Institute of Paper Science
and Technology

IMPULSE DRYING
OF
LINERBOARD: CONTROL OF DELAMINATION

Project 3470

Report 2

A Yearly Progress Report
to
THE U.S. DEPARTMENT OF ENERGY

October, 1990

Atlanta, Georgia

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

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By

David I. Orloff

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SUMMARY

Research at the Institute of Paper Science and Technology, IPST, has resulted in the development of a roll coating material for press rolls that may be used to extend impulse drying operating temperatures while avoiding sheet delamination. The low thermal conductivity, low density and low specific heat of the coating reduces energy transfer to the sheet, thereby reducing the extent of flash evaporation within the sheet during nip depressurization. Sealing the coated surface results in maximum vapor pressure development at the roll-sheet interface, thereby maintaining high water removal and energy efficiency characteristic of impulse drying.

Short dwell time experiments consistent with current paper machine speeds and existing long nip widths were conducted with linerboard sheets preheated to a temperature characteristic of commercial conditions. Comparison between sheet properties of impulse dried and wet pressed sheets showed a marked improvement in outgoing solids, density and specific elastic modulus.

In particular, 205 gsm linerboard at 85°C and 30% solids was impulse dried for 20 ms at various peak pressures. At a peak pressure of 6.2 MPa initial platen surface temperature could be increased to 470°C without inducing sheet delamination. At 470°C outgoing solids were 48%. After finish drying, soft platen density and specific elastic modulus were 0.76 g/cc and 0.135 MN m/kg, respectively.

LITERATURE REVIEW

The pulp and paper industry is one of the largest industrial consumers of energy in the United States (1-3). A total of 2.3 Quads are consumed by the industry annually, based on thirty million BTU's per ton of paper produced and annual production of 76 million tons. Drying is the largest single energy user in the papermaking process and accounts for about one quarter of the energy used.

The impulse drying process under development at IPST employs a heated roll press to activate a more efficient water removal mechanism. During the process, wet paper is brought into contact with a hot metal roll, typically heated to between 200°C (400°F) and 400°C (700°F), while pressures between 3 MPa (400 psi) and 5 MPa (700 psi) are maintained in the sheet for times between 15 to 30 milliseconds.

The water removal mechanism is different from that involved in conventional wet pressing and evaporative drying processes. Previous research (1-3) has shown that, during impulse drying, high pressure steam is generated rapidly at or near the interface between the sheet and the heated roll surface. As moisture is converted to steam by heat transferred from the hot roll, the steam layer grows and displaces liquid water from the sheet into a water receiver, typically a press felt. As most of the water is removed in the liquid phase, as opposed to conventional drying where all of the water is evaporated, there is a large energy saving.

As the impulse drying process is terminated before the sheet is completely dried, flash evaporation of residual water within the sheet results in a distinctive density profile through the sheet, characterized by dense surface layers and a bulky midlayer. For some grades and conditions, this translates into improved physical properties. For other grades flash evaporation can cause delamination of the sheet.

In early simulations, Arenander and Wahren (4) and Burton (5,6) reported delamination during intense impulse drying. Thereafter, delamination was viewed as a phenomena that would be encountered only under extreme conditions which could easily be avoided in commercial practice.

However, during a joint feasibility study by Beloit Corporation, Weyerhauser Corporation and IPST, delamination emerged as a major problem. As reported by Crouse, Woo and Sprague (7), various degrees of delamination were experienced with linerboard impulse dried at press roll surface temperatures above 150°C. When delamination was avoided by operating below this limit, water removal efficiencies were not significantly different from those obtained by conventional pressing. Hence, it was concluded that to realize the potential of impulse drying it would be necessary to alleviate delamination.

Based on the hypothesis that delamination occurs when excess energy is transferred to the sheet, Orloff (8) and Santkuyl (9) investigated various alternate platen materials that were expected to alter the heat flux to the sheet during the impulse drying event. These included, two solid platens: one of steel and one of aluminum, as well as two porous platens made from sintered stainless steel, at two different porosities. Although the heat flux from the aluminum platen was expected to be substantially higher than that for the steel platen, the effect on delamination was found to be negligible. The porous platens, were expected to result in a lower heat flux and to provide venting of steam generated at the platen/sheet interface. While experiments with the porous platens showed no evidence of delamination, water removal was substantially reduced. Analysis of the mass of water transferred to the felt compared to the mass of water lost from the sheet confirmed that significant steam venting occurred. Venting and the associated reduction in steam pressure are consistent with the observation of reduced water removal as the impulse drying mechanism is suppressed.

In a recent patent application, Orloff (10) demonstrated that nonporous low thermal diffusivity surfaces made from machinable ceramics could be used to extend the range of impulse drying operating conditions while avoiding sheet delamination. Preliminary experiments by Orloff (11) showed that these materials operate by reducing heat transfer to the sheet during nip depressurization. Such a reduction results in lower average sheet temperatures and less delamination inducing flash vaporization.

More practical roll coating materials have been investigated by Orloff (12). Using plasma sprayed ceramic coatings, sealed with high temperature polymers, 205 gsm linerboard was impulse dried from 30% solids for dwell times of 20 ms. The experiments showed that plasma sprayed ceramic coatings have the potential for extending the maximum roll surface operating temperature and achieving impressive water removal without inducing sheet delamination.

In addition to IPST research, other research groups have also begun to address the delamination problem. In a recent patent, Pulkowski (13) describes various impulse drying configurations using the concept of a heated porous roll or fiber belt. It is claimed that the porous surface (2µm minimum pore diameter) allows the vapor pressure within the sheet to be relieved and the amount of heat transferred from the surface to be reduced. While delamination is controlled, the patent recognizes that reduction of vapor pressure will also result in reduced water removal.

Following a similar line of reasoning, Stenstrom (14) proposed venting the surface of the heated roll by drilling 2-5 mm diameter holes at 10 mm intervals on the surface of the heated metal roll. While no experimental results were reported, Stenstrom expects that delamination would be controlled. Unfortunately, he also expects problems associated with uneven pressing and marking of the paper surface.

In a recent review article, Back (15) suggested that impulse drying induced delamination might be overcome by satisfying the following requirements:

1.) using the longest possible dwell time to achieve maximum outgoing solids and z-directional wet strength.

2.) using a low rate of depressurization to reduce delamination inducing drag forces resulting from the vapor exiting the sheet.

3.) achieving a low outgoing maximum temperature in the moist web.

Back further suggested that this later requirement could mean monitoring a temperature gradient in the hot roll mantle, so that the ingoing surface temperature is high but the outgoing surface temperature is low due to heat transfer.

IPST CONCEPT

Based on work by Orloff (8), it was surmised that delamination might be controlled by reducing the temperature within the sheet just prior to opening the nip. A reduced sheet temperature would reduce the quantity of flashed vapor formed during nip decompression. It was further reasoned that a press roll surface made of a material with low thermal mass would tend to suppress heat transfer to the sheet by reducing heat transfer from the interior of the roll to the roll surface.

Preliminary experiments (12), using a machinable solid ceramic platen to simulate the roll press surface, demonstrated this effect. Temperature histories, were measured with 0.001" diameter thermocouples layered in 205 gsm linerboard sheets. As shown in Figures 1 and 2, temperatures in the portion of the sheet closest to the platen were substantially lower for the ceramic (Cotronics) platen than for a steel platen operating at similar conditions. Note that sheets dried with the steel platen were delaminated while those dried with the ceramic platen were not delaminated.

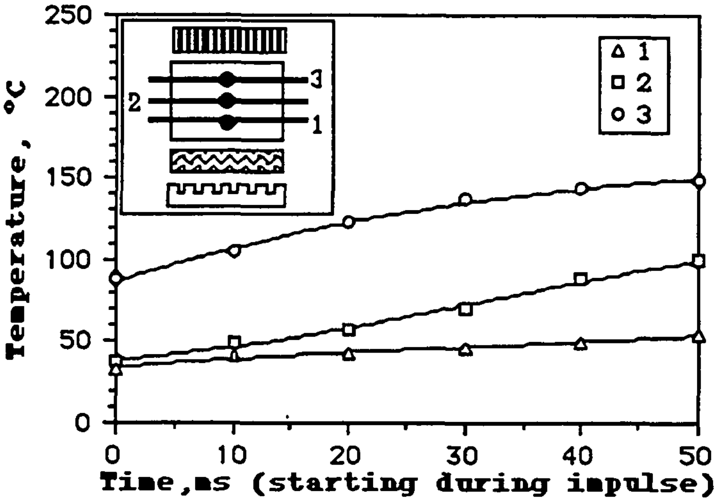

Figure 1: Internal sheet temperature of 205 gsm linerboard as a function of time during impulse drying using a steel platen.Ingoing sheet temperature=20°C, peak pressure=3.4MPa, initial platen temperature=260°C, ingoing felt moisture=16%.

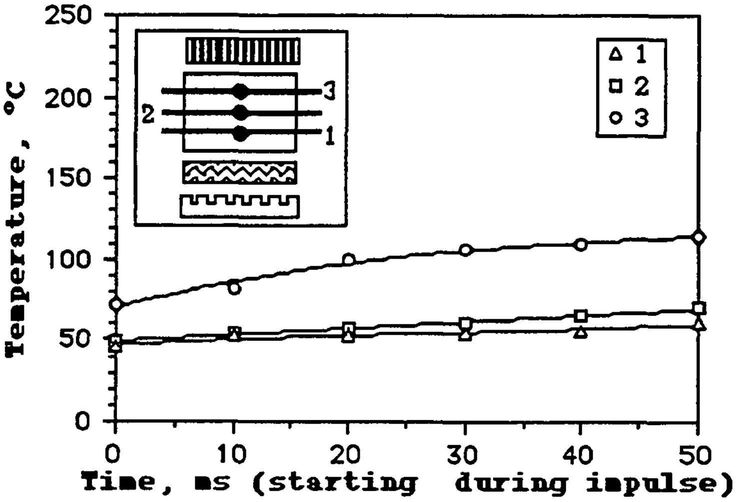

Figure 2: Internal sheet temperature of 205 gsm linerboard as a function of time during impulse drying using a Cotronics ceramic platen.Ingoing sheet temperature=20°C, peak pressure=3.4MPa, initial platen temperature=260°C, ingoing felt moisture=16%.

PRACTICAL ROLL COATING DESIGN

As the machinable ceramic (Cotronics #914) could not be fabricated into a roll, another technology for developing a nonporous insulating roll coating was explored with the Fisher-Barton Corporation.

The actual heat and mass transfer in the nip is quite complicated. However, for the purpose of designing a suitable roll surface, heat flux from the roll surface to the wet paper may be assumed to be dominated by conduction. This assumes that moisture will be regenerated at the paper/roll interface by a heat pipe effect. Under these assumptions, the ratio of the instantaneous heat flux from a ceramic roll surface to that from a steel roll surface at the same temperature is given by;

$$\frac{Q}{Q_{STEEL}} = \frac{K}{K_{STEEL}}\left[\frac{K_{STEEL}+K_{PAPER}}{K+K_{PAPER}}\right]$$

Where K is defined as;

$$K = \frac{\lambda}{\sqrt{\alpha}}$$

Choosing the following values for wet paper,

$$\lambda_{PAPER} = 0.4\ \mathrm{W/m^{\circ}C}$$

$$\alpha_{PAPER} = 1.3 \times 10^{-7}\ \mathrm{m^2/s}$$

and the following correlation for steel,

$$K_{STEEL} = 17400 - 22.2\,T + 0.095\,T^2 - 0.00013\,T^3\ ,\ \frac{W\sqrt{s}}{m^{2\circ}C}$$

The relative heat flux of a given ceramic surface can be determined from its thermal properties.

Plasma sprayed ceramic coatings can be made with porosity from 5% to about 30%. The properties of the coating are a function of the properties of the component ceramics and the porosity of the coating as given by,

$$K = K_{SOLID}\left\{\frac{1-V}{1+C'V}\right\}^{1/2}$$

Based on temperature dependent solid ceramic properties reported by Battelle (16), the relative heat flux for a number of potential ceramics can be estimated. Figures 3 and

4 show the relative heat flux as a function of coating porosity at 300°C and at 500°C, respectively.

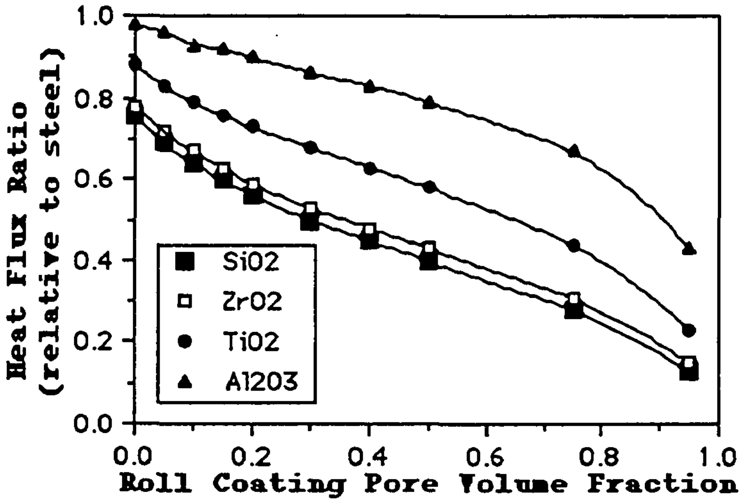

Figure 3: Calculated heat flux ratio (relative to steel) as a function of the internal porosity of the plasma-sprayed ceramic coating for various ceramic compositions at 300°C.

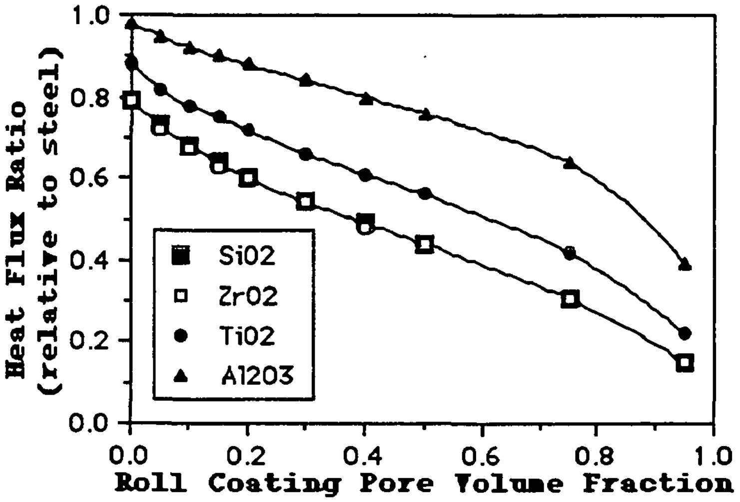

Figure 4: Calculated heat flux ratio (relative to steel) as a function of the internal porosity of the plasma-sprayed ceramic coating for various ceramic compositions at 500°C.

Based on these calculations, either zirconium oxide or silicon dioxide would substantially reduce the instantaneous heat flux. Clearly, it is advantageous to increase the porosity of the coating to a maximum consistent with roll coating strength requirements.

To minimize sheet delamination a press roll coating should have the following characteristics:

1. It should have as low a value of K as practical.
2. It should be designed to resist spalling due to mismatch of coating and the base roll thermal expansion coefficients.
3. Its surface should be sealed to prevent steam vapor venting and absorption.
4. Its surface should also provide a low surface energy to minimize sticking.

With these requirements in mind, a press roll coating was developed in a joint research program between IPST, Fisher-Barton Company and Sandia National Laboratory, funded through a grant from the U.S. Department of Energy. An early prototype of the coating was applied to a steel platen and evaluated for its water removal and delamination control characteristics.

Fisher-Barton fabricated the prototype platen. The roughened surface of the steel platen was coated with a 0.11 mm nickel chromium bond coat, a 0.38 mm 15% porosity zirconium oxide-8% yttrium oxide layer, and a ground 0.05 mm 7% porosity zirconium oxide-8% yttrium oxide outer layer. Once received, the platen was coated with a sealant and high temperature polymeric release agent.

EXPERIMENTAL RESULTS

SINGLE FELTED PRESSING BASELINE STUDY

For proper evaluation, impulse drying should be compared to single felted extended nip wet pressing. Such a comparison should show the improvement in water removal and sheet physical properties contributed by the impulse drying mechanism. To provide this comparison, a single felted wet pressing baseline study was carried out. A steel platen coated with polymer release agent was used. Handsheets at various ingoing solids were preheated by steaming and then wet pressed with the heated steel platen. The platen was heated to the temperature of the preheated sheet. Water removal, expressed as moisture ratio change, was defined as:

$$\text{Moisture Ratio Change} = \frac{\text{Ingoing Weight - Outgoing Weight}}{\text{Oven Dried Weight}}$$

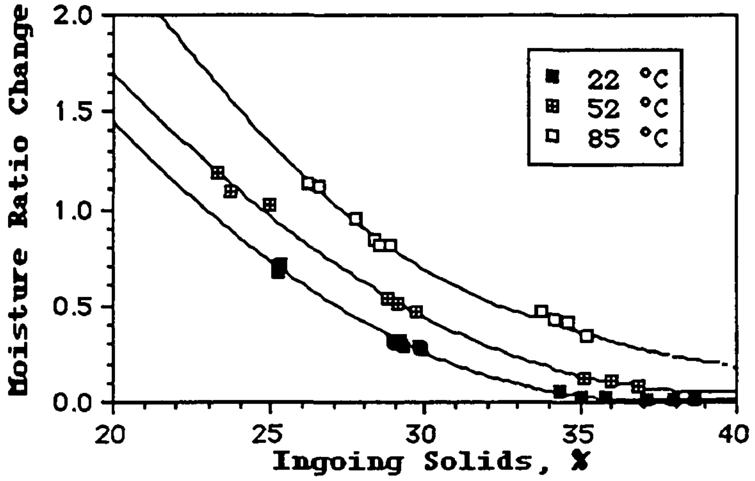

Figure 5: Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of ingoing solids and ingoing sheet temperature. Dwell time=20ms, peak pressure=1.7MPa, impulse=0.015MPas.

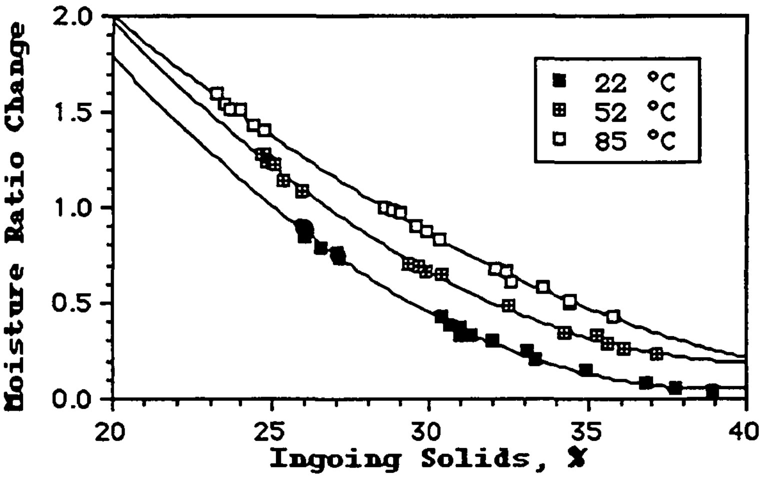

Figure 6: Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of ingoing solids and ingoing sheet temperature. Dwell time=20ms, peak pressure=3.1MPa, impulse=0.028MPas.

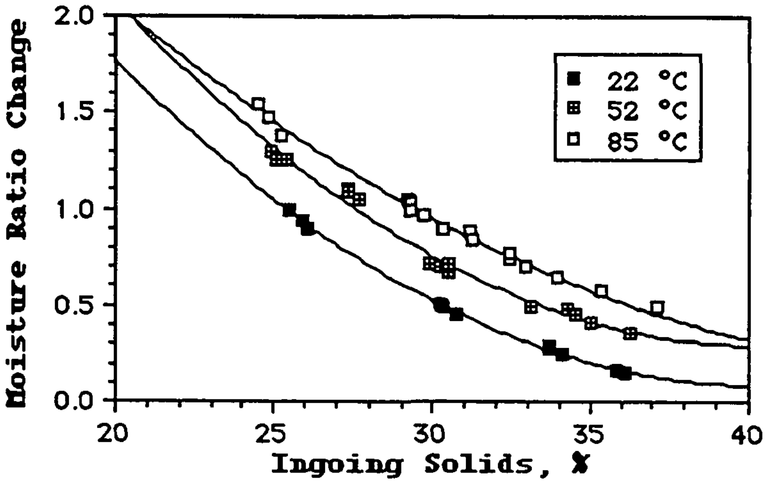

Figure 7: Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of ingoing solids and ingoing sheet temperature. Dwell time=20ms, peak pressure=4.8MPa, impulse=0.044MPas.

As expected, water removal increased with increasing ingoing sheet temperature and with increasing peak pressure. Pressing has a diminishing effect as the ingoing solids increased.

Figure 8 shows similar data obtained at a dwell time of 60 ms and a peak pressure of 3.13 MPa.

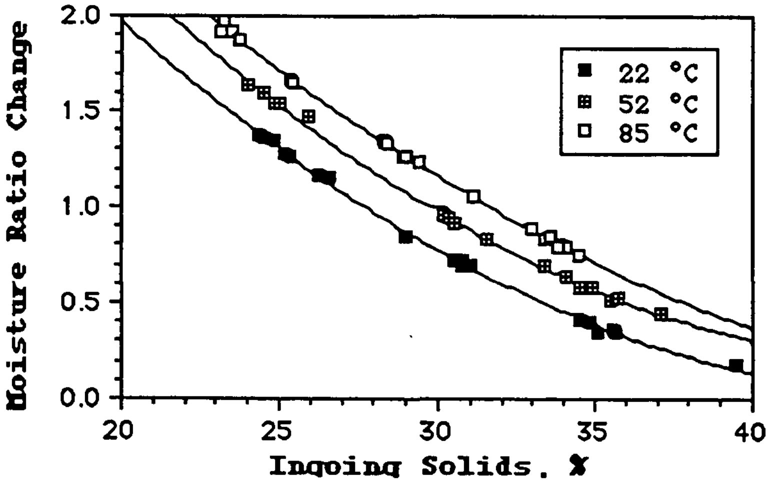

Figure 8: Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of ingoing solids and ingoing sheet temperature. Dwell time=60ms, peak pressure=3.1MPa,impulse=0.140MPas.

Using the data shown in Figures 5 through 8, water removal could be predicted from impulse, independent of peak pressure. Figure 9 shows this result for sheets having an ingoing solids of 30%. It was concluded that the furnish was flow controlled.

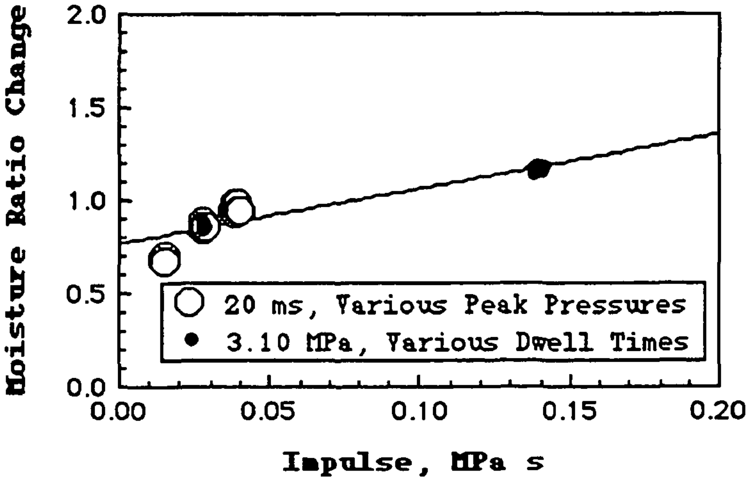

Figure 9: Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of impulse. Ingoing sheet temperature=85°C, ingoing solids=30%.

Water removal was correlated to ingoing sheet temperature and impulse, as shown in Figure 10. The improvement in water removal with increased ingoing sheet temperature may be attributed to a reduction in the viscosity of water and increased sheet compressibility. While the present data are at lower impulse than those of Back (18), they are consistent with his data.

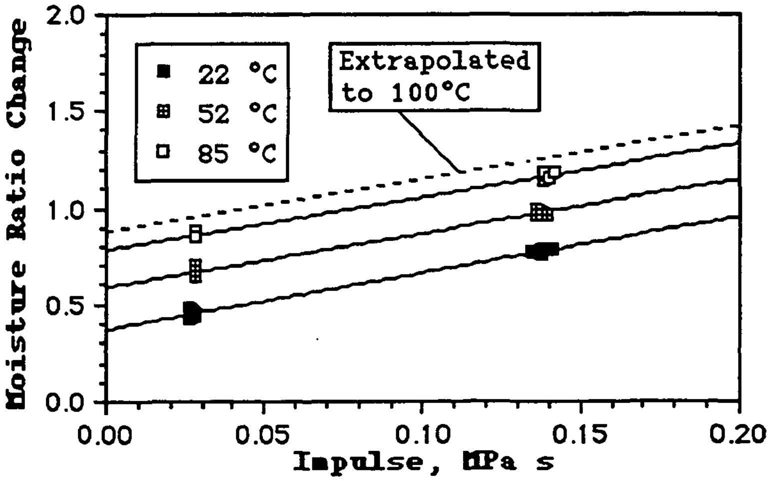

Figure 10: Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of impulse and ingoing sheet temperature. Ingoing solids=30%.

IMPULSE DRYING PERFORMANCE

Using the experimental methods described in the Appendix, an impulse drying simulation was conducted to compare the performance of the prototype zirconium oxide platen to a steel platen. For this purpose it was decided to impulse dry from an ingoing sheet temperature of 85°C and an ingoing solids of 30%.

At a constant dwell time of 20 ms, 205 gsm linerboard sheets were impulse dried at three peak pressures and over a range of initial platen temperatures from 85°C to 500°C. Data acquired at a platen surface temperature of 85°C was used as the wet pressing baseline. Figures 11 and 12 show the water removal, expressed as a moisture ratio change, for the steel and the prototype zirconium oxide coated platen. Moisture ratio change was calculated from the sheet weight after impulse drying, the calculated weight after steaming and the oven dried weight.

Referring to Figures 11 and 12, water removal increased with increasing initial platen surface temperature. A regression analysis on the data showed that, except at the lowest pressure, water removal was independent of platen type. At a given initial platen surface temperature, the zirconium oxide surface should transfer significantly less energy to the sheet than the steel surface. Hence, water removal must be independent of the total energy transfer to the sheet. Since increasing initial platen surface temperature results in increased water removal, it is speculated that the magnitude of the heat flux at the beginning of the process controls water removal.

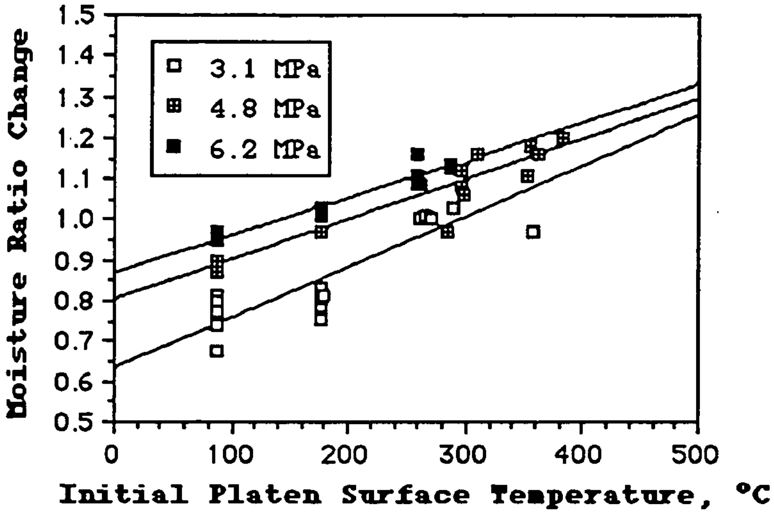

Figure 11: Moisture ratio change for impulse drying of 205gsm linerboard with a steel platen as a function of initial platen surface temperature and peak pressure. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.

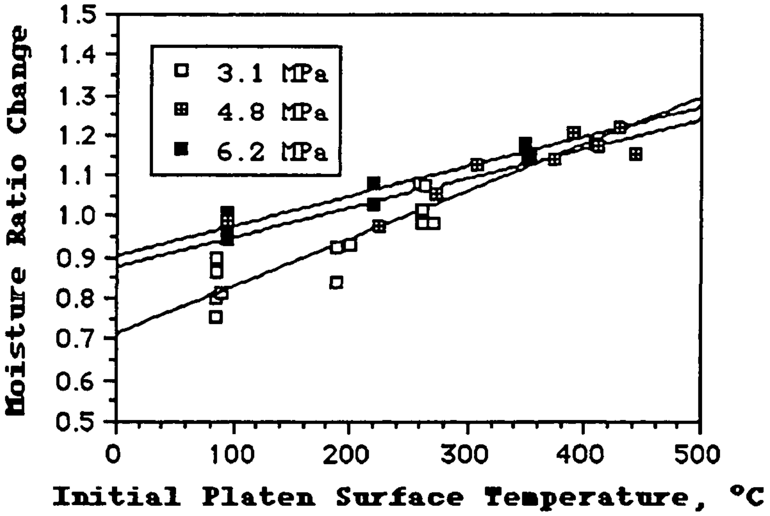

Figure 12: Moisture ratio change for impulse drying of 205gsm linerboard with the prototype zirconium oxide platen as a function of initial platen surface temperature and peak pressure. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.

While water removal efficiency is important, enhanced sheet property development is a key advantage of the impulse drying process. As shown in Figures 13 and 14, soft platen sheet density was measured using the ultrasonic test methods described in the Appendix. In addition to being a function of initial platen temperature, sheet density also tended to be higher when the prototype platen was used. This result is consistent with the concept that the prototype platen reduced the extent of flash evaporation which would otherwise result in midlayer bulk.

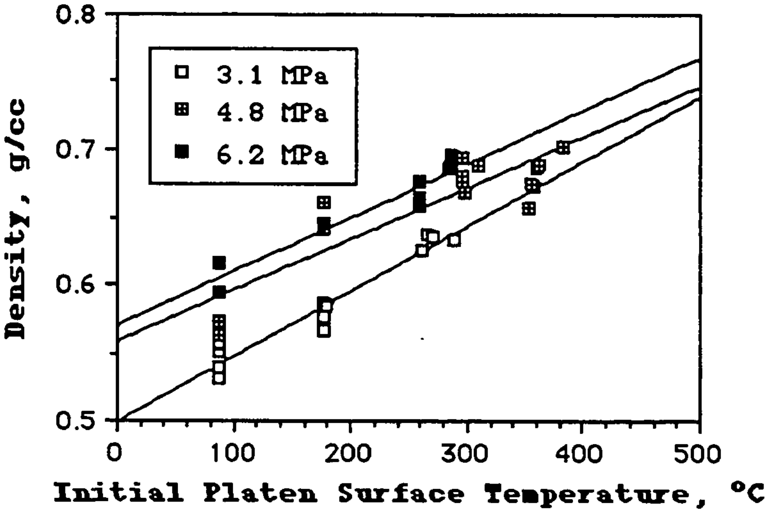

Figure 13: Soft platen density for impulse drying of 205gsm linerboard with a steel platen as a function of initial platen surface temperature and peak pressure. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.

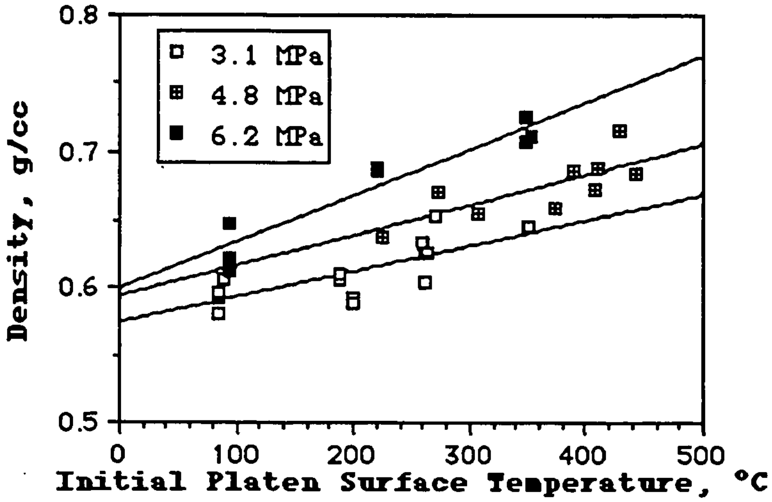

Figure 14: Soft platen density for impulse drying of 205gsm linerboard with the prototype zirconium oxide platen as a function of initial platen surface temperature and peak pressure. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.

The out-of-plane specific elastic modulus has been shown to be proportional to standard destructive strength tests such as the STFI compressive strength (12). Analysis of the current results showed that the specific elastic modulus was a function of sheet density and platen type as shown in Figure 15. For a given sheet density, the zirconium oxide surface resulted in slightly lower modulus, again suggesting a difference in internal sheet structure. While sheet strength at a given sheet density was lower, the prototype platen allows operation at much higher temperatures which result in improved sheet density and strength.

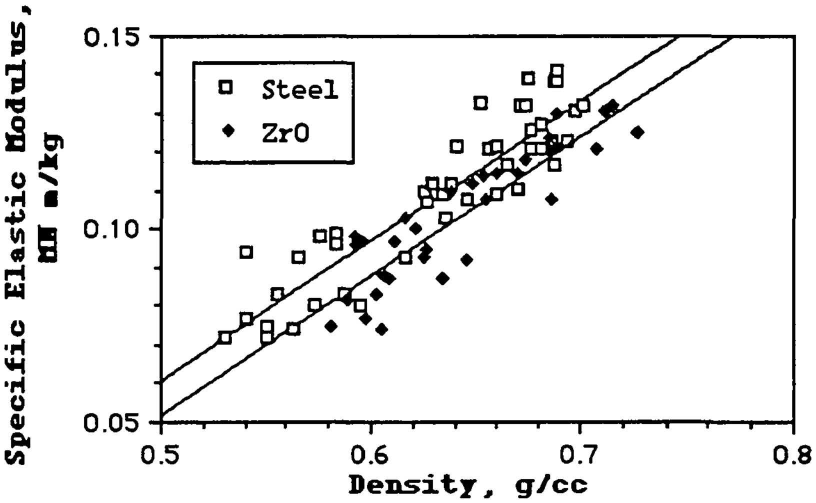

Figure 15: Specific elastic modulus for impulse drying of 205gsm linerboard as a function of soft platen density for the steel and prototype zirconium oxide platens. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.

As demonstrated by Crouse (7), sheet delamination limits the operating temperature of impulse drying roll surfaces and consequently limits water removal. Hence, to evaluate potential roll surfaces, the key performance variables were water removal and delamination control. With this in mind, a performance map showing the coefficient of variation of the specific elastic modulus vs. moisture ratio change was found to be useful. Comparative performance maps for each of the peak pressures investigated are shown in Figures 16, 17 and 18. Also shown are fitted equations to the data and a delamination criteria of 10% (as discussed in the Appendix). Based on the intersection of the fitted curves and the 10% line, a maximum moisture ratio change could be determined for each platen type at each peak pressure. At all pressures, the steel platen resulted in excessively high coefficients of variation at fairly low values of moisture ratio change. While the performance of the zirconium oxide surface was slightly better than steel at 3.1MPa, increasing the peak pressure significantly improved water removal without inducing sheet delamination.

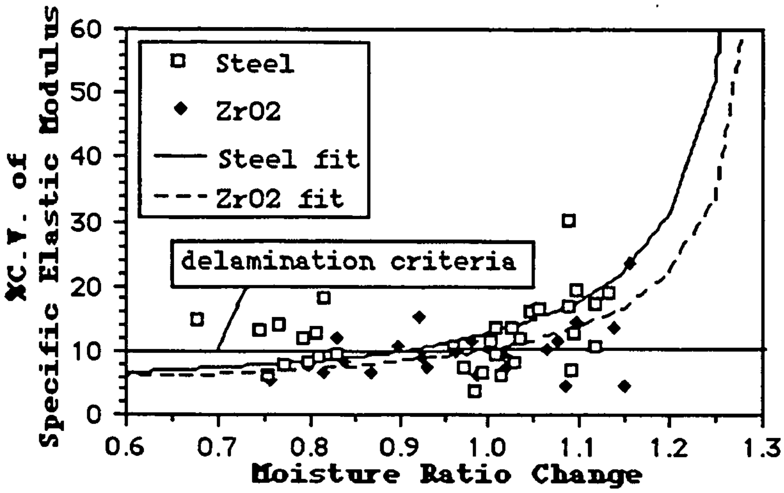

Figure 16: Coefficient of variation of specific elastic modulus as a function of moisture ratio change for impulse drying of 205gsm linerboard with steel and with the prototype zirconium oxide platens at a peak pressure of 3.1MPa. Dwell time=20ms, impulse=0.028MPas, ingoing sheet temperature=85°C, ingoing solids=30%.

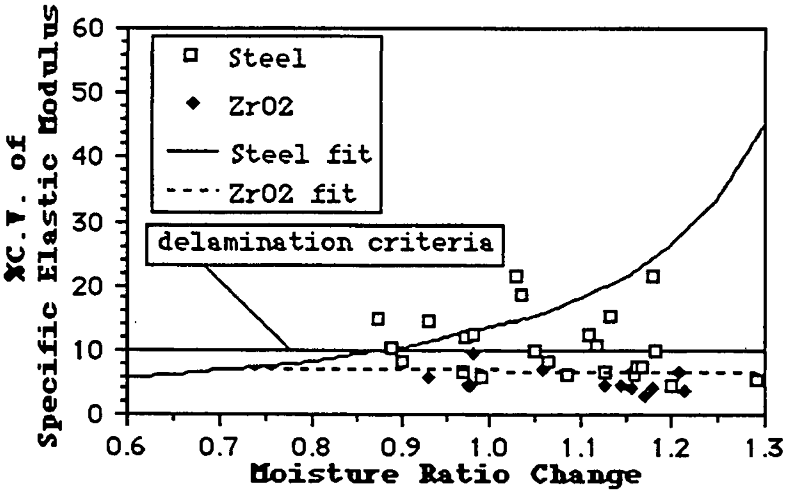

Figure 17: Coefficient of variation of specific elastic modulus as a function of moisture ratio change for impulse drying of 205gsm linerboard with steel and with the prototype zirconium oxide platens at a peak pressure of 4.8MPa. Dwell time=20ms, impulse=0.044MPas, ingoing sheet temperature=85°C, ingoing solids=30%.

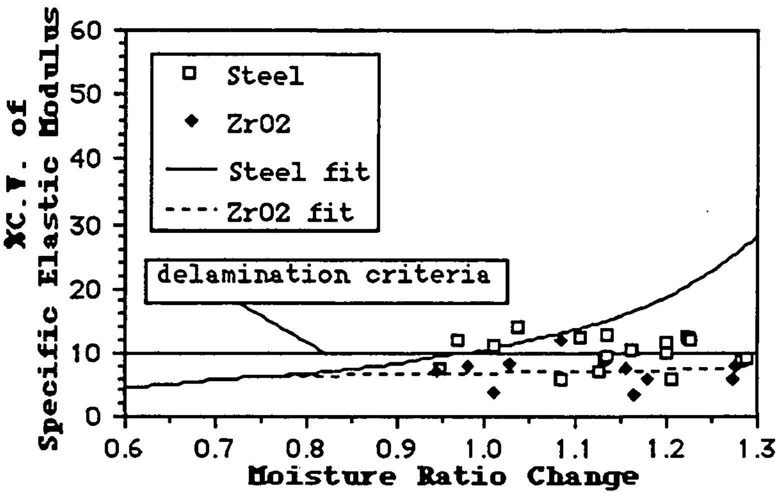

Figure 18: Coefficient of variation of specific elastic modulus as a function of moisture ratio change for impulse drying of 205gsm linerboard with steel and with the prototype zirconium oxide platens at a peak pressure of 6.2MPa. Dwell time=20ms, impulse=0.062MPas, ingoing sheet temperature=85°C, ingoing solids=30%.

As the ultrasound method does not detect delamination on the outer edge of samples or pin point surface delamination, visual observation was also used to assess maximum moisture ratio change and the corresponding maximum initial platen temperature. Table 1 shows a comparison of these limiting values based on ultrasound and visible delamination detection. In most cases the ultrasound technique was more conservative than visible observations in defining the maximum operating temperatures. Table 1 shows that the prototype platen significantly increased the operating temperature limit at peak pressures of 4.8 and 6.2 MPa resulting in a significant improvement in water removal.

TABLE 1

PLATEN	PRESSURE MPa	MAXIMUM MRC (Ultrasound)	MAXIMUM TEMP,°C (Ultrasound)	MAXIMUM MRC (Visible)	MAXIMUM TEMP,°C (Visible)
Steel	3.1	0.90	211	0.95	252
	4.8	0.88	77	0.93	128
	6.2	0.98	116	1.03	171
ZrO2	3.1	1.00	245	0.95	203
	4.8	>1.20	444	>1.20	444
	6.2	>1.25	470	1.27	498

Once maximum temperatures were defined, the platen materials were compared in terms of: maximum outgoing solids, maximum sheet density and maximum specific elastic modulus. Figure 19 shows such a comparison, where the most conservative maximum temperatures from Table 1 were used. The figure also includes the results for single felted wet pressing.

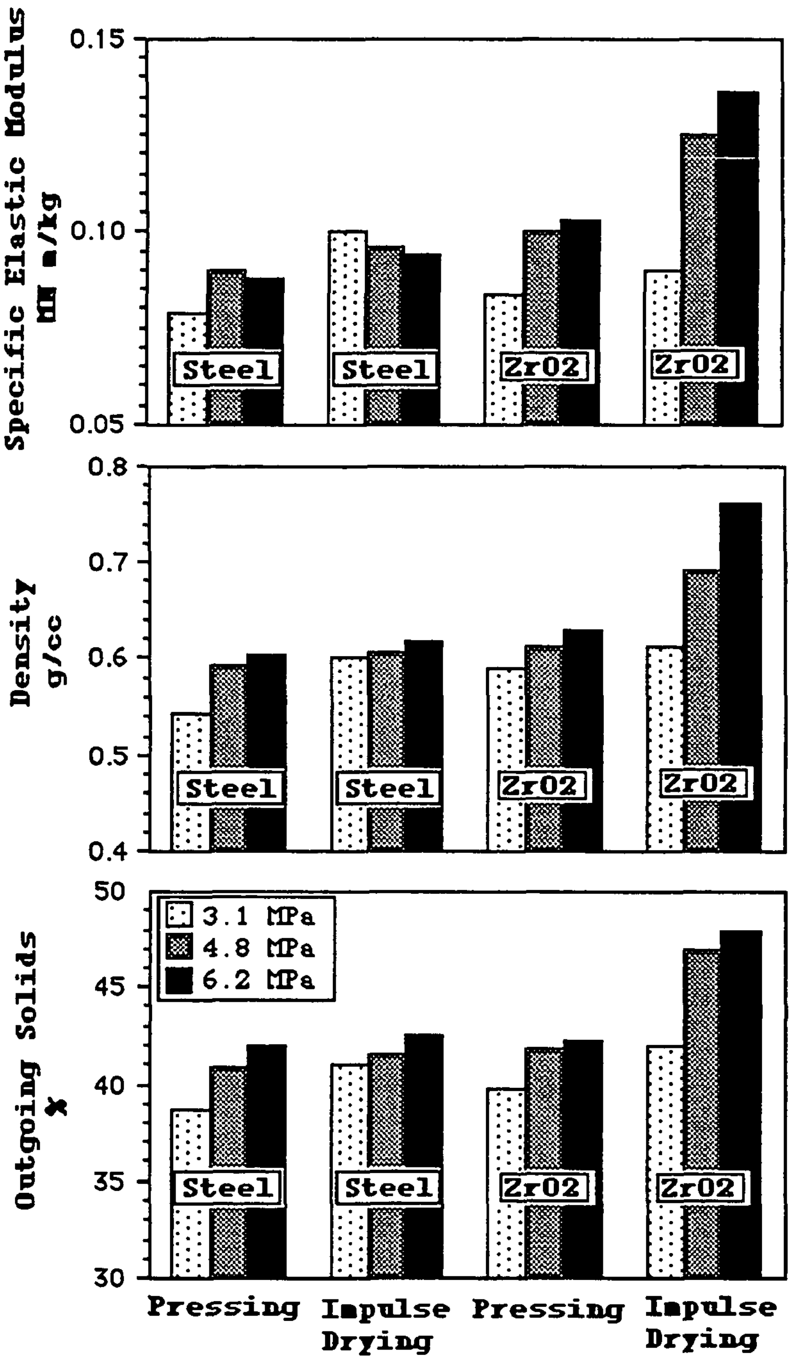

Figure 19: Maximum outgoing solids, soft platen density and specific elastic modulus as a function of peak pressure resulting from wet pressing and impulse drying of 205gsm linerboard with a steel platen and the prototype zirconium oxide platen. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.

Comparing pressing results achieved with both platen types showed similar results. As previously determined by Crouse (7), impulse drying with a steel surface showed no improvement over single felted wet pressing, because of sheet delamination. However, impulse drying with the prototype zirconium oxide platen, at high peak pressures, showed significant improvement over single felted wet pressing.

Impulse drying with the prototype platen allowed operation at a sufficiently high platen surface temperature such that vapor formed at the platen/sheet interface enhanced water removal and sheet property development. To demonstrate this point, it is instructive to extrapolate the wet pressing data, to an initial sheet temperature of 100°C as shown in Figure 10. At an impulse of 0.062MPas, corresponding to a peak pressure of 6.2MPa, wet pressing would result in a moisture ratio change of 1.05. From Table 1, impulse drying at the same peak pressure at an initial platen temperature of 470°C resulted in a moisture ratio change of 1.25. Hence, impulse drying yielded an additional moisture ratio change of 0.2 which cannot be explained by enhanced wet pressing resulting from viscosity and compressibility effects.

CONCLUSIONS

The simulations performed in this study clearly show the advantages of the prototype roll coating. It was found that at short dwell times and ingoing sheet temperatures consistent with current practice, the thermal properties of the platen surface have no effect on water removal but significantly influence sheet delamination.

It was demonstrated that by reducing the effective thermal mass of the platen surface and by increasing peak operating pressures, higher operating temperature can be used to achieve higher outgoing solids, higher final densities and higher specific elastic modulus without sheet delamination.

In particular, 205 gsm linerboard at 85°C and 30% solids was impulse dried for 20 ms at various peak pressures. At a peak pressure of 6.2 MPa initial platen surface temperature could be increased to 470°C without inducing sheet delamination. At 470°C outgoing solids were 48%. After finish drying, soft platen density and specific elastic modulus were 0.76 g/cc and 0.135 MN m/kg, respectively.

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SYMBOLS AND ABBREVIATIONS

SEM	Specific elastic modulus, MN m/kg.
CVSEM	Coefficient of variation of the specific elastic modulus, (%).
V	Pore volume fraction.
ρ	Density, g/m^3.
C_p	Specific heat, Ws/g°K.
λ	Thermal conductivity, W/m°K.
C'	Constant defined in Ref. 12.
α	Thermal diffusivity, m^2/s.
K	Ratio of the thermal conductivity to the square root of the thermal diffusivity.

APPENDIX: EXPERIMENTAL METHODS

The experimental methods used to evaluate the prototype are somewhat unique. In particular, control of ingoing solids and delamination detection require explanation.

PULP REFINING

A 58% yield southern unbleached kraft top sheet linerboard pulp was received at a freeness of 740 mL CSF. A 1lb Valley Beater was used to develop a beater curve, (see Figure A1), to determine the effect of freeness on STFI compression and burst strength.

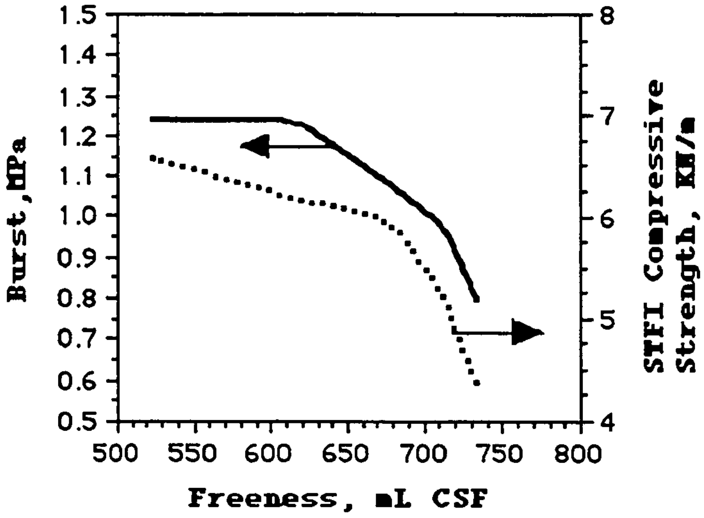

Figure A1: Beater curve for 205 gsm linerboard pulp.

Standard refining conditions were chosen such that Burst strength and STFI compressive strength were insensitive to small changes in freeness. Hence, freeness was controlled from 630 to 660 mL CSF.

SHEET PREHEATING

Figure A2 shows a schematic of the electrohydraulic press used to simulate single felted pressing and impulse drying. In the experiments of this study, handsheets were presteamed to various temperatures prior to pressing or impulse drying.

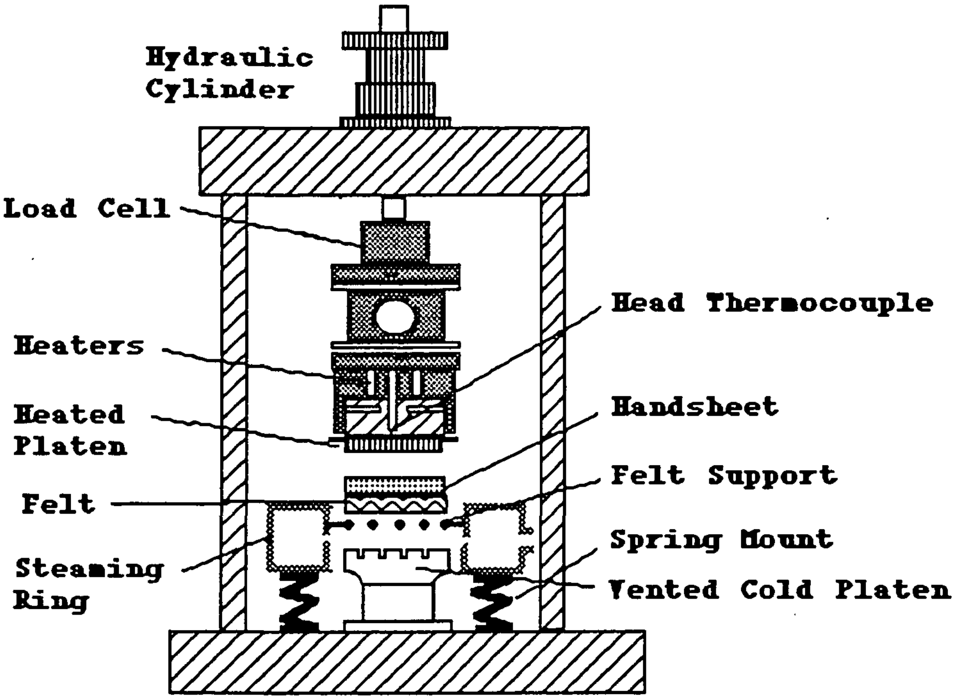

Figure A2: Schematic of the electrohydraulic press.

Figure A2 shows the presteaming configuration. Preweighed handsheets were placed on preweighed felts which were then placed onto a wire felt support attached to a preheated steaming ring. Steam exiting the ring flowed upward through the felt and the handsheet. By controlling steam pressure to 105 KPa and adjusting the steaming time and wait time before pressing or impulse drying, the initial temperature in the handsheet could be controlled. Achieving a handsheet temperature of 52°C required placing a paper board between the heated platen and the sheet during the wait period. Table A lists the conditions that were used to achieve various ingoing sheet temperatures reported in this study.

Table A

Handsheet Temperature, °C	Steaming Time, seconds	Wait Time After Steaming, seconds
25	0	0
52	40	60
85	40	0

The steam flow can uniformly raise the temperature of the sheet. Figure A3 shows internal handsheet temperatures during steaming and during the wait period (when steam flow was discontinued) for a 205 gsm handsheet composed of four 50 gsm layers.

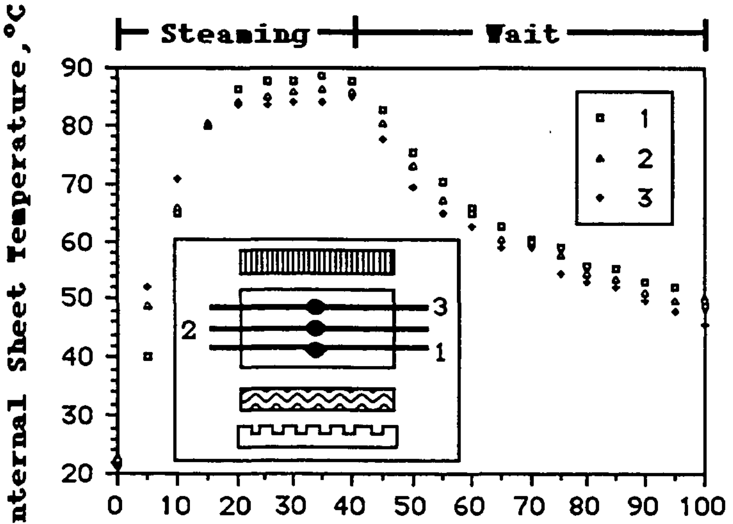

Figure A3: Internal sheet temperature of 205gsm linerboard as a function of time during steaming and wait period. Steel platen temperature=80°C.

With a platen temperature of 85°C, the temperature gradient through the center of the sheet was less than 3°C after 40 seconds of steaming and less than 4°C after a wait period of 60 seconds. When the platen temperature was raised to 315°C, as shown on Figure A4, the temperature gradient through the center of the sheet was less than 4°C after 40 seconds steaming and less than 2°C after a wait period of 60 seconds.

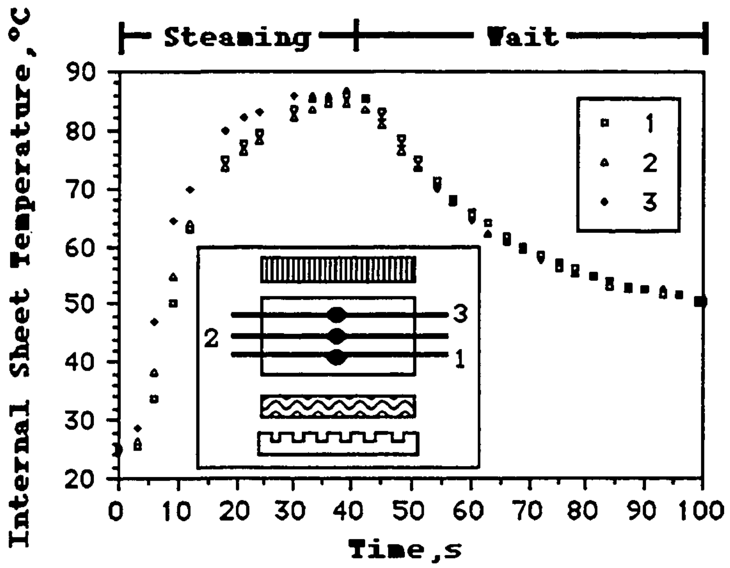

Figure A4: Internal sheet temperature of 205gsm linerboard as a function of time during steaming and wait period. Steel platen temperature=315°C.

In single felted pressing simulations the platen surface was maintained at the temperature of the preheated (steamed) handsheet so that there was little if any loss of moisture due to surface evaporation. Impulse drying simulations required that the initial platen surface temperatures be run over a range of temperature from low value equal to the handsheet temperature to a high of as much as 500°C. At high platen surface temperatures, thermal radiation during steaming can result in a substantial moisture loss. To maintain constant initial handsheet moisture prior to impulse drying, the moisture of handsheets prior to steaming were adjusted so that once steamed their average moisture was 30% solids. Figures A5 and A6 show the change in handsheet weight and felt weight due to steaming for 40 seconds while the platen surface temperature was held constant over a range of temperatures. For these calibration experiments, handsheet ingoing solids was 30% solids while ingoing felt moisture was 16%. Experiments starting at an ingoing solids of 25% showed identical results. Therefore, over a range of ingoing dryness from 25% to 30% weight changes due to steaming can be predicted from Figures A5 and A6.

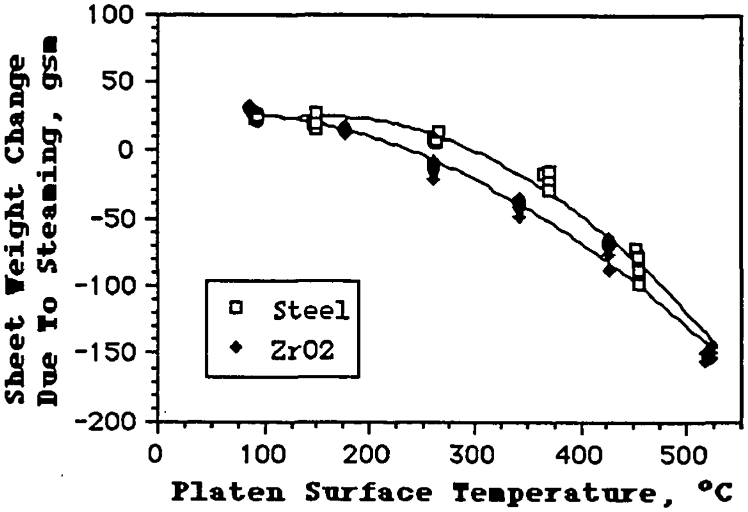

Figure A5: Sheet weight change due to steaming a 205 gsm linerboard sheet for 40 seconds as a function of platen surface temperature for steel and prototype zirconium oxide platens.

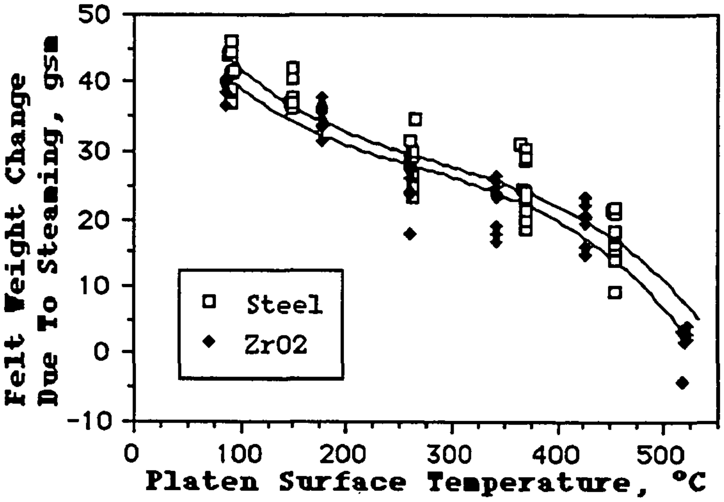

Figure A6: Felt weight change due to steaming a 205 gsm linerboard sheet for 40 seconds as a function of platen surface temperature for steel and prototype zirconium oxide platens.

IMPULSE DRYING AND FINISH DRYING

To simulate impulse drying, (see Figure A2), the heater set-point temperature was adjusted to obtain the desired initial platen surface temperature as measured with a surface thermocouple pyrometer. Based on the desired platen temperature, handsheets with proper ingoing solids were selected such that they would be at 30.0±0.5% solids after steaming. The basis weight of the handsheets was maintained at 205±10 gsm. Handsheets were positioned such that their wire side was in contact with the felt as shown in Figure A2. Felts made from Nomex fibers were used. A square wave generator was used to control the impulse. At the short dwell times of 20 ms. equipment limitations resulted in compression and decompression rates which increased when the peak pressure was increased. Figure A7 shows typical pressure vs. time curves which were reproducible to a precision of ±0.2 MPa peak pressure.

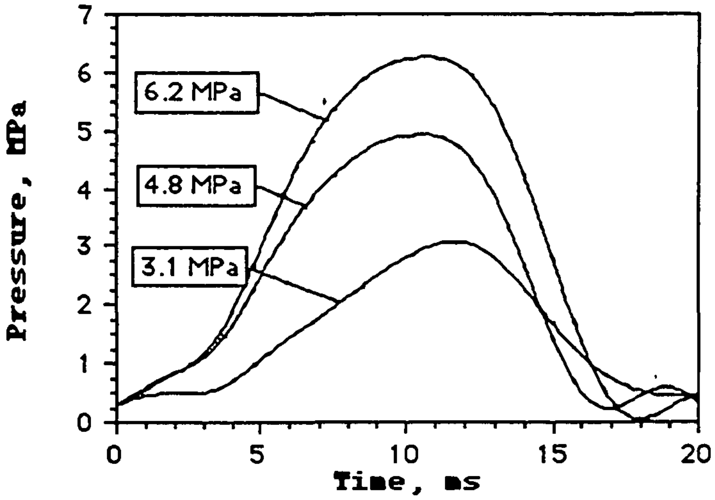

Figure A7: Pressure as a function of time for various peak pressures. Dwell time=20ms.

ULTRASONIC TESTING

Throughout the course of the research program, delamination was assessed by visual observation directly after impulse drying and before finish and oven drying. Visible delamination may be classified as either major or minor delamination. Minor delamination consisted of small blisters on the edges of the sheet or pinpoint size blisters on the heated surface of the sample. Major delamination consisted of discrete blisters having a diameter greater than 3 mm.

It was recognized that a quantitative measure for delamination was a necessity. With this in mind, samples were also evaluated using an out-of-plane ultrasonic test method (17,12). The method had the advantage of being; non-destructive, sensitive to delamination and predictive of standard destructive tests.

Samples which were impulse dried and then finish dried to 95% solids were tested ultrasonically. In the test, the speed of sound through paper was measured between 3/8" diameter soft platens. Using the measured sonic velocity, localized specific elastic modulus (SEM) were determined. By making 12 measurements at various locations on each sample, a coefficient of variation of the specific elastic modulus (CVSEM) was determined.

Blisters on the edge of sheets were typically missed during ultrasonic testing. In addition, very small surface blisters, tend to heal during finish drying. Hence, minor delaminations were not generally detected by the ultrasonic test method.

Major delaminations were distinguishable from nondelaminated samples based on the coefficient of variation of the specific elastic modulus (CVSEM). Figure A8 shows the cumulative probability of nondelaminated and major delaminated samples as a function of measured CVSEM. A critical CVSEM of 10% was chosen as a delamination criteria since 80% of samples showing no visible delamination have CVSEM below 10%, while 75% of samples showing major visible delamination were above a CVSEM of 10%. Hence a CVSEM equal to or greater than 10% indicates sheet delamination.

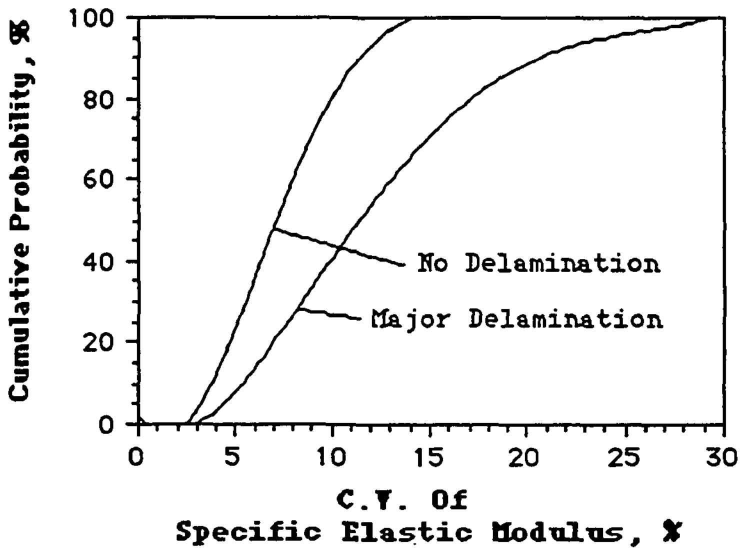

Figure A8: Cumulative probability of finding nondelaminated and major delaminated samples with coefficients of variation of specific elastic modulus less than the given amount.

ACKNOWLEDGEMENTS

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