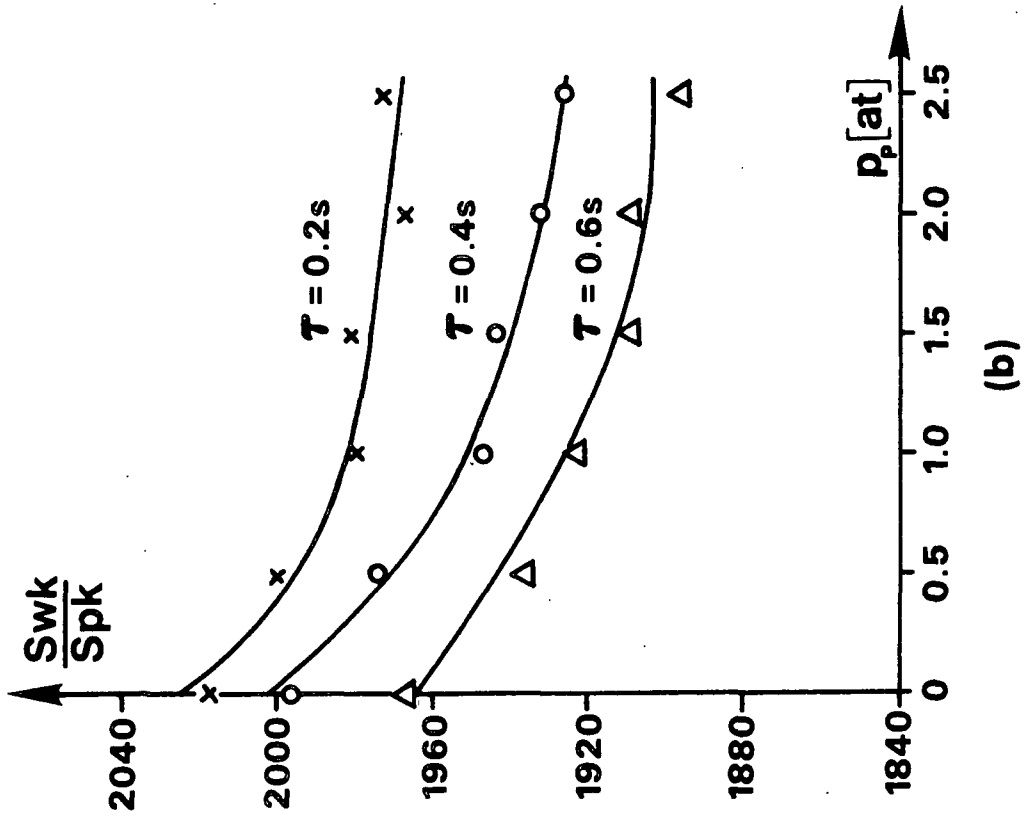
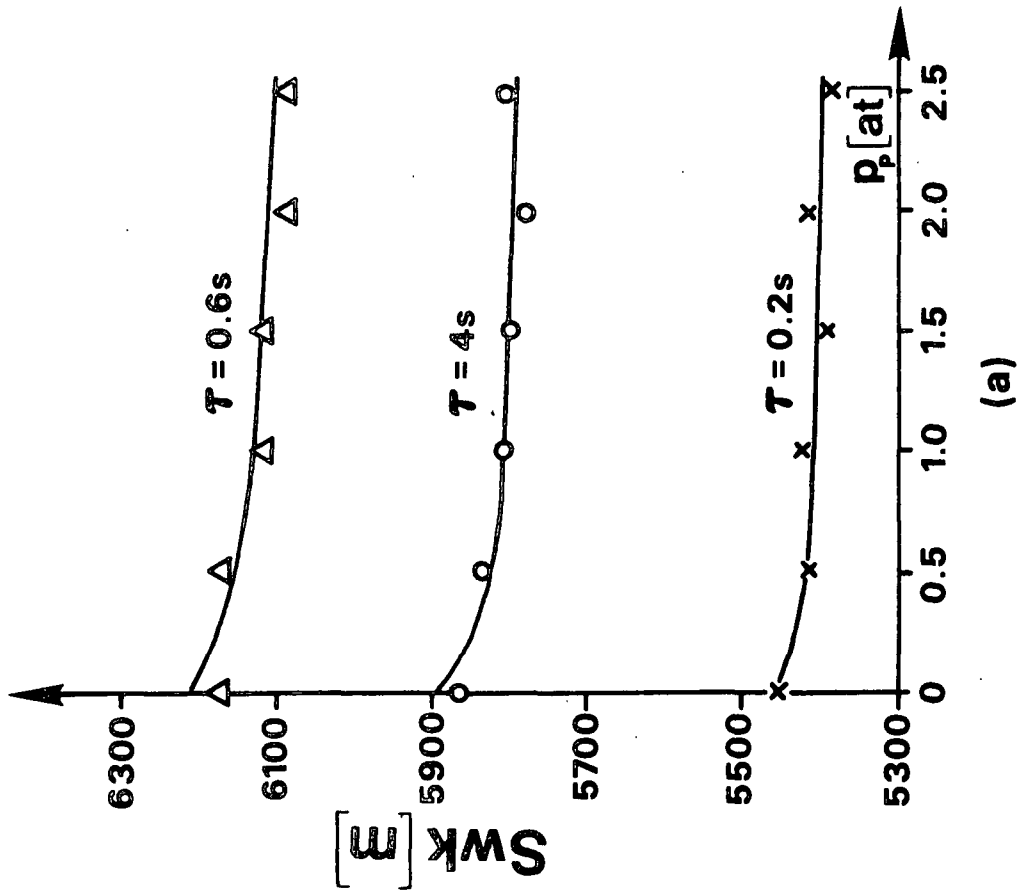
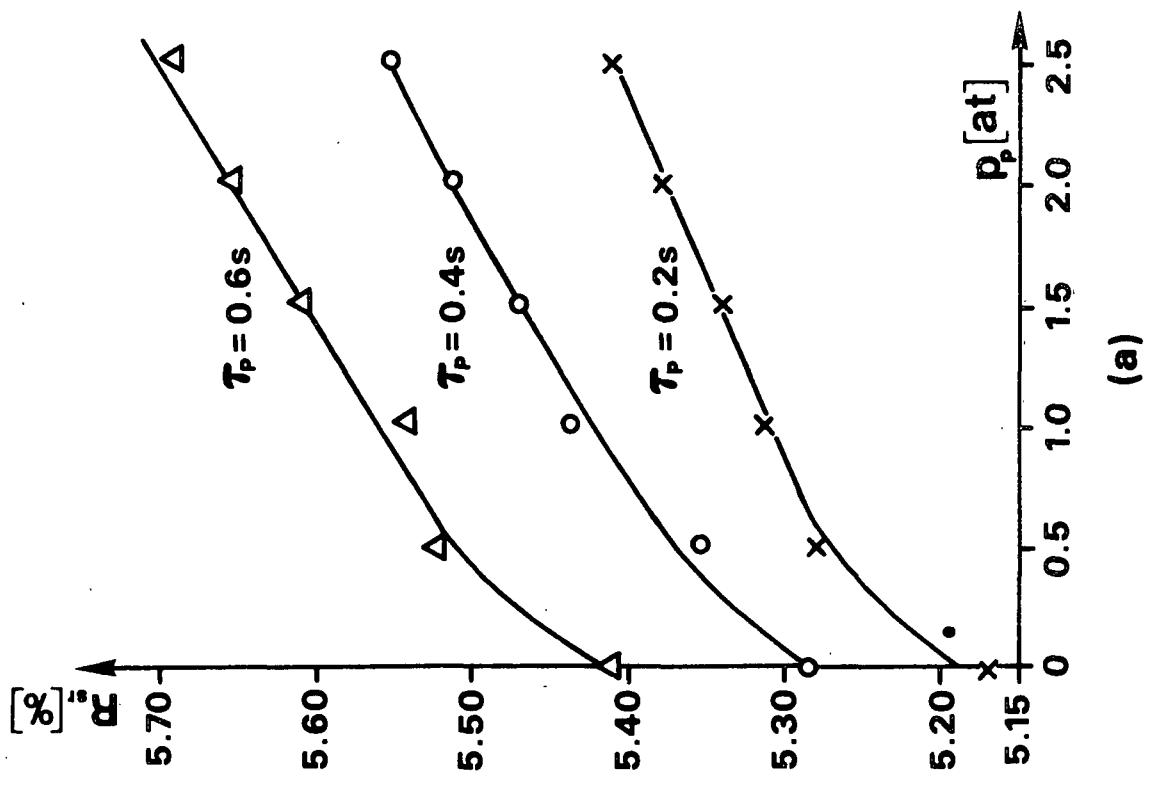
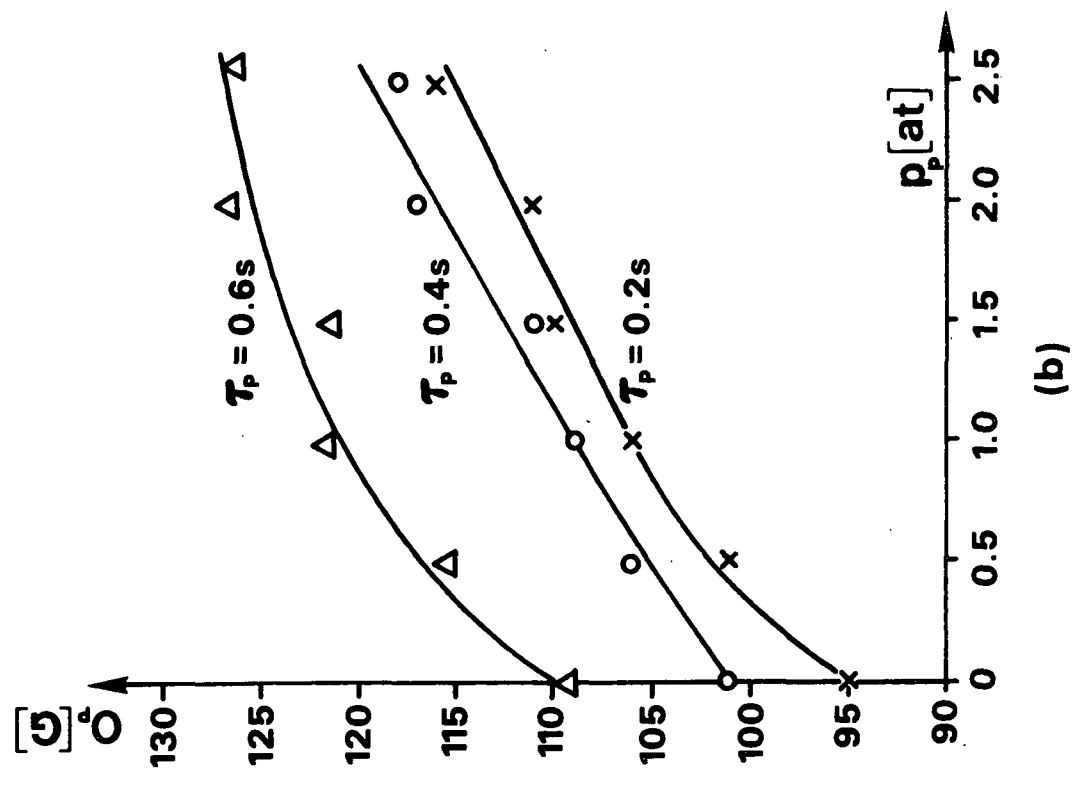


Figure 35. Breaking length and squareness as functions of blowthrough pressure differential.



(a)



(b)

Figure 36. Elongation at failure and tear strength as functions of blowthrough pressure differential.

Figure 34 shows final solids values as a function of the blowthrough air pressure differential. The following observations apply to these data:

- a. This type of blowthrough water removal is most effective on wet sheets (10-20% solids).
- b. Increased dryness from additional passes - more blowthrough time - seems mostly due to mechanical pressing and not to blowthrough.
- c. For the web tested and the prevailing dewatering conditions, the maximum solids level is limited to about 42%.
- d. More air pressure gives higher dryness levels, but the effect diminishes at a transition pressure (1.0-1.7 atm) which decreases with increasing initial dryness.

Figure 36 shows elongation at failure and tear strength as functions of blowthrough pressure. Both show significant improvement with mechanical pressing ($p_p = 0$) and even more dramatic improvement with increased blowthrough.

Other properties, not shown in these figures, were also altered. Blowthrough dewatering tends to give much higher bulk (100% more), higher porosity, and higher absorbency than conventionally consolidated papers.

Air pressing is thus effective in dewatering wet webs ($\leq 40\%$ solids) and in promoting bulk, absorbency, stretch, tear, and squareness. Tensile strengths tend to be degraded slightly. The efficiency (cost) of such pressing is hard to assess, but in one example cited (5) the direct air power delivered to the web was about 4 million Btu/ton which is substantial. The authors state that the primary advantage is in property control and not in energy cost reductions.

In some of the papers, experiments involving high temperature air and long exposures are cited. These constitute through-drying experiments and are not germane to the IPC projects.

The work outlined above has been cited because it is relevant and complementary to the IPC work, and it supports the expectation that displacement pressing of low solids sheets will result in high bulk levels. Most of the IPC work, however, is aimed at quite different objectives and operating regimes. For example, the displacement pressing process under study in this project has been shown to have the potential to:

- a. extend pressing solids levels from 50 up to 65% thus augmenting conventional drainage and pressing elements and displacing dryers,
- b. work over a range of mechanical pressures up to high levels to permit improvement and control of properties, including strength or bulk, thus making it attractive for use on several grades,
- c. reduce drying energy levels substantially and reduce dryer size or increase productivity, and
- d. work over the short time intervals characteristic of modern, high-speed machines.

All of these expectations fall well outside the range of the previously completed work and the capability of the various presses that have been developed. None has the potential for extension to the displacement pressing regime.

PRESSING PROCESS MODELS AND NIP EFFICIENCY

INTRODUCTION

The total energy consumption in the production of paper is about $30\text{-}50 \times 10^6$ Btu/ton, depending on grade. Almost 30% of this energy is used for drying the paper, whereas the energy for pressing is almost negligible. For each percentage point increase in dryness achieved through pressing, there is a corresponding 4-5% reduction in drying energy use. For current practice, maximum pressing dryness levels are around 45%. Ceckler and Thompson (13) pointed out that by improved water removal via wet pressing, energy savings as large as 28% can be expected. If only half of this potential saving could be realized on all U.S. paper machines, then 16 million barrels of oil per year could be saved.

Pressing to higher dryness levels has many benefits other than direct saving of drying energy. One of these is greater wet web strength. Increases in strength reduce the probability of a web break in the open draw between the press and the dryer. For many machines, web breaks constitute a serious speed limitation, thus pressing to higher dryness would lead to much higher production rates. The productivity of machines that are currently dryer-limited would also increase. The economic significance of improved runnability is great.

A third benefit from increased dryness is improved paper properties for better end-use performance, or more importantly, equivalent performance from less fiber or lower quality fiber. The latter translates directly to energy savings at the rate of $30\text{-}50 \times 10^6$ Btu/ton of fiber saved. Property improvements stem directly from increases in density which are known to occur as water removal effectiveness increases.

The incentive to increase water removal in the press section has led to improved felt design, operation at higher pressures, hot pressing and, more recently, the introduction of the extended nip press. The latter innovation is a very significant one, for as machine speeds have increased, the nip residence time has decreased. As shown in the University of Maine study and elsewhere, water removal depends on the impulse (the product of average pressure and nip residence time), particularly for heavier basis weight webs such as linerboard. There are practical limits to the pressure that can be applied without crushing the sheet, so significant increases in the impulse can be achieved only by increasing the nip residence time. The extended nip makes it possible to increase the nip residence time by at least one order of magnitude.

The use of steam showers to heat the web in the press section has also been shown to be beneficial, but the improvements in water removal are not dramatic. Attempts to improve wet pressing by modifications of the roll surfaces have led to marginal improvements at best.

A better understanding of the ultimate limits of water removal and quality development by wet pressing is needed to optimize the process to gain the benefits described above.

UMO WET PRESSING PROJECT RESULTS

Under the sponsorship of the U. S. Department of Energy (DOE), the Department of Chemical Engineering at the University of Maine at Orono recently completed a major study of the wet pressing process. One major objective of that work was to develop a model to predict the performance of real presses, given proper information about the furnish, the press design and the pressing conditions. To develop this model, it was necessary for the UMO to obtain compressibility, permeability and capillary pressure data on the furnish in question for conditions appropriate to the intended model use.

Moist web compression behavior is very time and moisture level dependent. Hence, the compressibility data had to be collected within the same time scale as occurs in a real press. To gather these data and also to simulate a pressing process, a laboratory compression tester was constructed, as shown in Fig. 37. An ample description of this tester is given in Ceckler and Thompson (13). Several aspects of design and test procedure should be noted, however.

1. The press uses a vented porous plate as the water receiver. A stainless steel plate with an average pore size of 40μ was selected to correspond to the pore sizes in typical pressing felts.
2. Proximity detectors were used to measure the separation between the pressing platen and the incompressible porous plate. This separation corresponds to instantaneous sheet thickness which was used to determine the compression behavior of the sheet. By assuming that the sheet was always saturated, instantaneous water removal was also obtained from sheet thickness. Total water removal in a given pressing simulation was taken to correspond to the minimum sheet thickness attained.
3. Saturation of the sheet and porous plate was assured by initially flooding the nip. A desired initial moisture ratio was established by presetting the thickness to that for a saturated sheet.

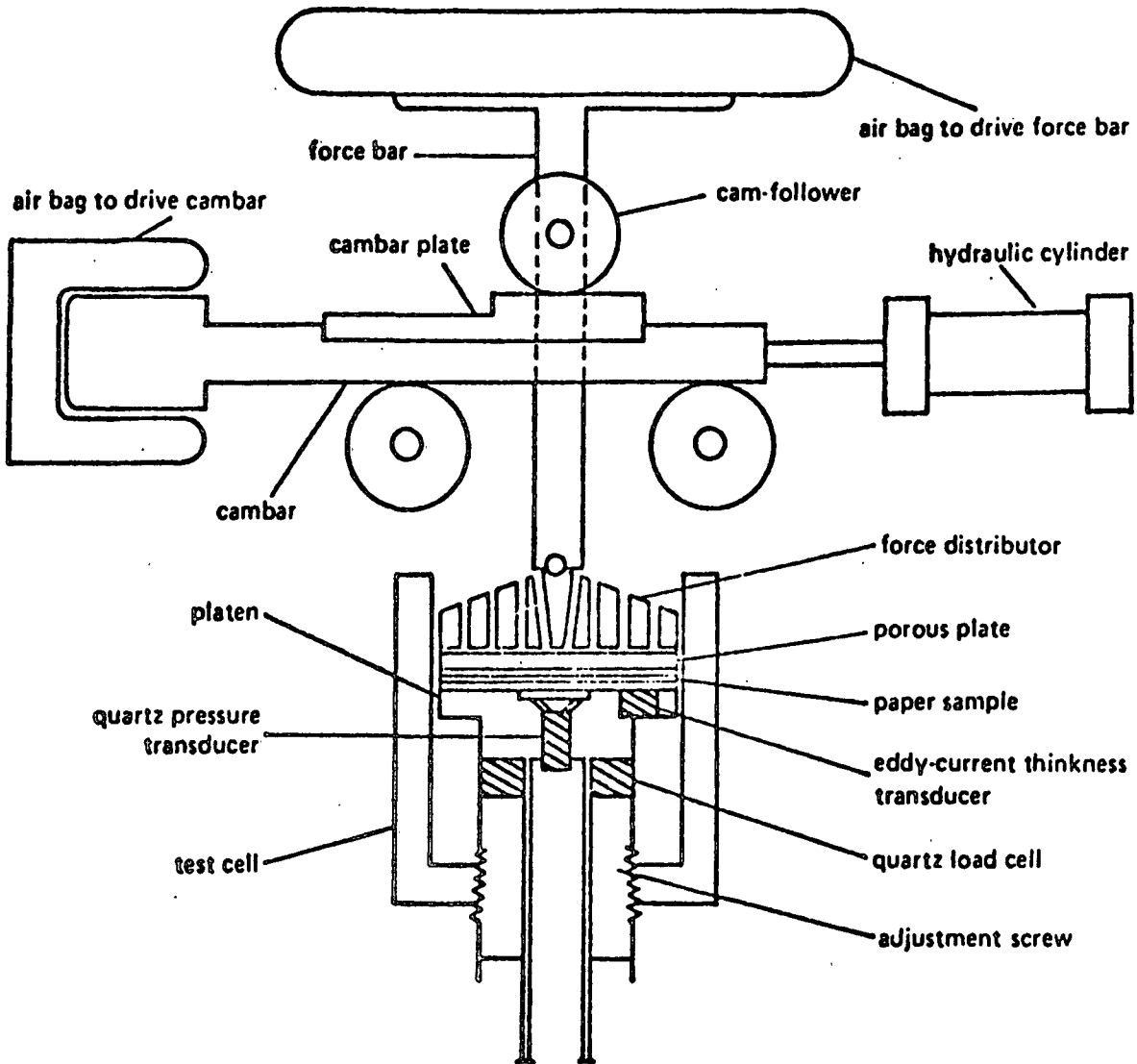


Figure 37. Schematic drawing of UMO compression tester.

Compressibility data, measured as described above, and permeability and capillary pressure data, measured initially in separate experiments, were used to develop a model to describe water removal in a press nip. This model was quite successful in describing water removal in the laboratory compression tester as illustrated by the data in Fig. 38. Absolute agreement between the water removal in the laboratory compression tester and a pilot press - Fig. 38 - was quite poor, however, although the trends were very similar. In general, the compression tester showed much higher water removal levels than the pilot press. Examination of the data showed that one set could be shifted by a common factor to coincide with the other set. This factor has been called a "nip efficiency" factor, but is more appropriately a correction factor to adjust the model data to agree with the real (pilot) press data. A given correction factor applies over only a very narrow range of furnish and pressing conditions, so a new one must be determined for each new set of conditions. The correction factor may vary over at least a 4 or 5 to 1 range; hence, the accuracy of the estimate of pressing behavior obtained with the model is critically dependent on the accuracy with which the correction factor is known.

Because the water removal determined in the lab press is always much higher than in the pilot press, the correction factor is always less than 1.0, sometimes substantially less, as in Fig., 38, for example. In the Phase I report (13), it was speculated that the porous plates used in the compression tester are more effective at water removal than are felts because they provide a more uniform application of pressing pressure. Interpretation of these results was confounded by the differences in the test equipment used for comparison; a lab compression tester operating in a perpetually saturated state with thickness determined water removal on the one hand, and a pilot press operating normally with gravimetrically determined water removal on the other.

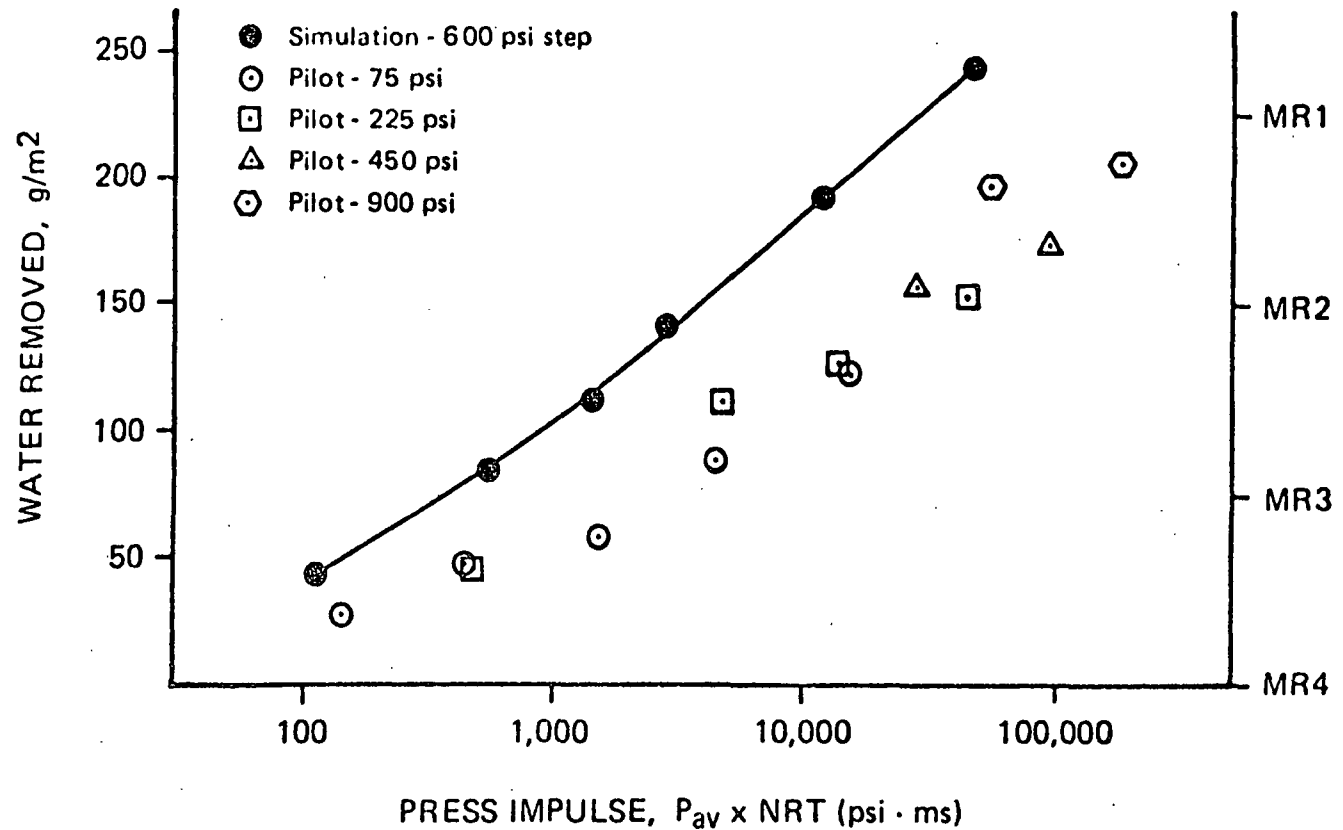


Figure 38. Comparison between pilot and laboratory simulations for 300 CSF bleached softwood kraft, 75 g/m².

Whatever the cause of the discrepancy between the water removed in a real press and that removed by the compression tester or predicted by the model, the difference is so large as to require further investigation. Accordingly, the second part of this limited study was undertaken to:

1. Compare the performance of porous plates and felts as water receivers, when tested under identical conditions accurately simulating commercial pressing.
2. Determine the characteristics of porous plates important to pressing performance, given a favorable result from Step 1.
3. Identify and assess the other factors having a potential to influence nip efficiency.

POROUS PLATES AND NIP EFFICIENCY

Because the emphasis of this pressing study was initially on determining whether porous plates promote greater water removal than felts, a variety of porous plates was obtained for use in the experiments. The plates used in the work reported here are identified in Table 1.

Table 1. Porous plate characteristics.

Designation	Material	Approx. pore size, μ	Surface
SB10	Sintered bronze	10	Unground
SB30	Sintered bronze	30	Unground
SB40	Sintered bronze	40	Unground
SS40 ^a	Sintered stainless steel	40	Ground
SS100	Sintered stainless steel	100	Ground

^a This is similar to the plate used in the UMO study.

A pressing pedestal (Fig. 39) was fabricated for use in the water removal experiments. It is a vented nip configuration (drilled plate) and has provision for use with any of the porous plates. When a felt is employed, it is placed on top of a very coarse (250 μ pore size) porous plate installed in the pedestal as a load spreader.

Many of the results reported here were obtained by using a falling-weight press simulator with this test head installed. Chang, Nett, and Beck (2), have shown that the falling-weight (Wahren-Zotterman) press simulator provides a very good simulation of a real press nip, including both the compression and expansion parts of the cycle. This system is particularly well suited for modest pressing pressures (<500 psi peak) and nip residence times up to 10 ms or so.

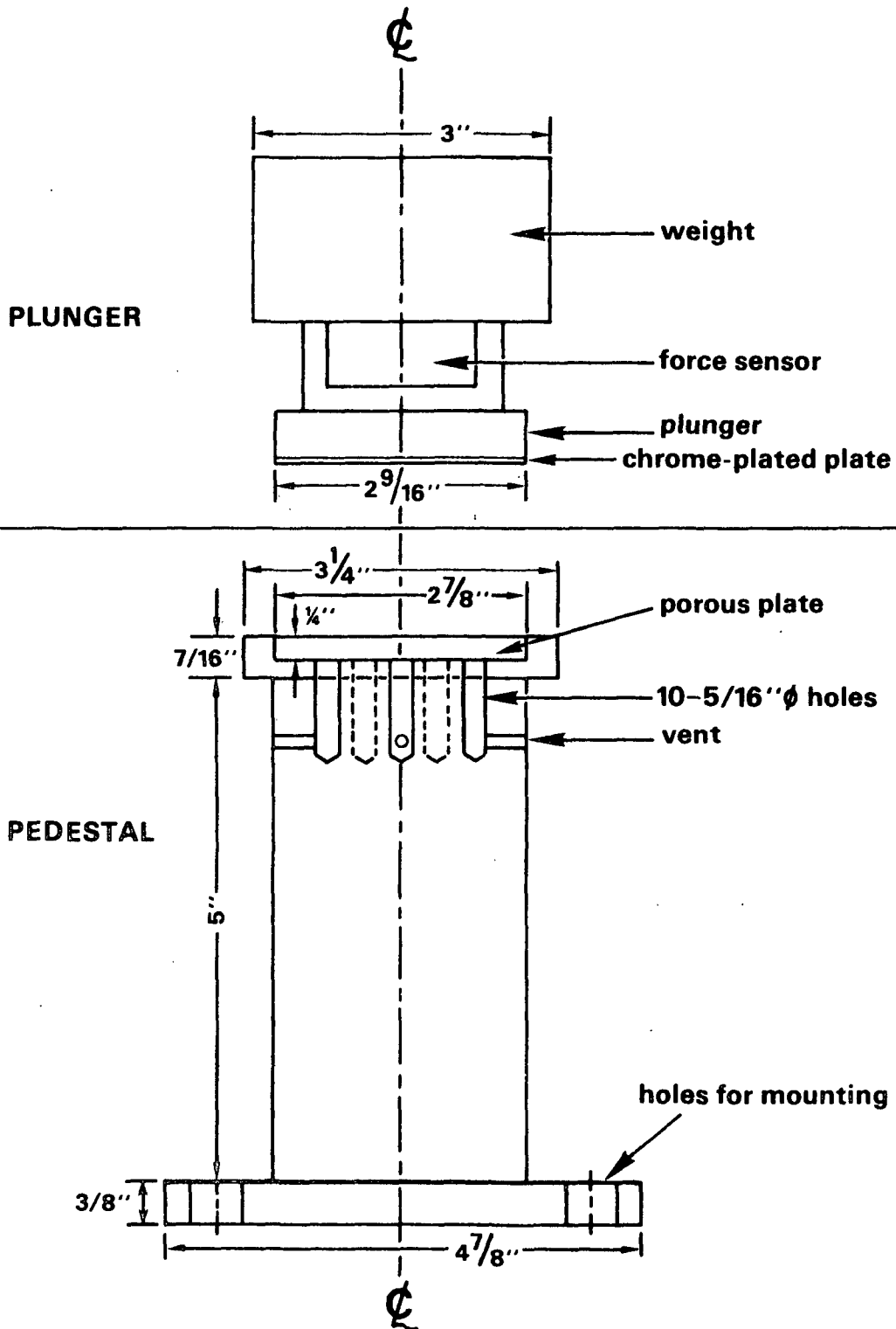


Figure 39. Pressing configuration for porous plate - felt comparison studies.

For high pressures and longer nip residence times, an electrohydraulic press has been used with the same pressing heads or variants thereof. In both presses, water removal was measured directly from initial and final weights. Pressed sheets adhere to the chrome plated surface assuring instantaneous separation of sheet and water receiver to avoid post-nip rewetting.

Results

Initial, exploratory experiments were performed using 60 g/m² handsheets formed from (once-dried) bleached softwood kraft pulp at about 700 CSF. The initial moisture ratio of the samples was 3.0 for all the tests.

For the purpose of comparison of porous plate performance with felt performance, it was considered appropriate to operate each water receiver at that initial moisture ratio for which water removal from the sheet is maximized. Based on tests at an operating condition of 600 psi peak mechanical pressure and 6.0 ms nip residence time, it was found that all the porous plates performed best when initially dry, while the felt performance was 6-7% better at 0.3 moisture ratio (the optimum value) than when dry. These "best" moisture conditions were then used in subsequent experiments, except as noted.

The water removal data from the tests just described and from tests at a higher impulse level are presented in Fig. 40 for the felt and the three best porous plates. For these test conditions, the felt promotes greater water removal than that achieved with any of the porous plates for both pressing conditions. The ranking of the three porous plates seems to be in agreement with expectations. That is, the rather smooth, small-pored plate is best; the very smooth, but larger-pored, plate is next; and the least-smooth plate is worst. Two other, still coarser, plates yielded even poorer performance.

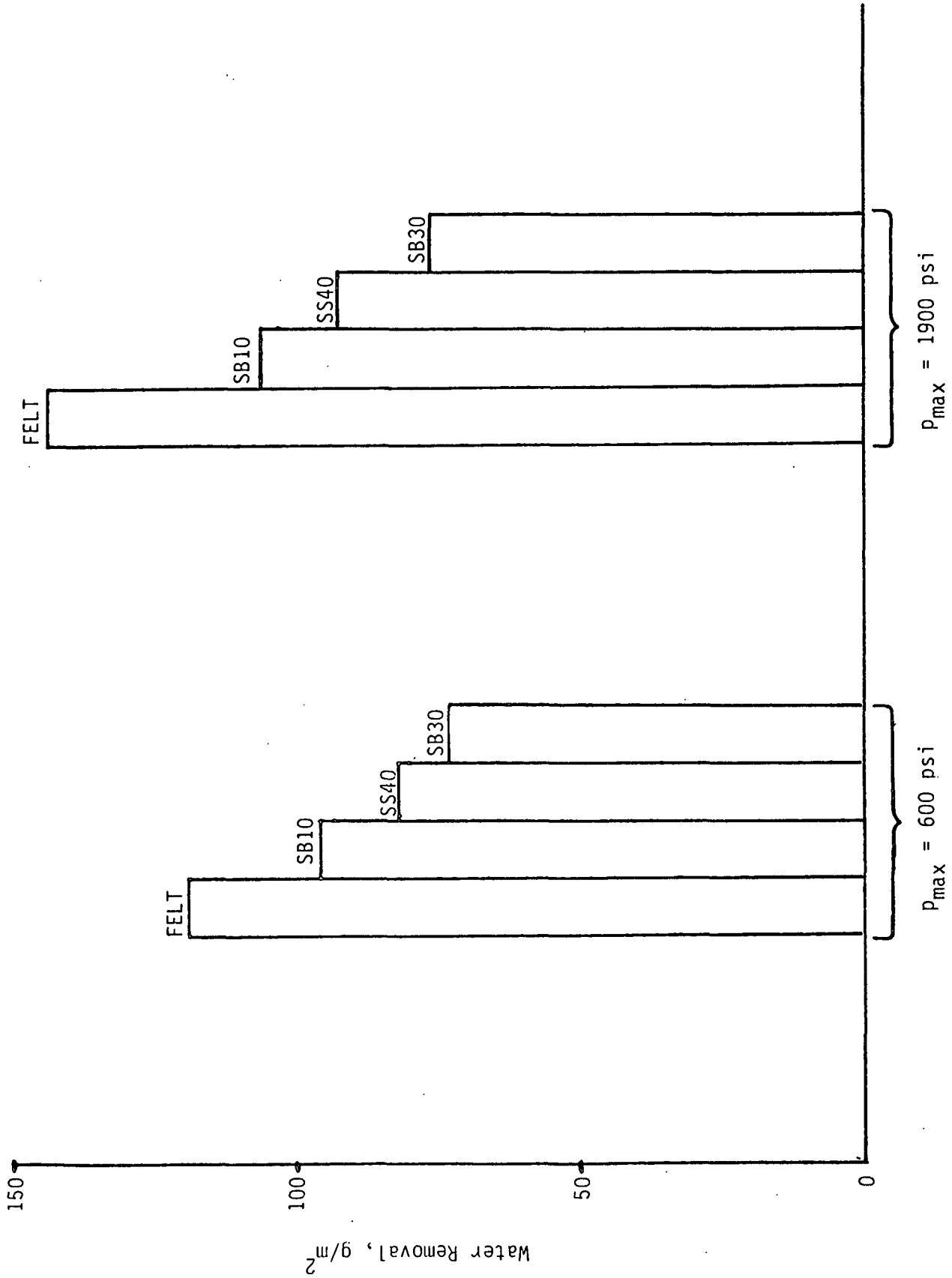


Figure 40. Effect of water receiver on water removal for 60 g/m² sheets of 700 CSF (once-dried) BSWK at 3.0 initial moisture ratio, 6 ms nip residence.

A few other felts were tested, at the same two operating conditions, to ascertain the importance of felt type. These included: a felt similar to the one used previously but unconditioned, a coarser felt, and a layered felt with one coarse layer. While the original felt remained at the top of the performance ranking, two of the other three had nearly as good performance, giving about 10 g/m^2 less water removal. The layered felt performed approximately the same as the best porous plate (SB10). The felt performance ranking was in accordance with expectations, since the coarser felts performed more poorly than the finer ones. The main conclusion from this test series is that, as a group, felts give better water removal than porous plates, at least for the (small) range of operating conditions studied.

To take the investigation a step closer to the conditions covered by the UMO study, sheets were prepared from (never-dried) bleached northern softwood kraft (BNSWK) pulp at 300 CSF. This is similar to the pulp used in many of the tests performed in the original UMO study. For tests at the same basis weight, initial moisture and impulse conditions used in the work discussed above, the results were as given in Fig. 41. While the quantities of water removal are about half those in Fig. 40, reflecting the greater difficulty of removing water from low freeness, never-dried pulps, the ordering is the same; the felt again has superior performance. In some similar tests at a higher basis weight (75 g/m^2), the SS40 plate showed slightly better performance than the SB10 plate, but still the felt was best.

With the availability of the electrohydraulic press system, it became possible to duplicate an operating condition (225 psi average pressure, 20 ms nip residence time) for which UMO water removal data were available over a range of basis weights, for both the felt and the SS40 plate as water receivers. Thus, a rather direct attempt at corroboration of the UMO data was possible.

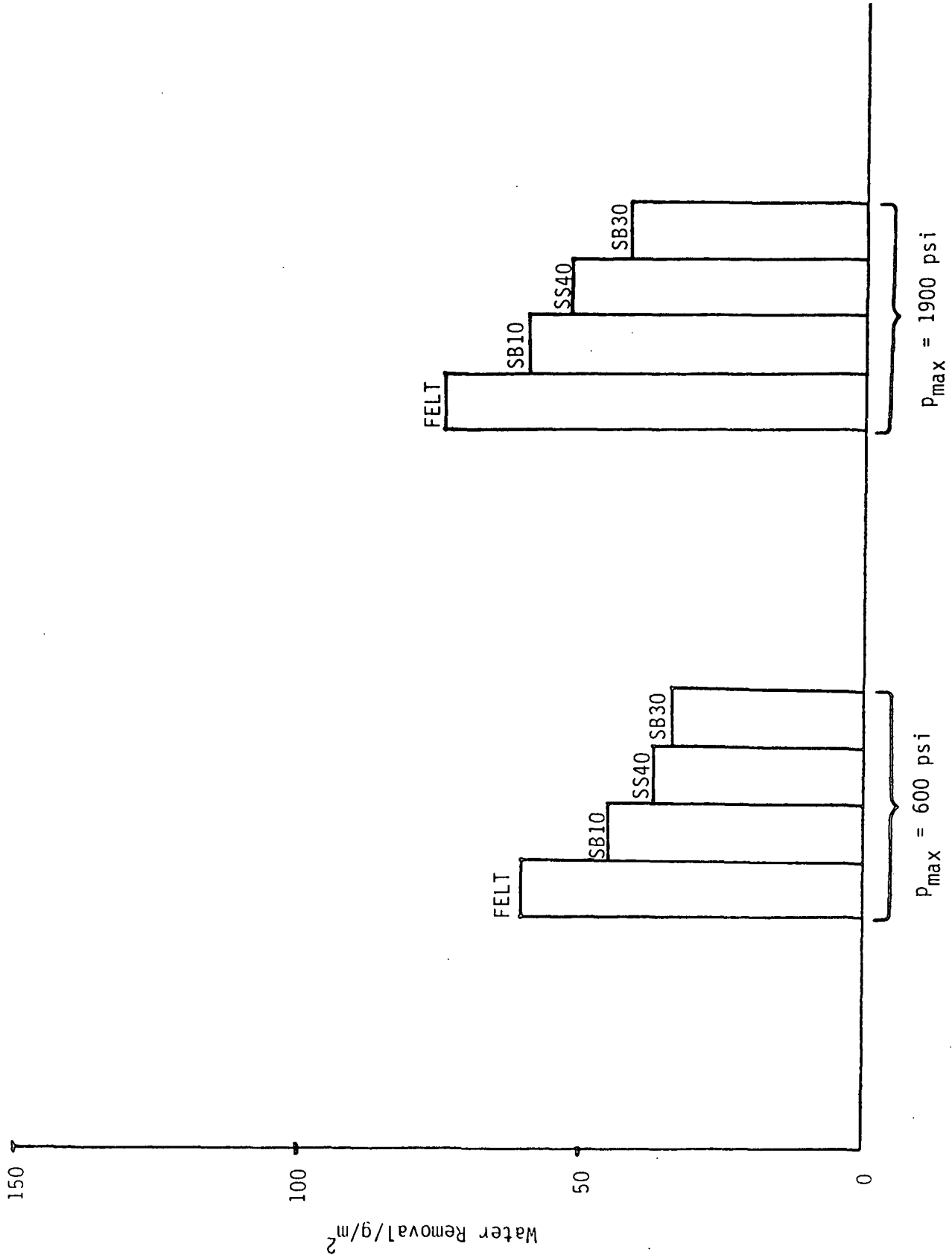


Figure 41. Effect of water receiver on water removal for 60 g/m² sheets of 300 CSF BNSWK at 3.0 initial moisture ratio, 6 ms nip residence time.

The results of the IPC tests and the UMO data are compared in Fig. 42. With the exception of the data at basis weights of 75 and 100 g/m², which seem to be out of line, the IPC data follow the UMO (Beloit) pilot press data (based on felt as the water receiver) fairly closely. For the conditions represented in Fig. 42, the IPC measurements indicate that felt performance continues to exceed porous plate performance at low basis weight, while the two water receivers behave rather similarly at high basis weight.

To even more closely simulate conditions used in many of the UMO laboratory tests, some tests similar to those just described, but with a "square" compression pressure pulse rather than a haversine pulse, were performed with the SS40 plate as water receiver. The water removal levels resulting from these tests showed a similar trend with basis weight, but slightly lower magnitudes, as compared to those shown in Fig. 42.

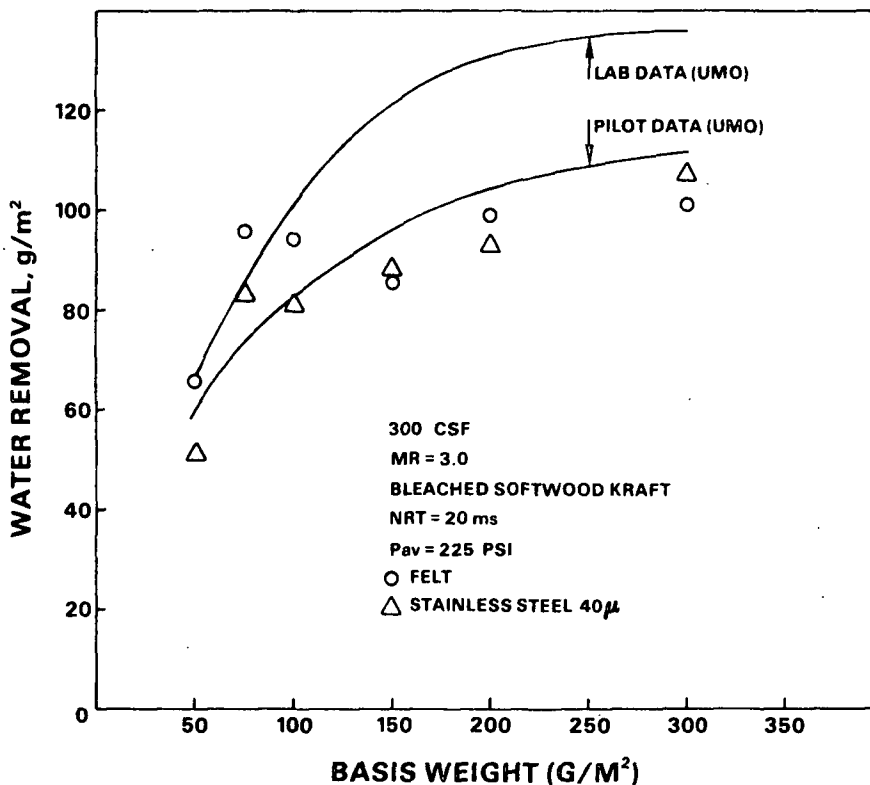


Figure 42. Comparison of data from the MTS system with results of the UMO study.

Finally, a series of tests over a range of impulse values was conducted with each of several water receiver configurations, each unvented. Sheets with a basis weight of 245 g/m^2 , made from a bleached sulphate softwood pulp, were used. A falling-weight press simulator, operating at nip residence times of 5-8 ms and pressures to about 1300 psi, was used for the tests. Results are shown in Fig. 43 for four sintered bronze plates with pore sizes of 10, 30, 40, and 90μ , for a felt alone, for a porous stainless steel plate with a pore size of about 40μ , and for the stainless steel plate backed by the felt. Ingoing moisture ratios were about 3.5.

These data show clearly that pressing with a felt removes more water than with any of the porous plate configurations. As previously noted and as expected, the smooth, smaller pore size plates do the best job, but none can compete with the felt.

These results strongly suggest that porous plates are inferior to felts as pressing water receivers. Furthermore, porous plates tend to plug, to contaminate and to seriouslypeen under pressing impact. Thus, their practical use as replacements for felts in wet pressing seems highly unlikely. The data also show that porous plates are not responsible for the exceptionally high water removal levels attributed to the UMO press. In fact, they probably detract from the water removal potential of the compression tester.

OTHER FACTORS IN NIP EFFICIENCY

Figure 44 shows a pressure-time pulse and the corresponding sheet density for a typical pressing event produced on a dropping weight (Wahren-Zotterman) type of press simulator. This pressing event is subdivided into several segments, each of which represents a distinctly different physical

BLEACHED SOFTWOOD SULPHATE PULP, 245 g/m²

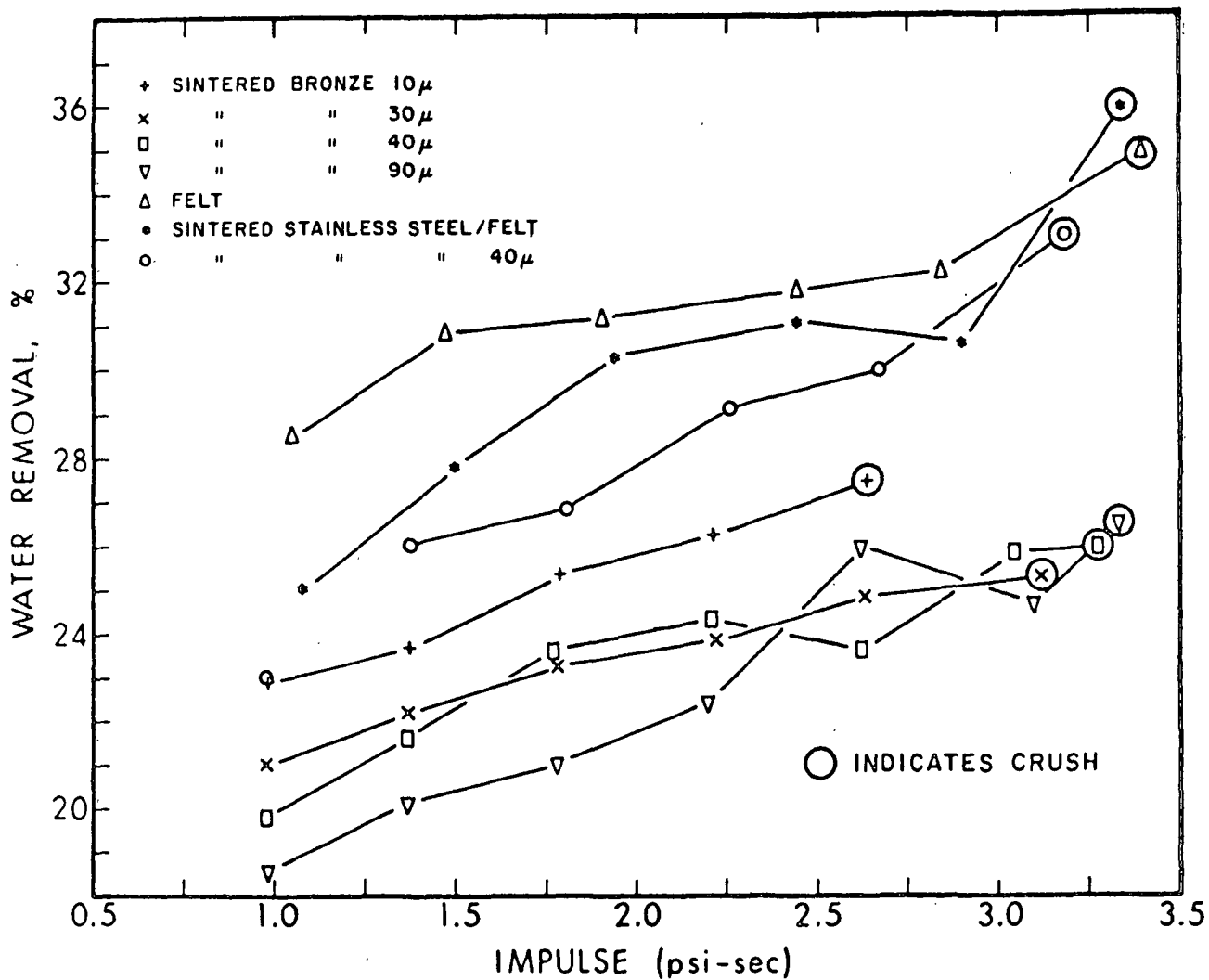
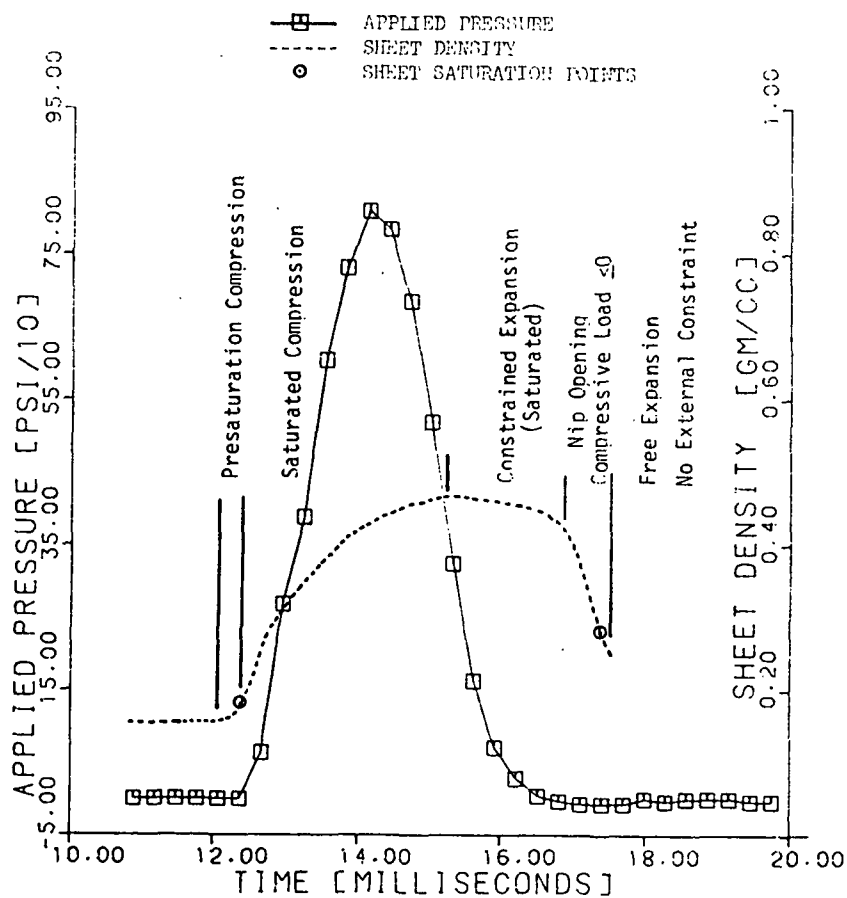


Figure 43. Water removal as a function of impulse for various water receivers.



R1L 55.6 GM/SQ-M MR = 4.8
 70 F 420 CSF

Figure 44. Instantaneous pressure and density curves for a typical wet pressing cycle.

process. These segments, labeled in Fig. 44, include presaturation compression, saturated compression, constrained saturated expansion, nip opening, and free expansion. Of these, the UMO model describes only the saturated compression segment. Hence, the nip efficiency factor must account for the important segments of the physical event that have been omitted from the model. For the pressing event characterized by the data in Fig. 44, water removal at the minimum thickness point is about 180 g/m² whereas the actual water removal is about 104 g/m², giving a nip efficiency of about 57%. By omitting the expansion and nip opening processes, the UMO model fails to account for the reabsorption of about 76 g/m² of water. In summary, the UMO models can be used to adequately describe water removal from the wet sheet only in the saturated compression segment of a pressing event.

Despite the scope and quality of the UMO work, the industry still lacks a predictive model, one that can be used to accurately estimate dryness and sheet density at the press exit. Further significant gains in improving pressing technology are critically dependent on having such a model. This requires developing a full understanding and mathematical description of the expansion and opening segments of the pressing event to complement the UMO description of the compression segment and the addition of density as a predicted variable in the model. A model of this type would allow prediction of both press exit dryness and density, given fundamental properties of the furnish. Furthermore, such a model should be highly instructive in the development of pressing strategies to provide the highly desirable combination of high dryness and low density, something which present pressing technology does not do. Finally, the model should be very helpful in guiding press design and operation to avoid the undesirable effects of crushing or incipient crushing, fines redistribution, and imprinting.

NEW MODELING OBJECTIVES

As suggested by the preceding sections, the extended objective of the research under this contract was to initiate development of a mathematical model for the segments of a wet pressing event not described by the UMO model. These include the constrained expansion of the wet web, the nip opening process, and the free expansion/post-nip contact zone. The two complementary models will then be combined into one model to describe the complete pressing process, obviating the need for the experimentally determined nip efficiency factor used in the UMO model. The resulting wet pressing model will include density, a fundamental sheet property, as a predicted variable. While this modeling task is a difficult one, the approach is straightforward, as outlined below.

APPROACH AND EXPERIMENTAL EQUIPMENT

The basic approach has been experimental in nature and based on the use of two unique platen-type press nip simulators and a laboratory pilot press. For several years, the Papermaking Processes Group of the Engineering Division has used dropping-weight press nip simulators (sometimes called Wahren-Zotterman simulators after the developers) to study wet pressing and impulse drying. At least two formal studies, Davis, Stratton, and Chang (14) and Chang, Nett, and Beck (2), and various contract research projects have shown that these simulators closely reflect the behavior of real presses and, hence, are good laboratory study devices. Fig. 45 shows a frontal view of the most advanced of these simulators, recently added to the Pressing and Drying Laboratory.

With reference to Fig. 45, a dropping-weight press nip simulator (simulator) consists of a weighted carriage suspended at a predetermined height over a wet sheet, a felt, and a pedestal supported by a load transducer. Upon release, the carriage drops to impact the wet sheet and then rebound. A special catching system prevents a second impact. Such impacts yield pressure-time histories on the moist sheet that are almost identical to those experienced in a rolling nip press (2). Carriage height and weight, and the elasticity of the pedestal may be varied to control peak pressure and nip residence time. The shape of the pressure pulse is essentially unchangeable and corresponds to that of a roll press. This device is ideally suited to simulating nips with residence times up to 10 ms. Both the carriage head and the pedestal may be changed to alter the pressing configuration.

Special instrumentation, recently developed for the dropping weight simulator in Fig. 45 (15), provides a unique new ingredient for the study of wet pressing, especially modelling. Four proximity detectors, located in the vent

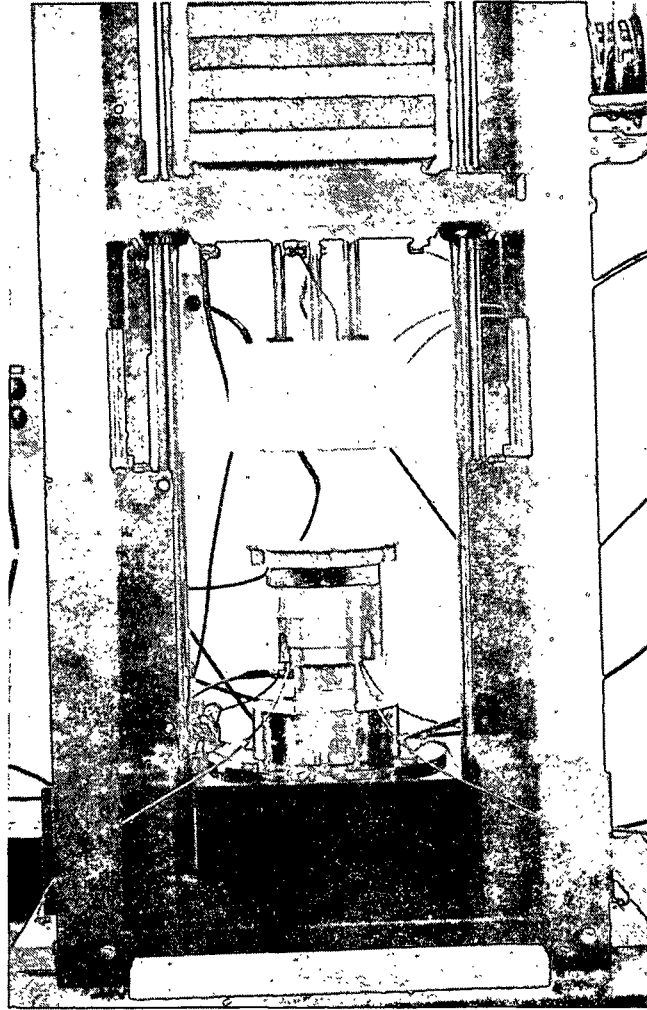


Figure 45. Press nip simulator - front view.

plate on the lower pedestal, track the motion of up to four targets distributed through the thickness of the wet sample. Special sheetmaking techniques have been worked out to ensure that the targets are embedded in the sheet and not sandwiched between plies. This approach totally avoids the development of a ply structure. The targets are so thin and open that they offer little interference with the wet pressing process. This instrumentation system and the associated procedures allow accurate measurements of instantaneous density development (wet

web compression) throughout the thickness of the sheet as the wet pressing event takes place. The example shown in Fig. 46 illustrates the type of measurements that can be made. Such measurements are unprecedented in wet pressing studies and provide data of profound value in the development of the model sought in this work.

Another recent addition to the Pressing and Drying Laboratory is an electrohydraulic press for the simulation of pressing events. This device, shown in Fig. 47, offers several advantages over the dropping-weight simulators. These include much higher load levels, longer nip residence times and easy electronic control of the pressure pulse shape. As a consequence, this device allows effective simulation of such new technologies as the extended nip press. The pressing heads from the dropping-weight simulator can be used on the electrohydraulic press, thus affording all the measurement advantages to both systems. Collectively, these two simulators can accurately represent almost any pressing event.

In wet pressing, dewatering is actually caused by a hydraulic pressure gradient developed by external compression of the fiber network. Historically, both measurement and prediction of the hydraulic pressure developed at the pressing platen surface has been difficult. For this study, suitable hydraulic pressure instrumentation has been developed by following the work of Beck (16) and Carlsson (17). Figure 48 shows an example of simultaneous measurement of compression pressure, hydraulic pressure and sheet thickness for a flat platen simulation of a real pressing event.

The final device, intended for use in verifying the model under development, is a pilot press. Specifications for this system have been established and construction is scheduled for the near future.

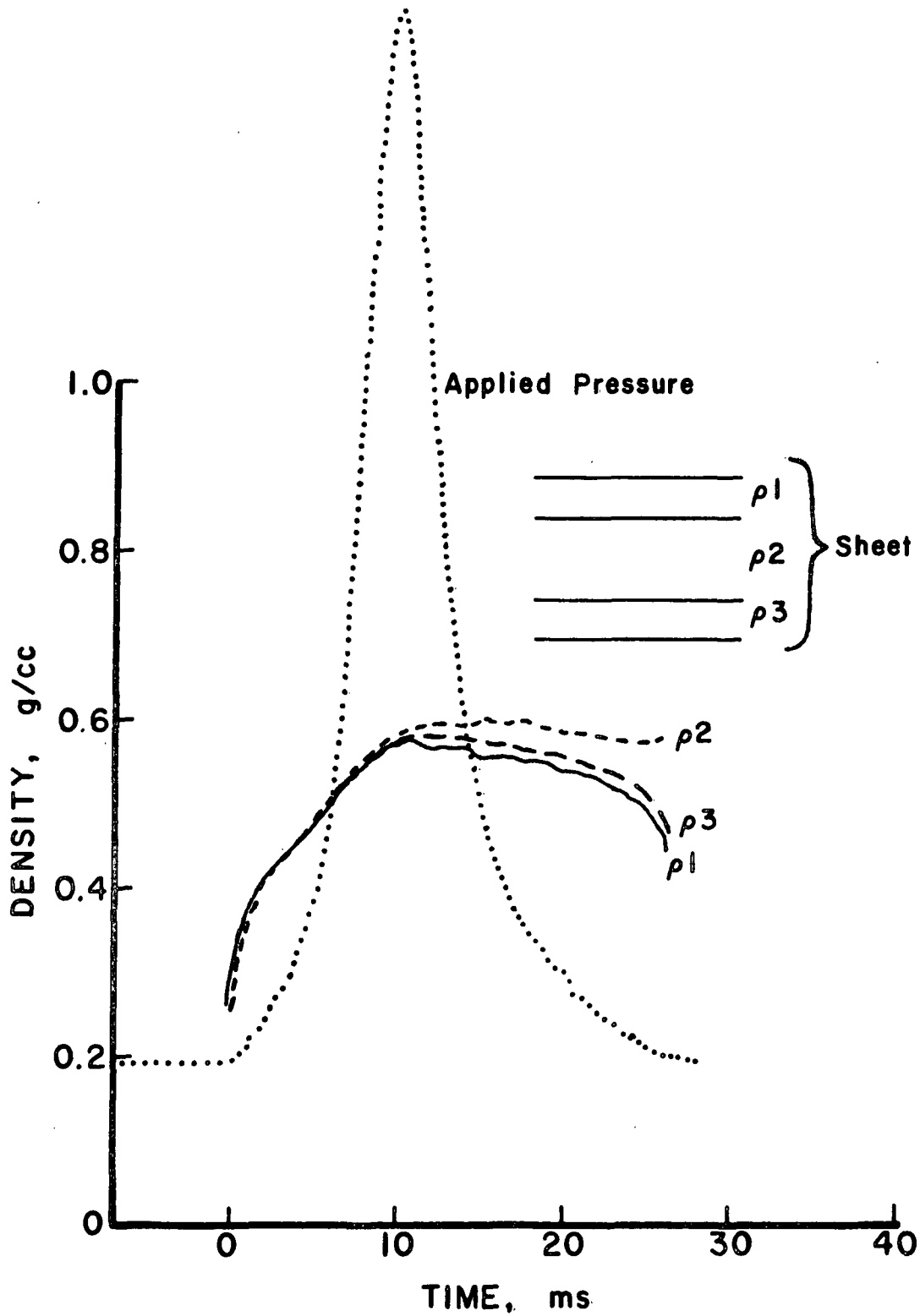


Figure 46. Instantaneous layer densities and applied pressure for wet pressing.

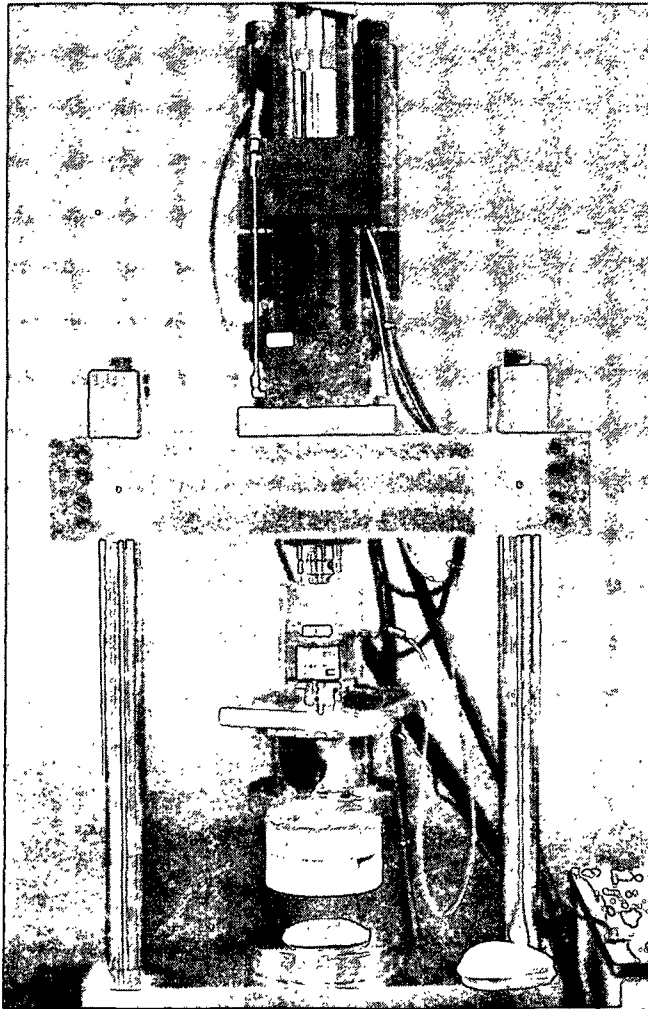


Figure 47. Electrohydraulic press nip simulator (MTS).

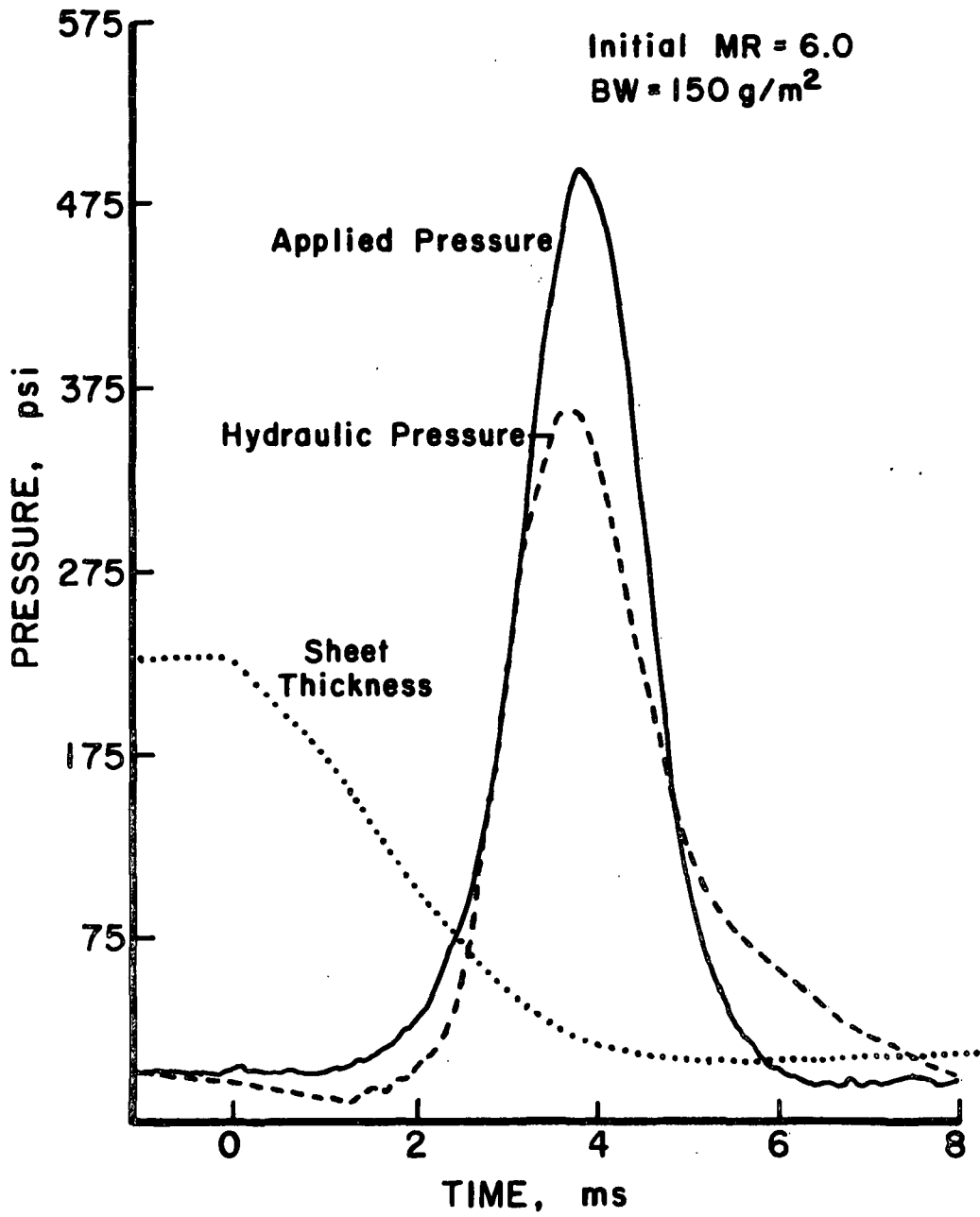


Figure 48. Hydraulic pressure and sheet thickness measurements for a typical wet pressing case.

MODELING STEPS AND EXPLORATORY EXPERIMENTS

At this point in the modeling process, the general approach has been worked out and several experiments have been conducted to explore various aspects of the wet pressing process and verify the experimental procedures. The steps in modeling and some of the early experimental data are presented below.

Compression-expansion Behavior of Wet Sheets

As a first step in the modeling process, the compression-expansion behavior of wet sheets will be determined using the press simulators and the thickness (compression) profile sensors. Based on data from these experiments, an appropriate model relating the sheet density profile to the compressive pressure will be developed. The UMO model structures, developed only for the compressive process, will be used where appropriate.

For unsaturated sheets or very slow compression processes, the hydraulic pressure will be negligible and the external load will be borne entirely by the fiber network. Compression-expansion data for a very slow process (at least 15 minutes residence time at each pressure value) are shown as density versus pressure on a log-log coordinate system in Fig. 49. These data are well described by the classical power law function $\rho = MP^N$ but the M and N values for expansion are quite different from those for compression. Both sets of coefficients are given in the figure. These data point out clearly that a compression model will not suffice for describing expansion.

Figure 50 shows similar data obtained under several different compression-expansion rates. None of these relationships can be described by the classical power law and the deviation becomes more serious as cycle times shorten.

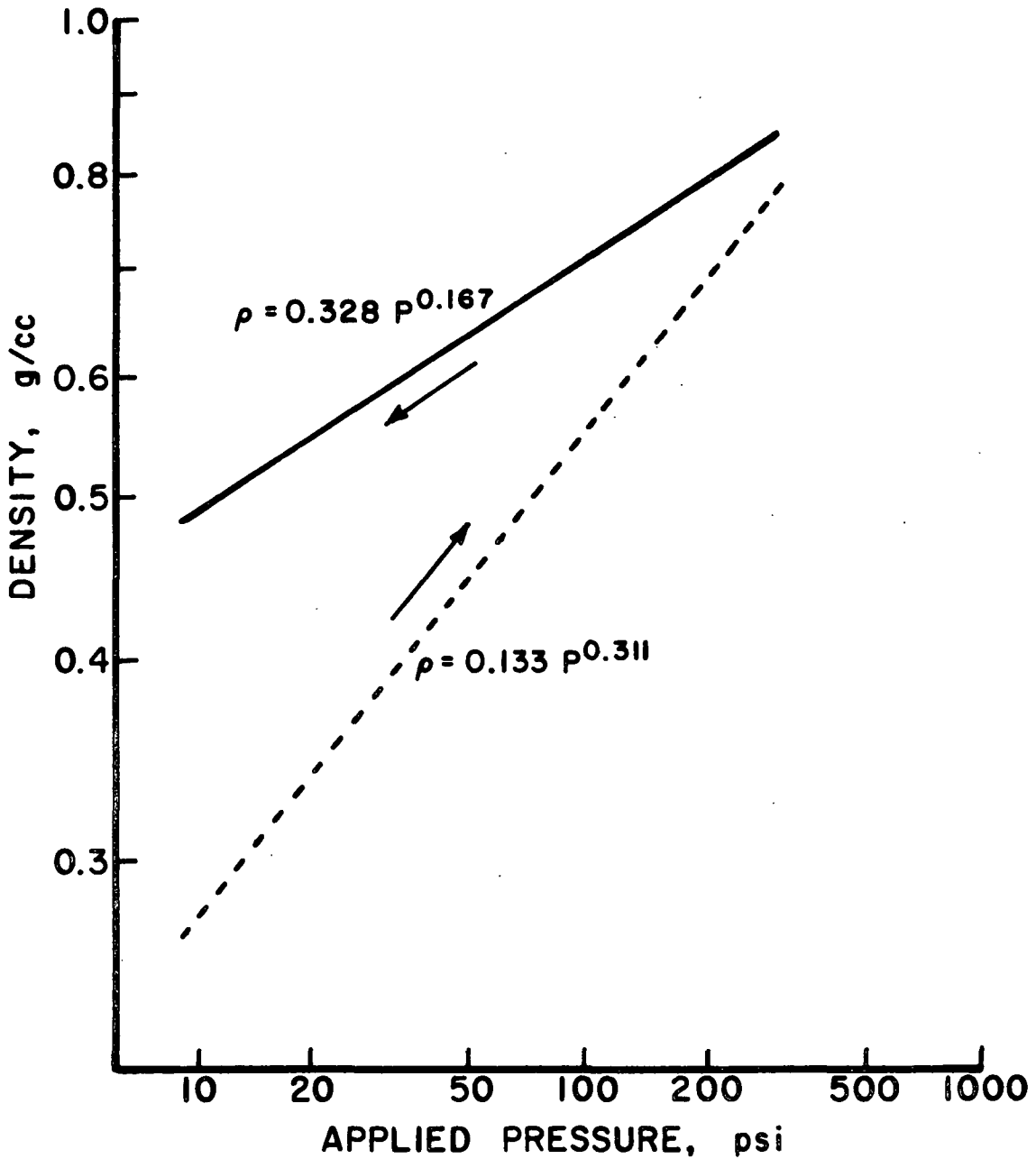


Figure 49. Compression-expansion data for a statically loaded wet sheet.

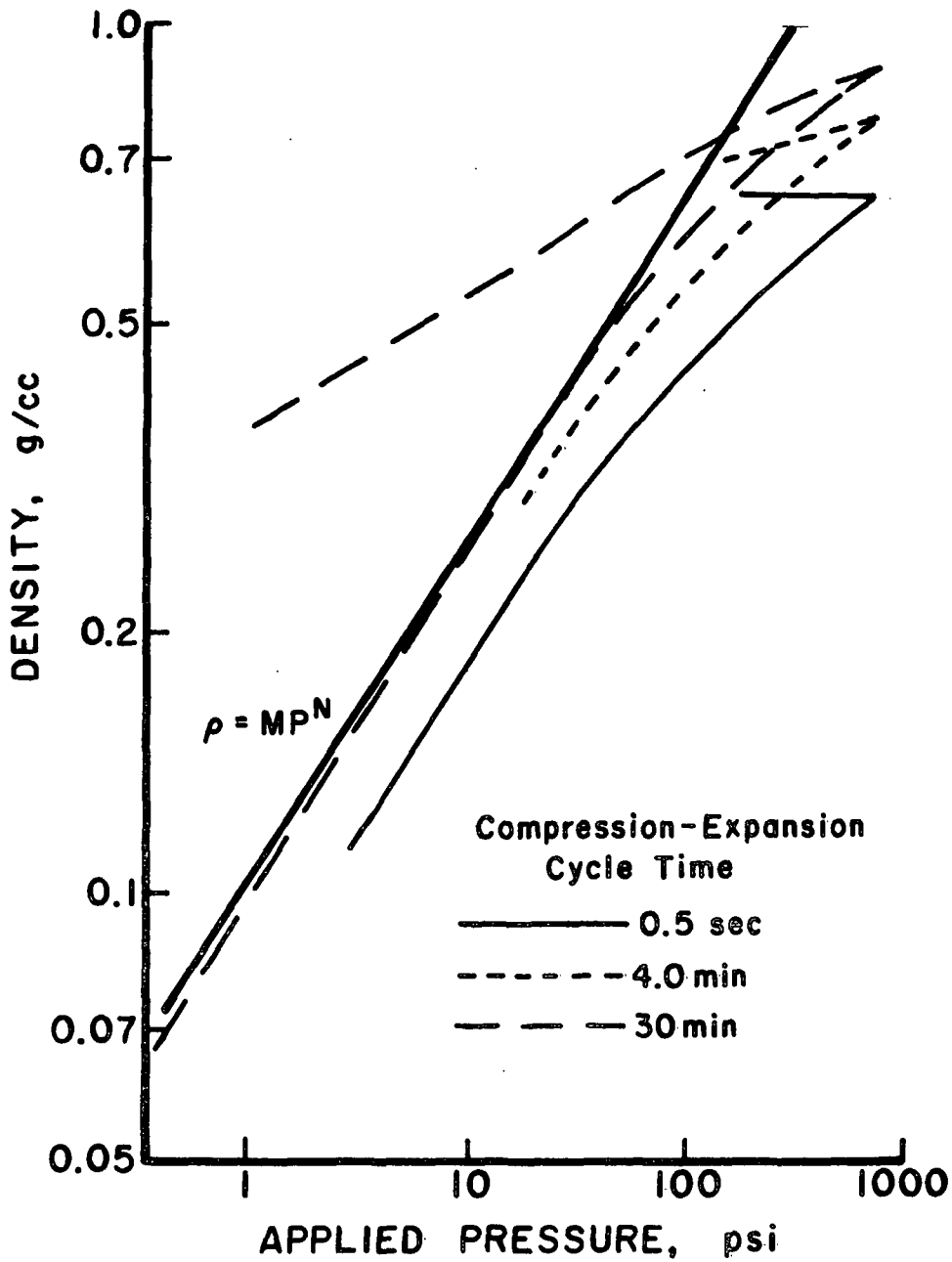


Figure 50. Compression-expansion data for wet sheets loaded and unloaded at various rates.

For the rapid compression-expansion cycles typical of wet pressing, the power law formula is an inadequate description. Experimental data to guide development of an appropriate model can be generated by first considering the behavior of moist but unsaturated sheets. These data will suffice to describe the true compression-expansion behavior (i.e., without fluid flow or fiber dewatering) of the network. Cycle times representative of wet pressing will be necessary, however. These data can be provided easily by the various press simulators.

In a second step, the compression-expansion behavior of saturated sheets will be examined. The hydraulic pressure developed across the sheet will be measured, Fig. 48, and subtracted from the external pressure to determine the load actually borne by the network. Under saturated conditions, liquid flow in the sheet produces a hydraulic pressure that varies continuously in the thickness direction. This, in turn, results in continuously varying local compressibility and flow resistance factors. The internal density profile system will be immensely helpful in modeling this process.

In some cases, it may also be necessary to consider the compression-expansion behavior of the felt, especially for the expansion and nip opening segments of the wet pressing cycle. Fig. 51 shows how sheet density and felt density can be simultaneously tracked in a wet pressing event. This is a unique measurement capability, believed to be a first.

Transport in the Expansion Zone

To the compression-expansion model, the appropriate transport equations will be added to describe the overall process from the nip entrance to the nip exit or the final saturation point, whichever occurs first. Modeling in the unsaturated expansion zone is complicated by capillary flow from the felt back

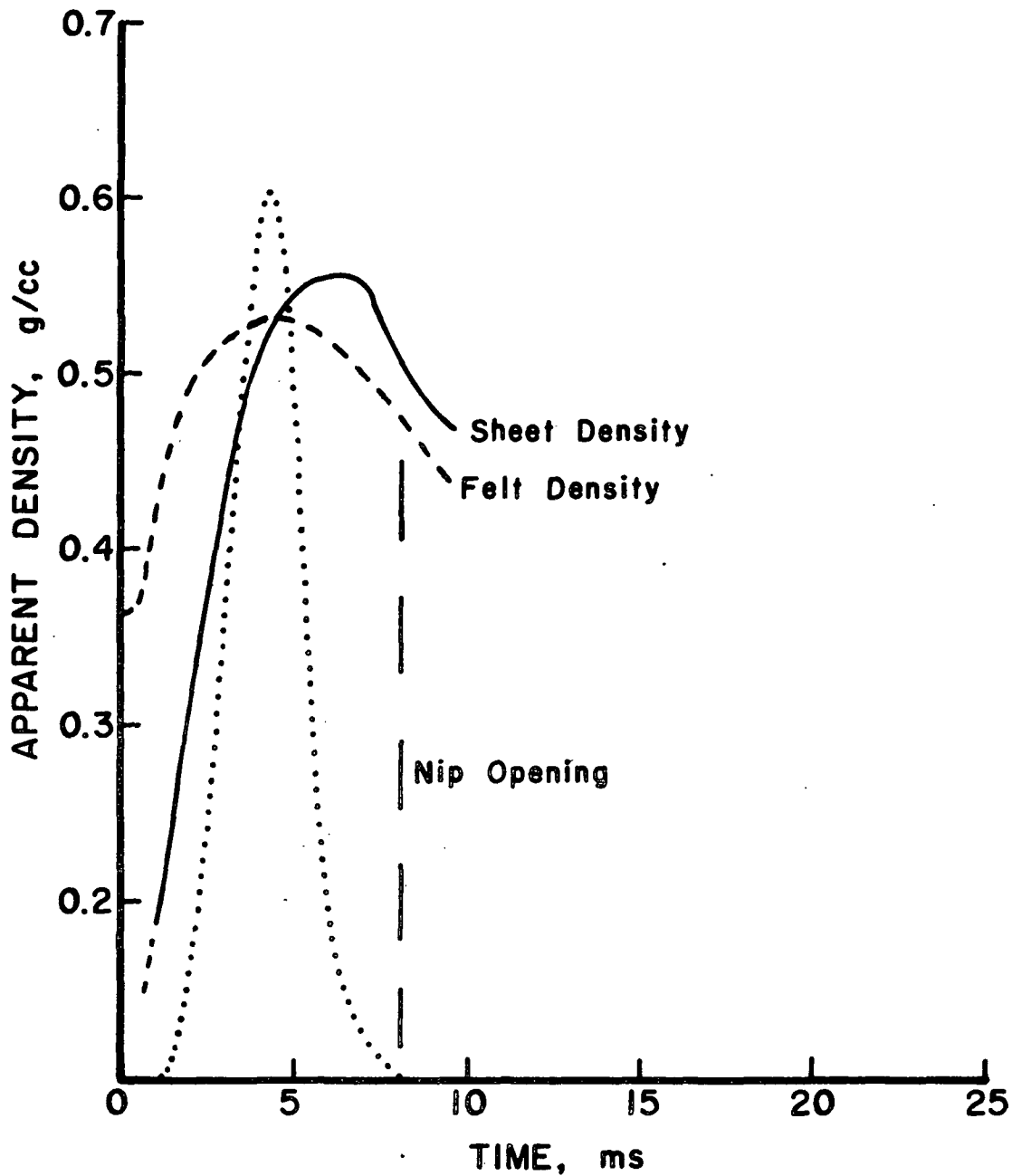


Figure 51. Simultaneous sheet and felt density measurements during wet pressing.

to the sheet and by possible air flow into the sheet and felt. The unsaturated state will propagate through the thickness of the sheet as the sheet moves toward the end of the nip. Internal sheet thickness measurements, provided by the special instrumentation system, will be vital in modeling this process.

Nip Opening

By definition, the nip ends when the sheet separates from either the roll or the felt. The thickness measuring system will be used to clearly identify this point, Fig. 52. Film splitting, interfacial forces, and the compression-expansion characteristics of both the sheet and the felt are expected to be major factors in determining when and how the system first divides. Special nip configurations to alter these forces will be used to identify and model the key mechanisms. Examples include incompressible water receivers Fig. 52, adhesion force suppressors on the pressing platen Fig 53, and so on. Most of the necessary techniques have already been worked out and demonstrated in early experiments.

Post-nip Zone

In the post-nip zone, the sheet may remain in contact with the roll or the felt, or it may run unsupported but under tension. System geometry and operating conditions and the nip opening forces described above will determine the actual course of events. In some cases, the web may initially run in contact with the roll or felt and then separate to run freely. The model must be capable of describing all of these cases. While in contact with the roll, the web will expand due to fiber reswelling (may be small due to the short time involved), free expansion, and centrifugal and other forces. Redistribution of the moisture in the sheet will also occur. At separation, film splitting will determine how the remaining water divides between the web and the roll surface.

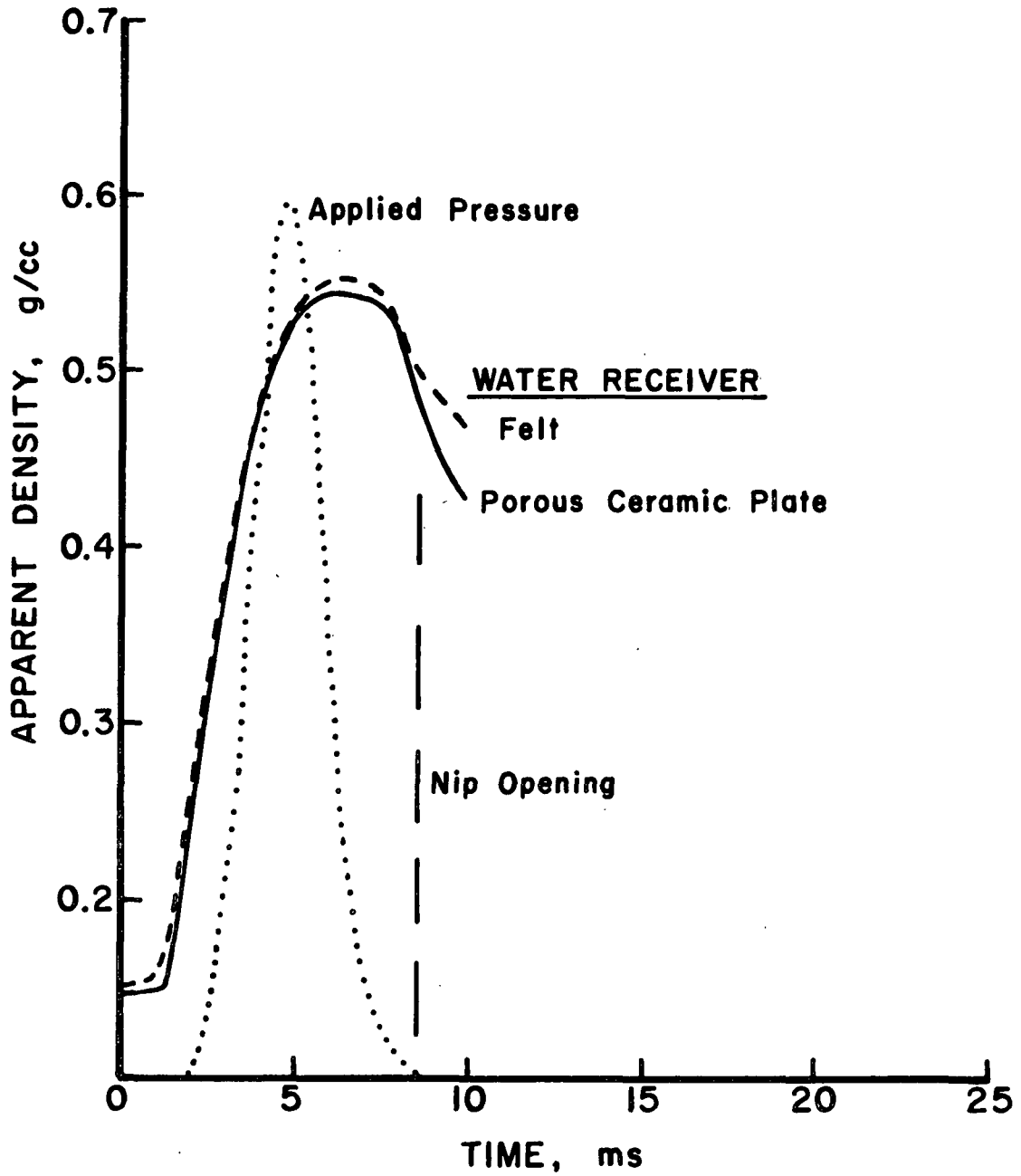


Figure 52. Effect of water receiver on nip opening process.

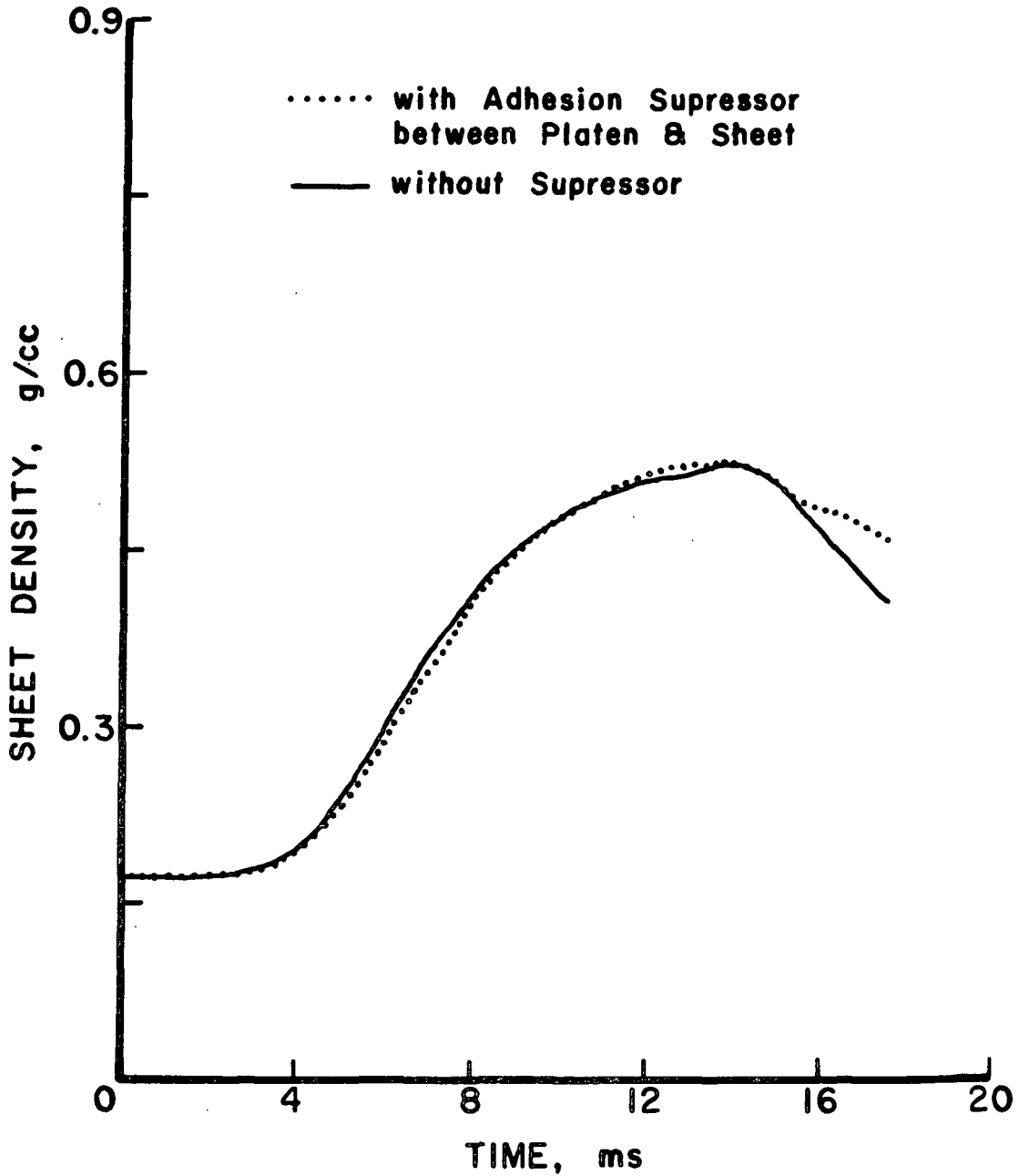


Figure 53. The effect of an adhesion suppressor on sheet density in the nip opening section of a wet pressing event.

When the sheet remains with the felt, capillary flow of water from the felt to the web (rewetting) must also be taken into account. All of these factors except those due to roll curvature and web tension can be effectively simulated in the dropping-weight and electrohydraulic presses; the roll press will be used for the remaining items.

When completed, the modeling process initiated under this contract, coupled with the UMO work, will provide a complete model for a wet-pressing process including extended nip or high impact pressing. This model will predict both water removal and density. The uses and benefits of this model have already been pointed out.

REFERENCES

1. Arenander, S., and Wahren, D., Tappi 66(9):123-126(1983).
2. Chang, N. L., Nett, M. R., and Beck, D. A., "A Comparison of a Wahren-Zotterman Press Simulator and a Pilot Press Nip," presented at CPPA Technical Section Annual Meeting, Montreal, Jan. 30-Feb. 3, 1984.
3. Holden, G. R., U. S. pat. 3,284,285(Nov. 8, 1966).
4. Brundrett, E.; Baines, O., Tappi 49(3):97-101(1966).
5. Kawka, W.; Rogut, R., Przegląd Papierniczy 26(2):52-6(1970).
6. Kawka, W.; Ingielewicz, H., Przegląd Papierniczy 28(11):381-7(Nov., 1972).
7. Kawka, W., Przegląd Papierniczy 30(1):10-18(Jan., 1974).
8. Kawka, W.; Ingielewicz, H., Przegląd Papierniczy 34(2):53-8(Feb., 1978).
9. Kawka, W.; Ingielewicz, H.; Marek, I., Przegląd Papierniczy 34(3):82-7 (March, 1978).
10. Kawka, W.; Stepień, K., Przegląd Papierniczy 35(11):402-4(Nov., 1979).
11. Kawka, W.; Szwarcsztajn, E., EUCEPA-79 International Conf., London, May 21-24, 1979, Paper No. 31.
12. Kawka, W.; Przegląd Papierniczy 39(11/12):403-7(Nov.-Dec., 1983).
13. Ceckler, W. H., and Thompson, E. V., Final Report of the University of Maine at Orono Wet Pressing Project, DOE/CS-40064-3, August 24, 1982.
14. Davis, E. J., Stratton, R. A., and Chang, N. L., "Water Removal Studies with the Wet Press Simulator," J. Pulp Paper Sci., Trans. Tech. Section 9 (3), TR68-73, July, 1983 and Proceedings 1982 International Water Removal Symp., Vancouver, BC, October, 1982.
15. Burton, S. W., An investigation of dynamic densification under impulse drying conditions. Progress Report Number Six, A-400, The Institute of Paper Chemistry, Appleton, WI, May 3, 1985:1-30.
16. Beck, D. A., Fluid pressures in a press nip: measurement and conclusions. Proceedings of the 1983 Tappi Engineering Conference, Book 2:475-487.
17. Carlsson, G., Some fundamental aspects of the wet pressing of paper. Doctoral dissertation. Stockholm, Sweden, Swedish Forest Products Research Laboratory, 1983.