*Institute of Paper Science and Technology*

# HIGH-INTENSITY DRYING PROCESSES – IMPULSE DRYING

## STATUS OF THE PILOT-SCALE RESEARCH PROGRAM

DOE/CE/40738-T14
Distribution Category UC-310

IPST Project 3595

## REPORT 14

A Progress Report

to the

U. S. DEPARTMENT OF ENERGY

April 1998



*Atlanta, Georgia*

## INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
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# HIGH - INTENSITY DRYING PROCESSES - IMPULSE DRYING

STATUS OF THE PILOT-SCALE RESEARCH PROGRAM

REPORT 14

A Progress Report

To the

U.S. DEPARTMENT OF ENERGY
Work Performed Under Contract DE-FG07-85CE40738

By

D. I. Orloff

April 1998

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
Atlanta, Georgia

Project 3595

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## A. SUMMARY

As of April 1998, the project was behind on schedule. This was as a result of the need for additional process development work. Work has focused on evaluating nip decompression and post-nip depressurization techniques as used on the Beloit X2 pilot paper machine. We have also concentrated on implementing impulse drying technology on Beloit's No. 4 and No. 2 pilot paper machines.

Experiments on Beloit's X4 pilot paper machine demonstrated that roll coating durability problems have been solved. They also showed that further development work on sheet picking, implementation of delamination suppression techniques and CD temperature control are necessary in order to ensure success on the X4 machine.

Experiments on the Beloit's X2 pilot paper machine were carried out to resolve issues identified on the X4 machine. Two methods of implementing press nip decompression were investigated. The results confirmed that the technology can be used to increase impulse drying operating temperatures. The work also led to the development of techniques to minimize picking.

## B. OVERVIEW

In January 1997 the Beloit X4 pilot paper machine was started up in a single-felted wet pressing mode to verify that 205 gsm linerboard could be produced at machine speeds of 1250 ft/min. The machine has a vertical twin wire forming section, while the press section was configured with a bi-nip roll press followed by a 10-inch-long shoe press (ENP). The bi-nip was set at a press loading of 400 pli on the first press and 600 pli on the second press. The ENP was configured with a post-nip roll wrap and set at 6000 pli. The press roll of the ENP was coated with Beloit "E" coating, while an Albany International "CSX" press felt was used. Employing a once-dried Kraft (composed of mixed softwood, hardwood, and OCC) repulped to a freeness of 670 ml CSF, press dryness of between 48 to 50% was achieved at a basis weight of 209 gsm. Samples from the reel were tested yielding an average caliper of 346 μm and an average apparent density of 0.605 g/cm$^3$.

Also in January 1997, the ENP roll on the Beloit X4 pilot paper machine was heated to 325°F and an attempt was made to thread a paper web through the press section. The paper stuck to the roll before the web could be broken back to the former. Attempts to clean the roll failed and it was decided to cool the roll down to facilitate cleaning. After cleaning the paper off the roll, two areas of cover failure were noticed. The failure occurred towards the bottom surface of the coating and not in the bond coat or at the steel surface of the roll. This event ended the scheduled impulse drying experiments. Co-current roll coating durability testing at IPST had shown that a coating of similar composition (but reduced thickness) had been exposed to nearly 5 million thermal and mechanical cycles without failure. Based on these results, and a comparison of the coating thickness on the ENP roll and the IPST roll, it was decided to go ahead with the March X4 experiments with a roll coated with a thinner coating of Beloit "E".

Also in January 1997, low-speed heated roll press experiments, performed at Beloit, suggested that a post-nip roll wrap does help to inhibit sheet delamination during impulse drying.

In February 1997, an investigation was begun on what mechanisms could cause such a failure. A literature search was performed and development of an analytical model and experimental data were begun by IPST. To confirm IPST roll durability results, the IPST press roll on the roll durability test facility was thoroughly cleaned and the coating was examined under 30X magnification. This magnification makes it possible to identify defects on the order of 5-10 mm in width, which were typical crack widths observed on the failed X4 roll. An examination did not reveal any cracking.

In March 1997, experiments were continued on the Beloit X4 machine. The thinner roll coating survived, felt performed above expectations, and threading was accomplished at high temperature. Linerboard, at a basis weight of 205 gsm, was produced at speeds of 1250 to 1500 ft/min. No roll coating cracking or spalling was noted after two weeks of operation at speed, load, and temperature. The Albany International CSX felt operated to 500°F, at a speed of 1500 ft/min and a press load of 6000 pli. The machine could be threaded at a roll temperature of 400°F. CD temperature uniformity, basis weight, and load are important at thread-up.

The control of CD roll surface temperature specifically during initial roll heating, threading, and steady state operation is important and required additional development. Sheet picking was observed at higher roll temperatures than were previously observed on Beloit's heated roll press and IPST's MTS. This made CD roll surface control critical during attempts to set the roll temperature between the sticking temperature and the critical impulse drying temperature. The available post-nip felt wrap yielded a pressure of 20 kPa, which was insufficient to prevent sheet delamination even for high freeness. As a result, the picking temperature was higher than expected and the critical temperature was lower than expected, resulting in a nonexistent operating window. It was observed during the trial that Teflon blocks holding thermocouples to the heated roll surface yielded MD streaks in the web where there was no picking while adjacent areas of the sheet showed picking. This suggested two courses of action: either include Teflon in the roll surface coating or apply it continuously, with a Teflon doctor, during normal roll operation.

In April 1997, it was decided to continue the shakedown work on Beloit's, more readily available, X2 pilot paper machine. In order to address the sticking problem, Beloit initiated development of a new roll coating, Beloit G, in preparation for June roll sticking experiments on the X2 machine. That trial used two different furnishes, the furnish used in the March '97 trial and a once dried Virgin softwood Kraft furnish from a different source. The objective of the trial was to evaluate the roll coating susceptibility to sticking under wet pressing conditions and under impulse drying conditions at temperatures of 300 °F to 450 °F. Beloit also scheduled time in July to optimize the decompression ramp of the press shoe pressure profile. IPST began supporting the development of an optimized shoe profile by conducting MTS simulations.

In May 1997, a laboratory investigation to determine a range of ramp profiles which are both physically possible on a shoe press and which provide a reasonable increase in critical temperature was performed at IPST. The work was done using the same furnish as was used during the March '97 X4 trial and was performed on the MTS hydraulic press. The results were evaluated and suggested ramp profiles were communicated to Beloit. During that time, Beloit began building the new shoe which was designed to incorporate a ramp on the end of a shortened ENP shoe. The design allowed for the start pressure and duration of the ramp to be adjustable when the shoe is taken out of the machine.

Additional roll durability testing brought the IPST press roll, with the four coatings to approximately 10 million thermal/mechanical cycles. The roll was cleaned and examined under 100X magnification. There were no new cracks observed (when the roll was delivered to IPST, one coating had some small (< 5 mm long) cracks along the edges of the coating; these have not changed in size or appearance). Some pitting (< 1 mm diameter) was observed in the Beloit A coating. The Beloit E coating showed only one or two pits over its entire surface.

In June 1997, the furnish used in March '97 was run on the X2 machine equipped with the new Beloit "G" press roll coating. The shoe used was a standard shoe with no ramp. The intent of this trial was solely to investigate sticking. The new roll coating was successful in preventing sticking at roll temperatures of 180 to 210°C. This range was chosen as it caused considerable sticking during the March trial. As a last step, the 100% Virgin Kraft was run. There was also no sticking with that furnish in the temperature range of 356 to 410°F.

In July 1997, an X2 machine trial took place as planned. This trial used a once-dried Virgin softwood Kraft furnish at 550 ml CSF, 30% ingoing solids, and at a machine speed of 1250 fpm. As with all previous X2 trials, sheet weight was limited to 100 gsm. The purpose of this trial was to evaluate recent shoe modifications and determine an optimized ramp for the operating conditions. The shoe evaluated was a 6-inch-long shoe with an 8-inch extension designed to produce a ramp at the end of the main profile. The extension was adjustable when taken out of the machine. This allowed limited but time consuming modification of the ramp characteristics. This preliminary work showed the ramp could be used to increase the critical temperature by at least 40 to 70°F.

In August 1997, an X2 machine trial took place as planned. This trial used the same once dried Kraft, at 550 ml CSF, at an ingoing solids of 30%, 100 gsm, and at a continuous machine speed of 1250 fpm. The purpose of this trial was to continue the work begun during the July X2 trial, specifically optimization of the trailing ramp portion of the pressure pulse. The shoe evaluated was the same as was used in July 1997. During the trial a profile was found which made it possible to impulse dry the sheet with a roll temperature in excess of 405°F. In addition to this work it was also shown that by applying a Teflon doctor blade to the heated roll surface, with sufficient pressure, picking can be significantly reduced. Physical testing of samples from the August X2 trials showed a 100°F increase in critical temperature, and a 6% increase in dryness, and up to a 20% increase in STFI.

The shoe used in the trial had the disadvantages of requiring that it be removed from the ENP in order for the ramp profile to be adjusted and that the short shoe resulted in peak loads that induced picking. To rectify these shortcomings, a standard 10-inch shoe would be used with two newly designed modifications. One was a more "user friendly" shoe that could also be used on the X4 machine. The other was a mechanism for applying air pressure to the web just as it exits the nip. The mechanism would apply air pressure (~30 psi max.) over an area the full CD width of the machine and about 4 to 7 inches in the MD direction. It can best be thought of as a stationary hover craft. A preliminary version of the device was tested on Beloit's heated roll press using large hand sheets. A version of the device which could be used on both the X2 and the X4 was jointly designed by Beloit and IPST. The geometry of the two machines requires that each use a slightly different design. Specifically, IPST personnel performed an analysis to determine the air flow requirements for such a device. The air flow required is such that a high flow rate compressor is required.

In September 1997, preliminary tests of a prototype "hover press" on Beloit's slow speed heat roll press indicated that there was no decrease in outgoing solids resulting from the applied air pressure. Additionally, the process appeared to inhibit delamination.

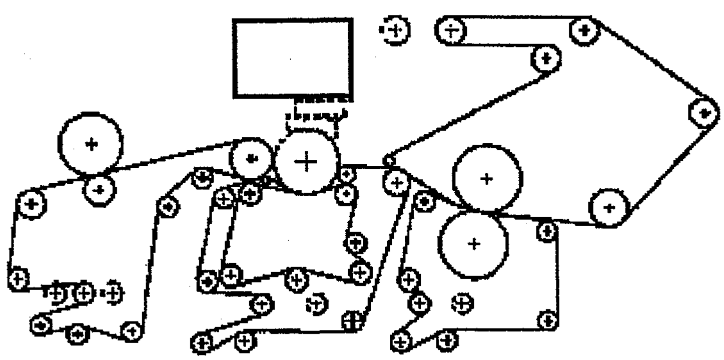
In October 1997, meetings were held between Beloit and IPST to scope out X2 experiments planned for December 1997. It was agreed to use a standard 10-inch shoe with a 4-inch ramp extension as well as a "hover press." Beloit designed the ramp extension so that the applied pressure, and the resultant ramp profile can be adjusted while the machine is running. This provides a significant advantage over the previous design. The "hover press" was designed with chambers allowing for progressive decreases in applied air pressure as distance from the nip exit increases. The peak applied air pressure was 30 psig. IPST arranged to have a large capacity (600 CFM at 30 psig) air compressor available for the test to supply air to the "hover press."

In December 1997 and early January 1998, impulse drying experiments were conducted on the Beloit X2 pilot paper machine. In December, the research team concentrated on installing the equipment and determining optimum operating conditions for both the new press shoe and the "hover press." A full week of experiments were conducted in early January, in which the optimum internal ramp and external hover press combinations were evaluated for a range of freeness and over a range of machine speeds. In addition, two blanket drainage geometries were also investigated. The results of these experiments are detailed in section C, D, and E of this report.

## C. THE SUMMER EXPERIMENTS

The purpose of the experiments, conducted in July and August 1997, was to verify that the ramp decompression concept could be used to extend the temperature operating window of high-speed continuous impulse drying and that sheet/roll surface picking could be eliminated by proper choice of press roll surface and/or by Teflon doctoring.

These and later experiments were conducted on Beloit's X2 pilot paper machine. While the machine has certain limitations with regard to basis weight, ingoing solids and width, it has the advantages of having an induction heated open extended nip press and was readily available. The open extended nip press was desirable as it did not significantly limit press shoe length and geometry. An overall schematic and diagram of the X2 machine is shown in Figure 1 and a close-up showing the location of the hover press is shown in Figure 2.



Schematic Diagram Of Beloit X2 Pilot Paper Machine

Figure 1. X2 Pilot Paper Machine.

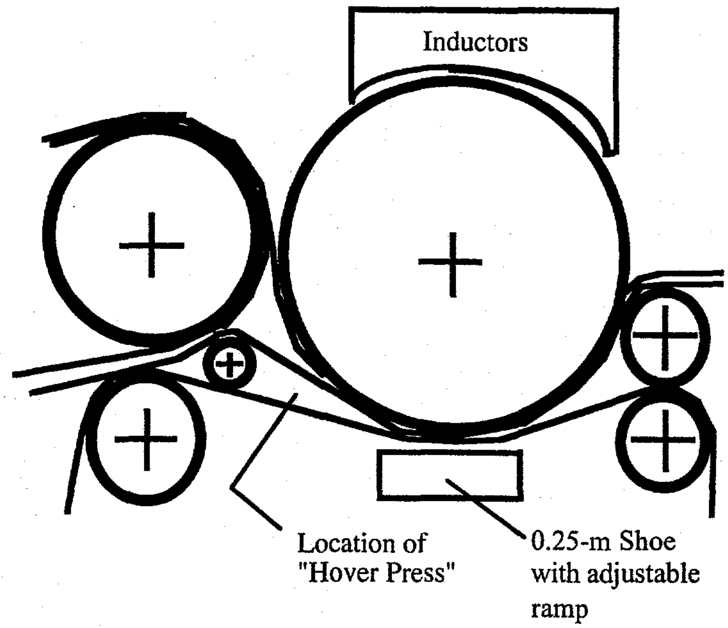



Figure 2. Close-up of January 1998 configuration of impulse dryer on the Beloit X2 pilot paper machine.

As the shape of the pressure profile, generated by the press shoe and the "hover press" were major variables of the experiments, its measurement was considered to be of importance. To this end, the Institute purchased and utilized a TechScan pressure measurement system to both statically and dynamically measure pressure profiles. Typical profiles at a press load of 6000 pli, used during the July and August experiments are shown in Figure 3. The "standard" profile corresponds to the pressure distribution resulting from a commercial Beloit 10-inch shoe. The "Short/Ramp" profile corresponds to the profile obtained from a 7-inch shoe followed by a 7-inch adjustable ramp. The specific ramp profiles investigated during the July and August experiments are shown in Figure 4. Note that the ramps used in July and August each followed the short shoe as indicated in Figure 3.

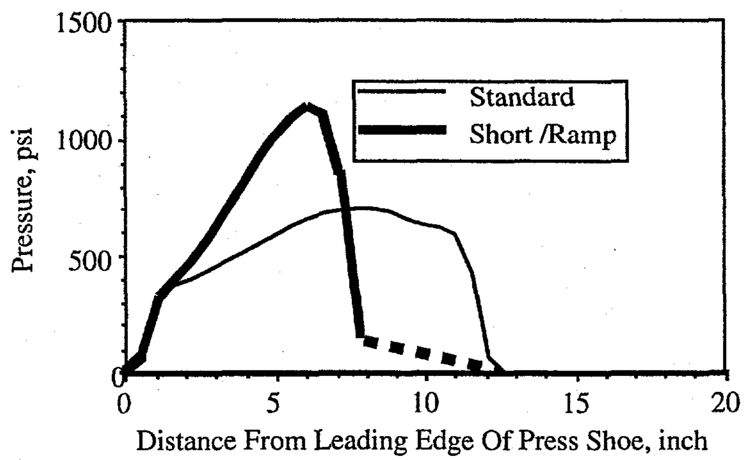



Figure 3. Measured pressure profiles of the standard 10" and "short shoe" used in the July and August 1997 experiments on the Beloit X2 pilot paper machine.

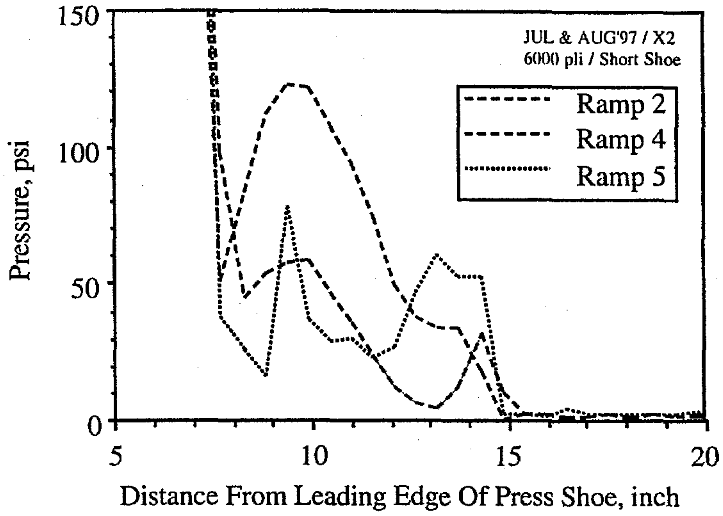
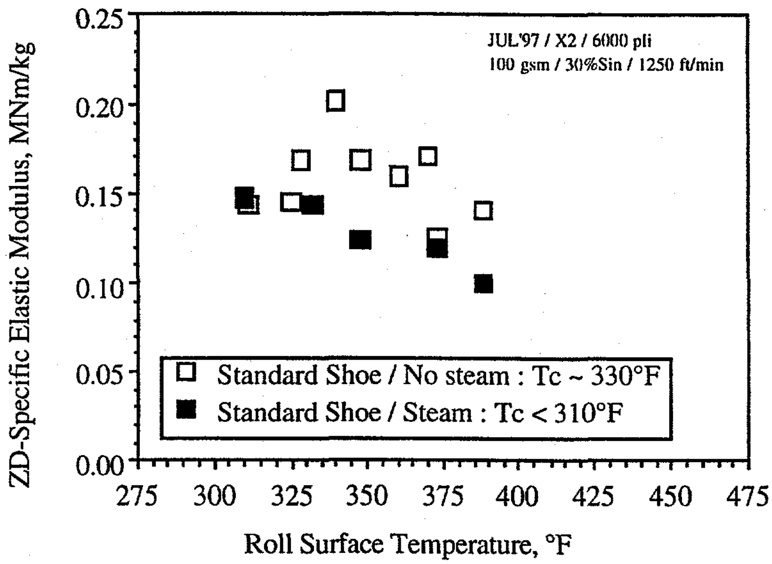
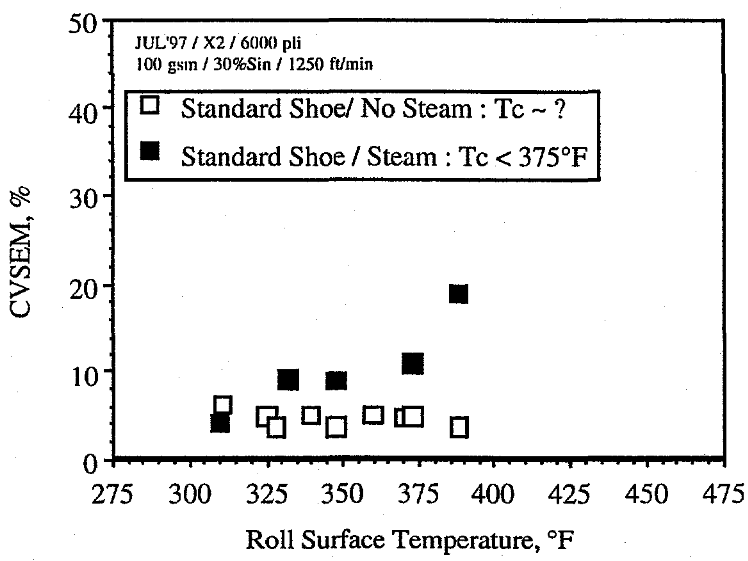



Figure 4. Measured pressure profiles of various ramp decompression profiles used in the July and August 1997 experiments on the Beloit X2 pilot paper machine.

The first objective of the July experiment was to characterize the performance of the standard 10-inch shoe with and without the use of a steambox just prior to the impulse dryer. Under both conditions of ingoing temperature, the roll surface temperature increased over a range of temperatures from 300 to 400°F. Samples of paper produced at these conditions were then finish dried on a cylinder dryer and tested. Figure 5 reports the zd-specific elastic modulus as a function of roll surface temperature, while Figure 6 shows the corresponding coefficients of variation. Based on these test results, the critical impulse drying temperature of the unheated web was about 330°F, while that of the preheated web was less than about 310°F. As web preheating added an extra complication to the experiments and is generally ineffective at low freenesses, it was decided to delete the steam box from future experiments.




<u>Figure 5.</u> Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using a standard 10-inch press shoe with and without steam preheating.




<u>Figure 6.</u> Coefficient of variation of the out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using a standard 10-inch press shoe with and without steam preheating.

The second objective was to determine whether the use of the short shoe with the ramp could be used to increase the critical impulse drying temperature above that obtained using the standard 10-inch shoe. The short shoe with the ramp was so designed as to generate the same impulse (area under the pressure - time curve) as the standard shoe. These experiments were conducted without the use of the steam box. Figure 7 reports the zd - specific elastic modulus as a function of roll surface temperature for ramp #2. The corresponding coefficients of variation of the elastic modulus are shown in Figure 8. Based on these measurements, a critical impulse drying temperature of 400°F was obtained. Hence it was concluded that the modified profile resulted in an increase in the window of operation of about 70°F.

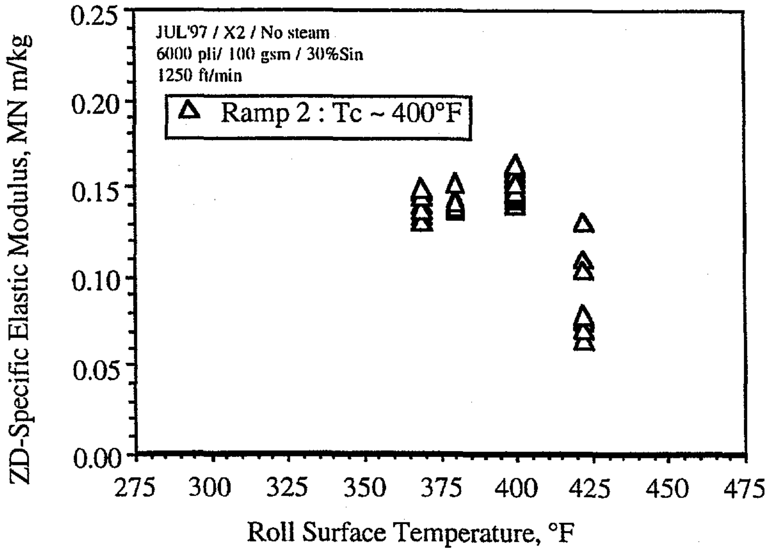



Figure 7. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using a "short shoe" with ramp #2 without steam preheating.

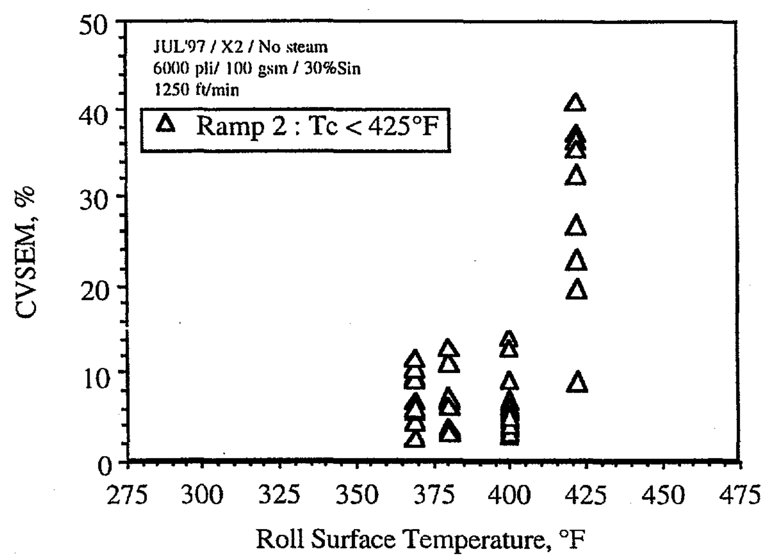



Figure 8. Coefficient of variation of the out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using a "short shoe" with ramp #2 without steam preheating.

Additional, more detailed, experiments were conducted in August. In these experiments, attempts were made to adjust the ramp profile shapes more closely to those of laboratory simulations. The resulting ramps (#4 and #5) were generally of lower pressure than ramp #2 but were still jagged in shape. Table 1 shows the setup conditions of the gap former and the impulse dryer. The furnish used for this as well as the July and January experiments was a once-dried Virgin unbleached softwood Kraft. The furnish was repulped and minimally refined to a freeness of 570 ml CSF for the August experiments. The ingoing solids to the impulse dryer was maintained between 31.5 and 32.2% solids while the basis weight was set at a nominal 100 gsm. Permeability testing of the wet web showed that the specific surface was between 3.2 and 4.1 $m^2/g$ as shown in Table 2. The machine was operated at 1250 ft/min.

Table 1. Comparison of Operating Conditions in August 1997 and January 1998

| Section Of P.M. | Operating Condition | August 1997 (570 ml CSF Case) | January 1998 (540 ml CSF Case) |
|---|---|---|---|
| Forming | #1 Wire | 145 x 104 , 507 CFM | 152 x 68/34, 503 CFM |
| | #2 Wire | 182 x 145 | 161 x 110, 471 CFM |
| | Pressure | 145 in $H_2O$ | 130 in $H_2O$ |
| | Flowrate | 905 gpm | 600 gpm |
| | Thick Stock | 148 gpm | 140 gpm |
| | Temperature | 47 °C | 43 °C |
| | pH | 7.7 | NA |
| Pressing | Solids In | 32% | 25% |
| | Press Shoe | 6-inch with ramp extension | 10-inch with adjustable ramp |
| | Felt | AI 289250 CSX | AI 289249 CSX |
| | Wrap Roll | inside link | outside link |
| | Blanket | grooved | op. side- blind drilled/ dr. side- grooved |

Table 2. Ingoing Web Properties

| Case<br>Date - Ramp #<br>P.M. Speed | Freeness, ml CSF | Ingoing Solids, % | Specific Surface, $m^2/g$<br>Average<br>Std. Dev. | Specific Volume, $g/m^3$<br>Average<br>Std. Dev. | OD Basis Weight, $g/m^2$<br>Average<br>Std. Dev. |
|---|---|---|---|---|---|
| Aug'97- Ramp 4<br>1250 ft/min | 570 | 32.2 | 3.20<br>0.03 | 1.16<br>0.02 | 105.5<br>6.8 |
| Aug'97- Ramp 5<br>1250 ft/min | 570 | 31.5 | 4.07<br>0.87 | 1.10<br>0.03 | 105.5<br>6.8 |
| Jan'98 - Ramp 8<br>1250 ft/min | 540 | 24.6 | 6.60<br>1.43 | 1.84<br>0.09 | 98.5<br>4.9 |
| Jan'98 - Ramp 8<br>1250 ft/min | 458 | 27.5 | 11.16<br>1.28 | 1.75<br>0.09 | 97.6<br>2.9 |
| Jan'98 - Ramp 8<br>2500 ft/min | 460 | 26.1 | 14.97<br>1.71 | 1.77<br>0.01 | 97.9<br>2.6 |

Using the short shoe with ramps #4 and #5, impulse drying experiments were conducted at a press load of 6000 pli over a range of press roll surface temperatures between 375 and 475°F. As shown in the zd-elastic modulus plot of Figure 9 and the coefficient of variation plots of Figure 10, the critical impulse drying temperature was about 424°F for ramp #4 and 408°F for ramp #5. In Figures 11 through 16 important paper physical properties are compared at the various critical temperatures and to corresponding wet pressing controls. In particular it is noted that impulse drying yielded a 5-point increase in press dryness, increased sheet smoothness and Gurley as well as improvements in STFI compression strength and ring crush.

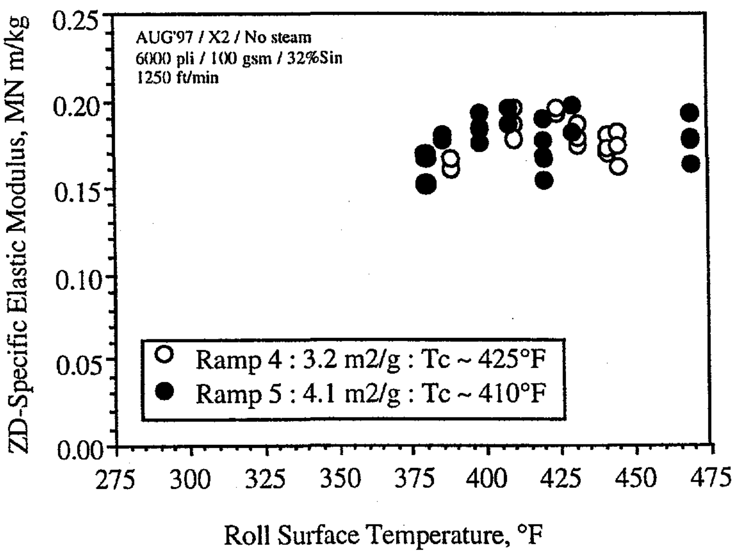



Figure 9. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using a "short shoe" with ramps #4 and #5 without steam preheating.

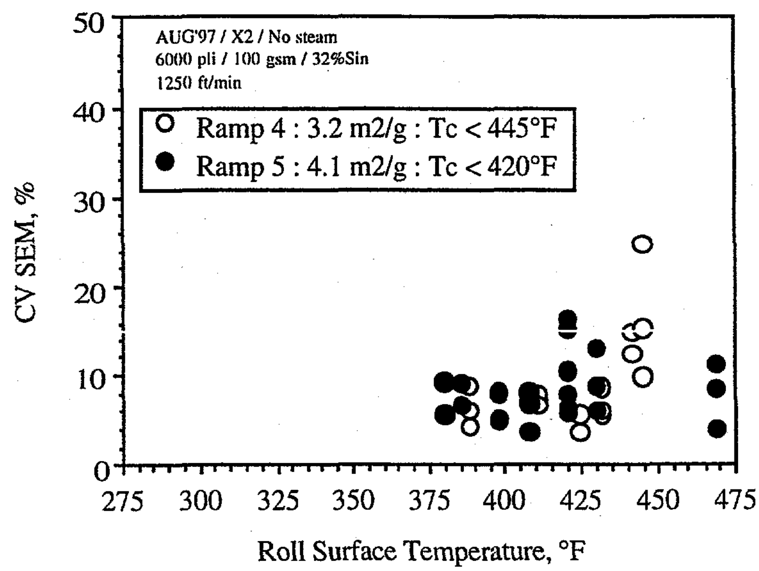



Figure 10. Coefficient of variation of the out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using a "short shoe" with ramps #4 and #5 without steam preheating.

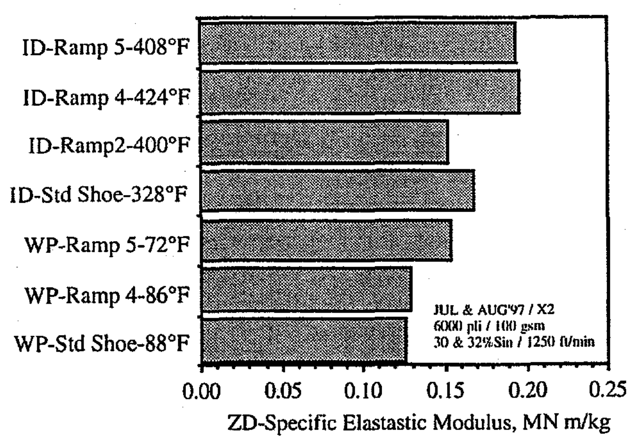



Figure 11. Out-of-plane specific elastic modulus of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions.

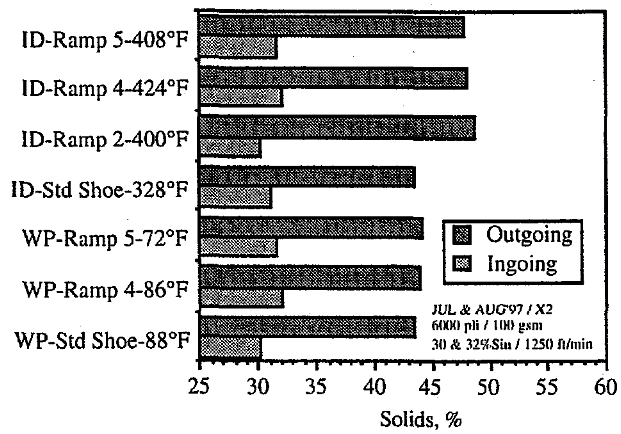



Figure 12. Ingoing and outgoing solids of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions.

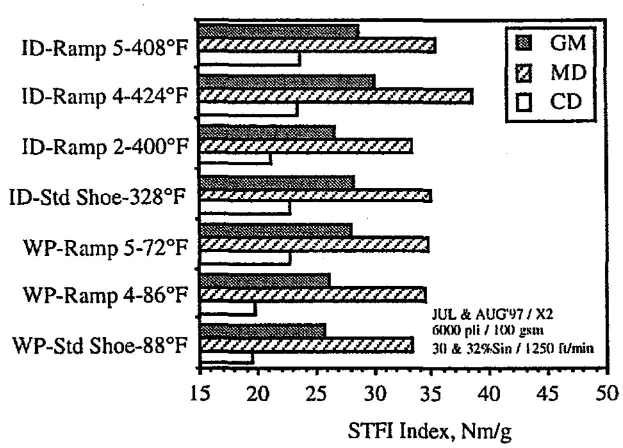



Figure 13. CD, MD, and GM STFI compression index of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions.

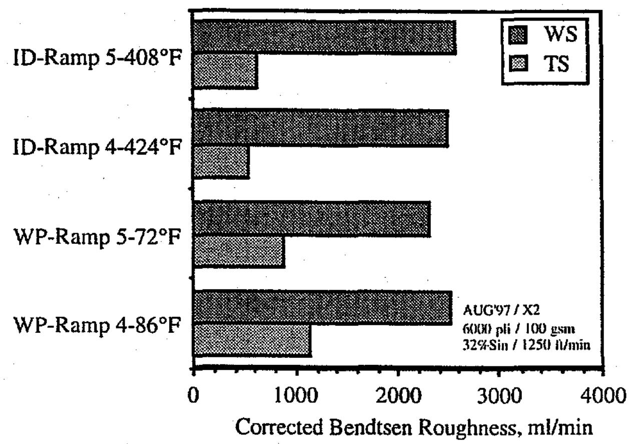



Figure 14. Corrected Bendtsen Roughness of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions.

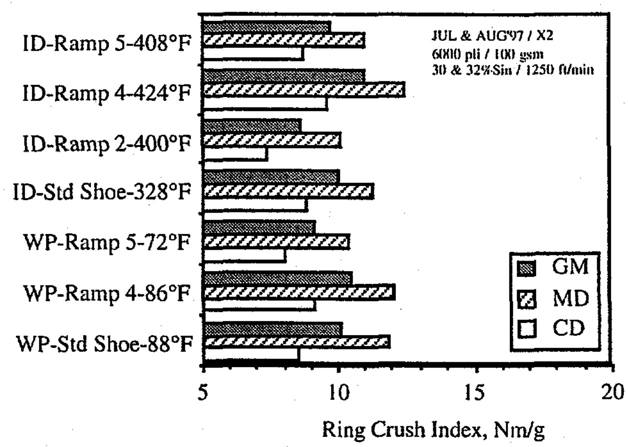



Figure 15. CD, MD, and GM Ring Crush index of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions.

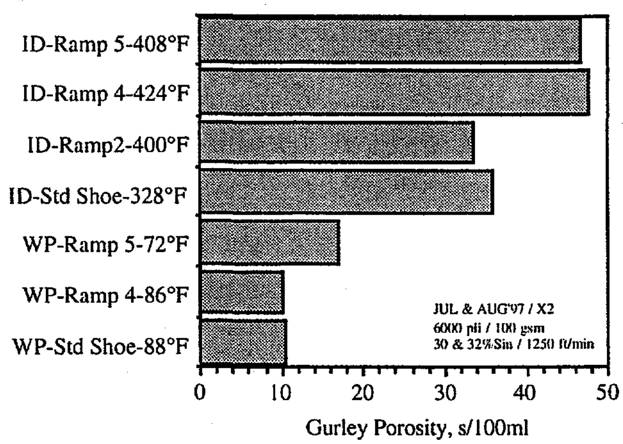



Figure 16. Gurley Porosity of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions.

In addition to demonstrating the usefulness of modifying the press shoe, the August experiments also demonstrated the usefulness of using a heavily loaded Teflon doctor to minimize and, under some conditions, eliminate sheet/press roll picking. To further explore the variables influencing picking, a side experiment was conducted at various press loads while maintaining the press roll surface temperature at 400°F. It was found that picking decreased with decreasing press load. The experiments were also useful in showing the minimum press load that would be required for impulse drying performance to surpass that of 6000 pli wet pressing. Figure 17 to 23 show these comparisons. It was observed that an impulse dryer operating at 3000 pli would be superior to a similarly configured wet press operating at a press load of 6000 pli, see in particular Figures 19 and 20.

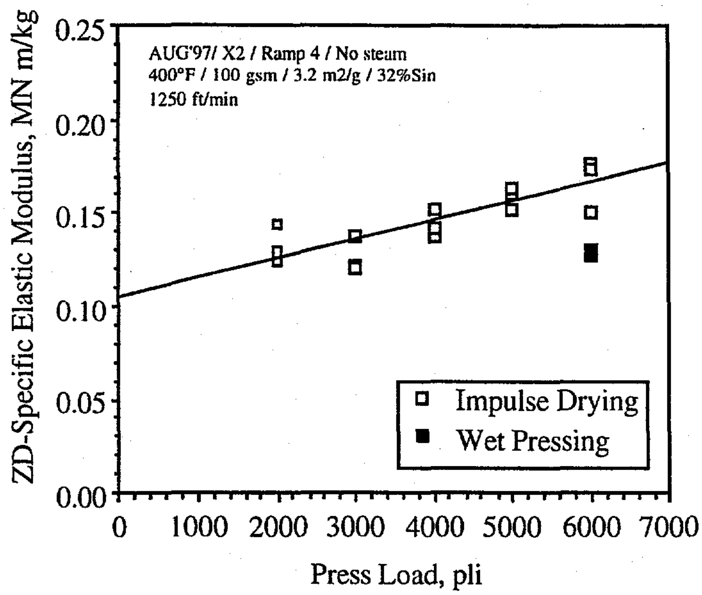



Figure 17. Out-of-plane specific elastic modulus of impulse dried paper as a function of press load at a fixed press roll surface temperature of 400°F using a "short shoe" with ramp #4 without steam preheating.

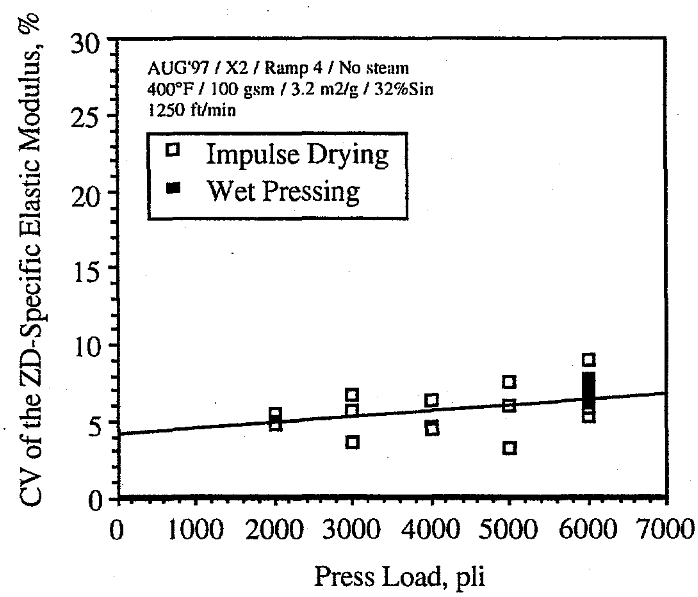



Figure 18. Coefficient of variation of the out-of-plane specific elastic modulus of impulse dried paper as a function of press load at a fixed press roll surface temperature of 400°F using a "short shoe" with ramp #4 without steam preheating.

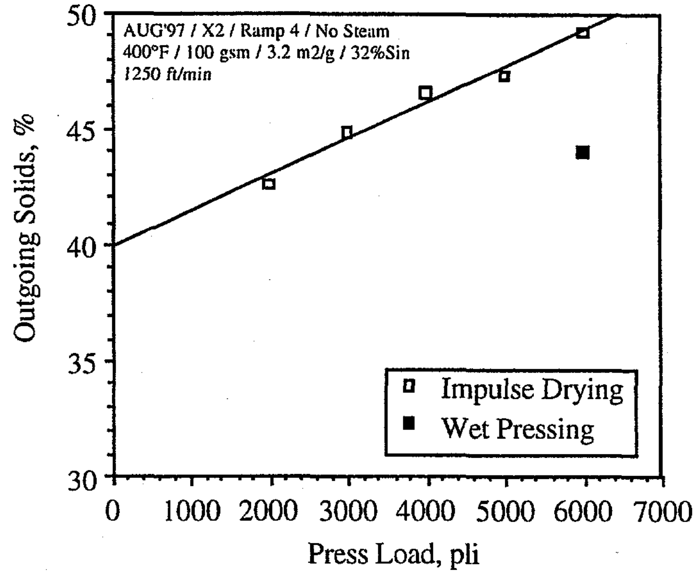



Figure 19. Outgoing solids of impulse dried paper as a function of press load at a fixed press roll surface temperature of 400°F using a "short shoe" with ramp #4 without steam preheating.

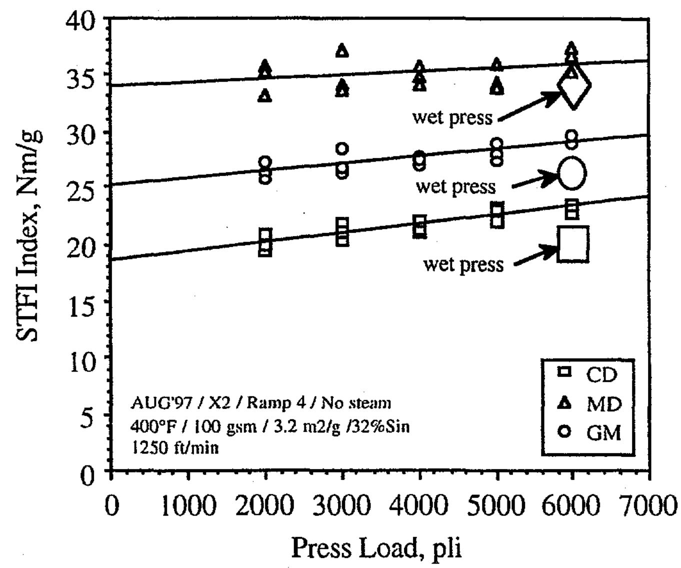



Figure 20. CD, MD, and GM STFI compression index of impulse dried paper as a function of press load at a fixed press roll surface temperature of 400°F using a "short shoe" with ramp #4 without steam preheating.

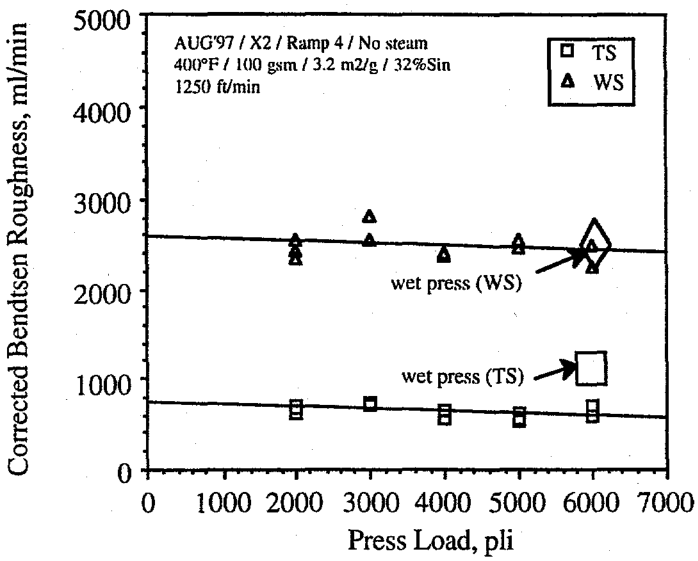



Figure 21. Corrected Bendtsen Roughness of impulse dried paper as a function of press load at a fixed press roll surface temperature of 400°F using a "short shoe" with ramp #4 without steam preheating.

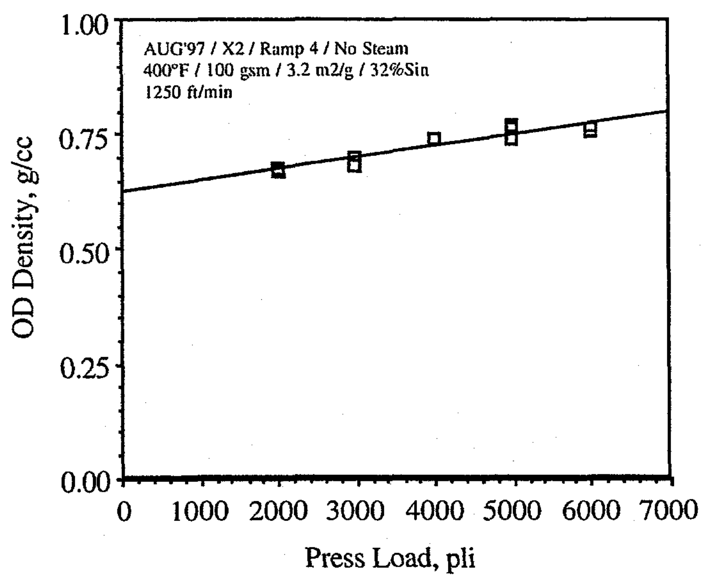



Figure 22. Oven-dried density of impulse dried paper as a function of press load at a fixed press roll surface temperature of 400°F using a "short shoe" with ramp #4 without steam preheating.

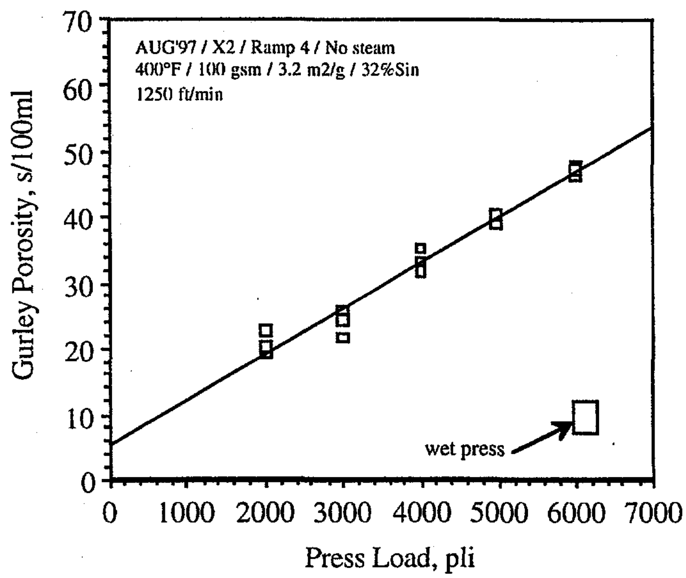



Figure 23. Gurley Porosity of impulse dried paper as a function of press load at a fixed press roll surface temperature of 400°F using a "short shoe" with ramp #4 without steam preheating.

## D. THE WINTER EXPERIMENTS

There were a number of objectives of the January experiments. These included the evaluation of an improved adjustable (on-the-fly) press shoe ramp and the evaluation of an initial version of the "hover press." It was also desirable to determine the effect of refining and machine speed on critical impulse drying temperature and runnability (sheet/press roll surface picking).

The August experiments had indicated that picking could be reduced by reducing the press load. This was interpreted to mean that the press shoe profile should be designed in such a way as to minimize the peak pressure while maximizing the impulse. Hence, the improved adjustable ramp was designed to follow a standard 10-inch shoe. To contain the shoe and ramp within the existing open extended nip press, the new adjustable ramp length was limited to a length of 4 inches. Figure 24 shows three press shoe pressure profiles that were investigated during the January experiments. The following nomenclature was used:

- Ramp 8 Off - Hover Off, signifies that the ramp as well as the "hover press" were installed but not pressurized.
- Ramp 8 On - Hover Off, signifies that the ramp was pressurized while the "hover press" was not pressurized.
- Ramp 8 On - Hover On, signifies that both the ramp and the "hover press" were pressurized.

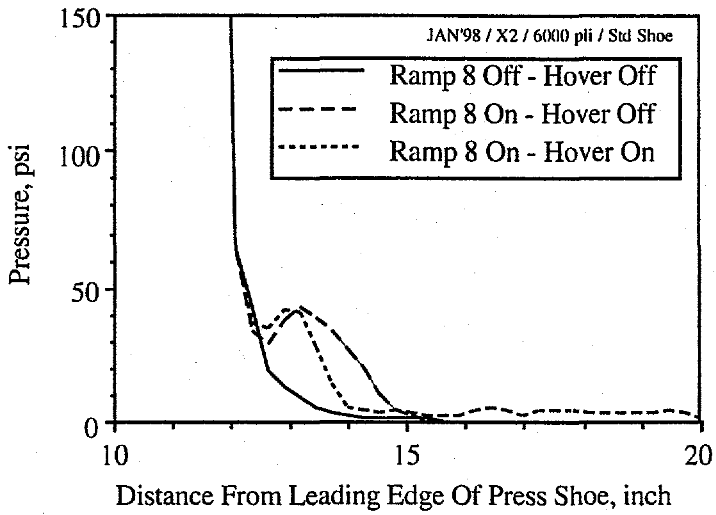



Figure 24. Measured pressure profiles of various ramp decompression profiles used in the January 1998 experiments on the Beloit X2 pilot paper machine.

The January experiments also provided an opportunity to explore whether blanket design would influence impulse drying. To accomplish this, the drive side of the blanket was grooved while the operator side was blind-drilled. Table 1 documents the forming and pressing conditions that were employed in January.

The same furnish used in the July and August experiments was also used in the January experiment. The ingoing solids, hydrodynamic specific surface and freeness of cases investigated are shown in Table 2.

The January experiments were conduced over a three-day period. At the start of each day, wet pressing controls were run for each of the three press shoe profiles. Afterwards, the press roll was heated to a range of temperatures and impulse drying samples were taken. The X2 machine was run at a speed of 1250 ft/min during the first two days and increased to 2500 ft/min on the third day. To investigate the effect of refining, the furnish was refined to 540 ml CSF on the first day and 460 ml CSF on the second and third day.

Figures 25 through 27 show the zd-specific elastic modulus as a function of press roll surface temperature for each of the press shoe pressure profiles at a freeness of 540 ml CSF and a machine speed of 1250 ft/min. As in previous studies, the drop off of the modulus is an indicator of the critical impulse drying temperature. It was observed that the grooved blanket consistently resulted in a higher modulus than did the blind-drilled blanket. This suggests that felt drainage may be a more important factor in impulse drying than had been previously realized. It also suggests that the blanket groove geometry should be optimized. Based on Figures 25 through 27 the critical temperature were determined and outgoing solids and paper physical properties reported at these conditions.

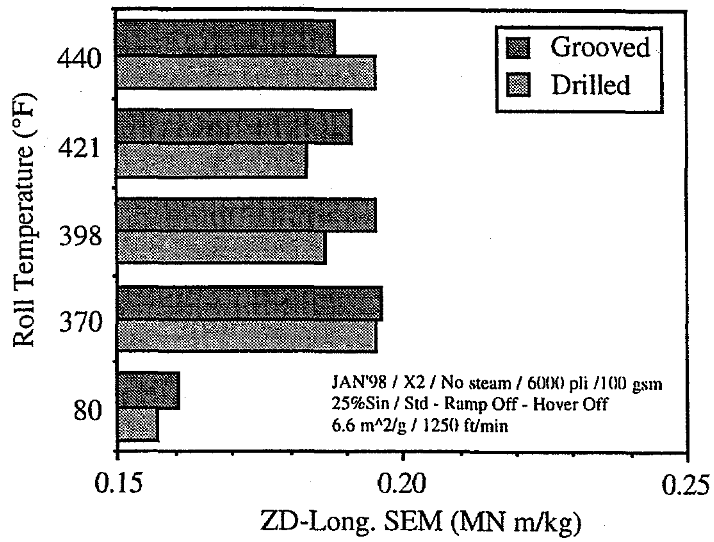



Figure 25. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using the standard 10-inch shoe with ramps #8 off and with the post-nip "hover press" off for both a drilled and a grooved blanket and without steam preheating.

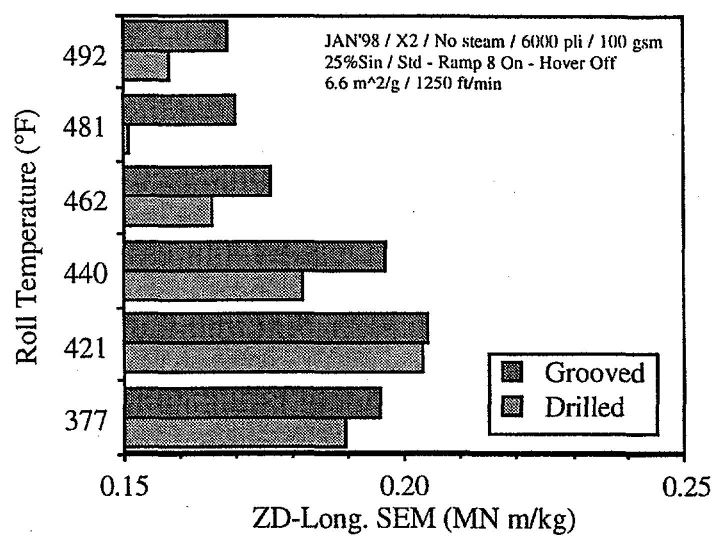



Figure 26. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using the standard 10-inch shoe with ramps #8 on and with the post-nip "hover press" off for both a drilled and a grooved blanket and without steam preheating.

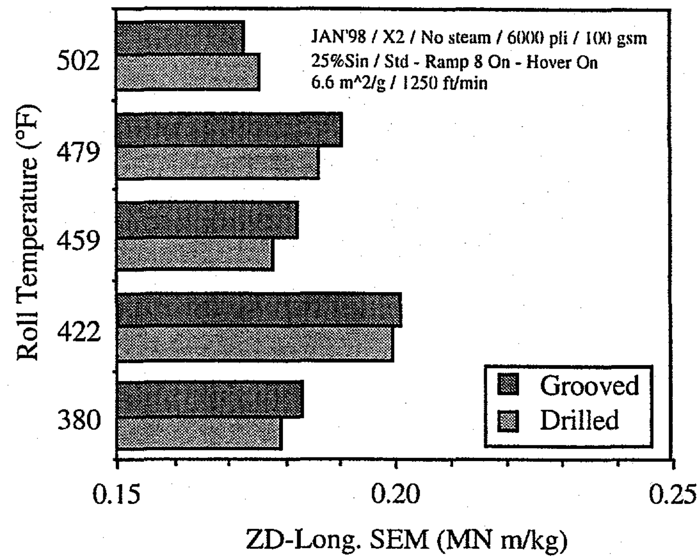



Figure 27. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using the standard 10-inch shoe with ramps #8 on and with the post-nip "hover press" on for both a drilled and a grooved blanket and without steam preheating.

Figures 28 through 31 show these values as compared to the wet pressing controls. It was observed that ramp #8 resulted in an increase of critical temperature of about 23°F over the ramp off case. It is also observed that the "hover press" encouraged rewetting, see Figure 28. The increase in press dryness of impulse drying over wet pressing was only about 2 percentage points compared to the 5 percentage points observed during the August experiment. This point will be discussed in more detail in the conclusions. Comparing the paper physical properties of the impulse dried samples to the wet pressed controls, a smoother sheet at marginally better STFI compression strength is produced.

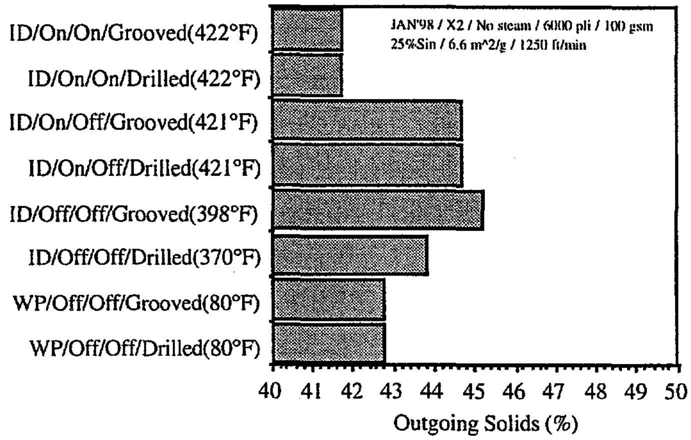



Figure 28. Outgoing solids of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

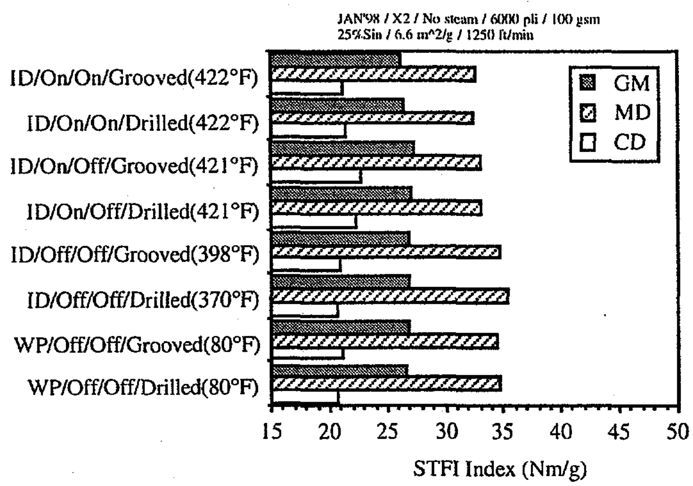



Figure 29. CD, MD, and GM STFI compression index of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

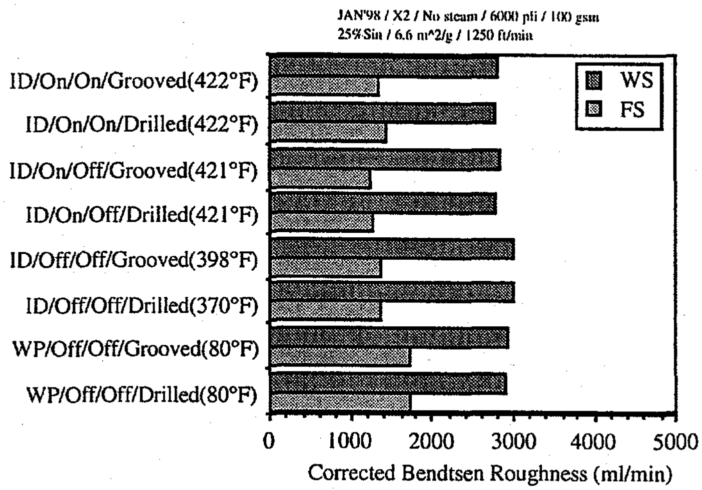



Figure 30. Corrected Bendtsen Roughness of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

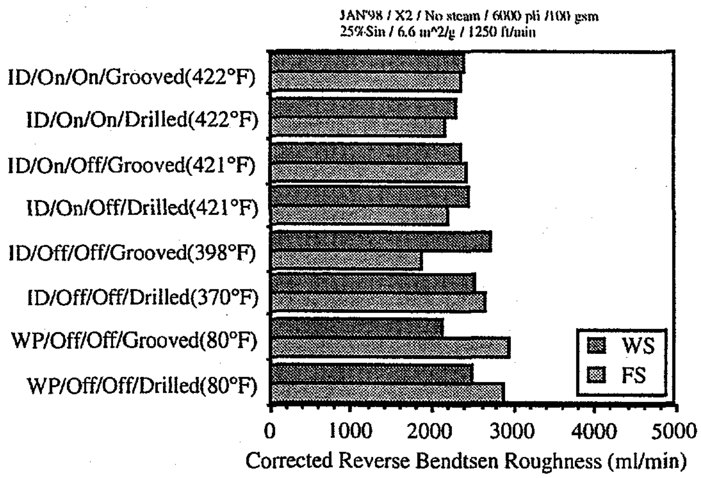



Figure 31. Corrected Reverse Bendtsen Roughness of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

Figures 32 through 34 show the zd-specific elastic modulus as a function of press roll surface temperature for each of the press shoe pressure profiles at a freeness of 458 ml CSF and a machine speed of 1250 ft/min. As in the previous case, the grooved blanket consistently resulted in a higher modulus than did the blind-drilled blanket. Based on Figures 32 through 34, the critical temperature were determined and outgoing solids and paper physical properties reported at these conditions.

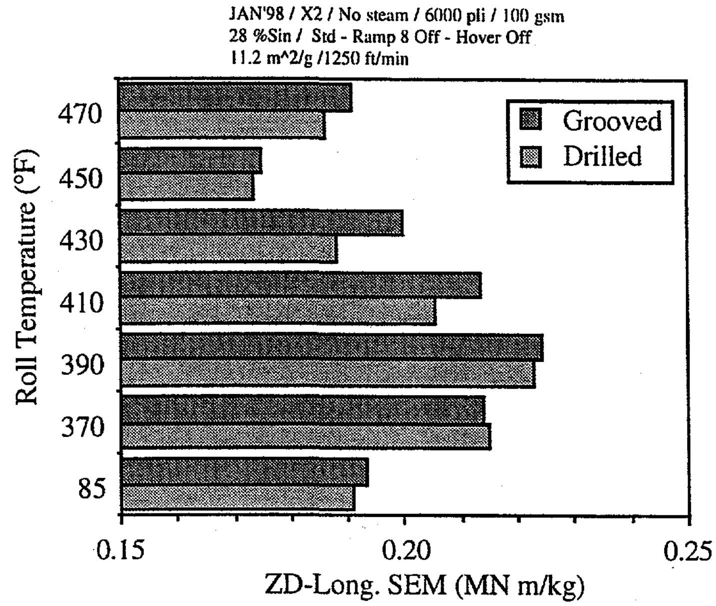



Figure 32. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using the standard 10-inch shoe with ramps #8 off and with the post-nip "hover press" off for both a drilled and a grooved blanket and without steam preheating.

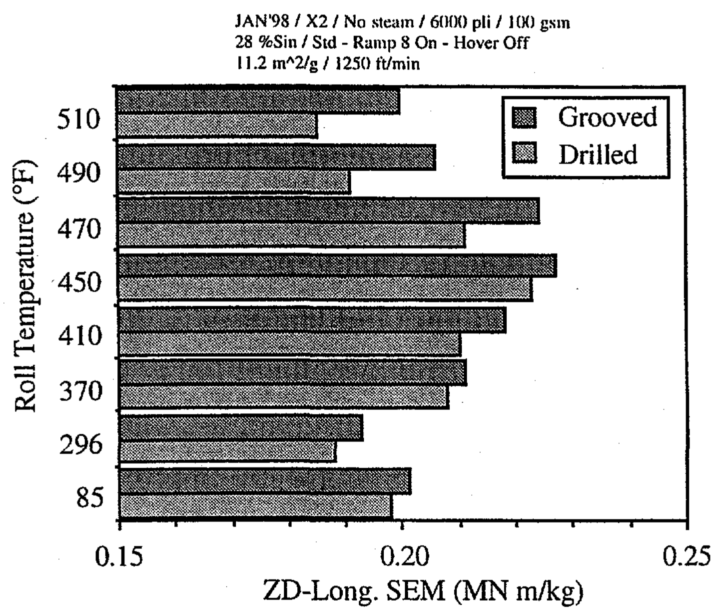



Figure 33. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using the standard 10-inch shoe with ramps #8 on and with the post-nip "hover press" off for both a drilled and a grooved blanket and without steam preheating.

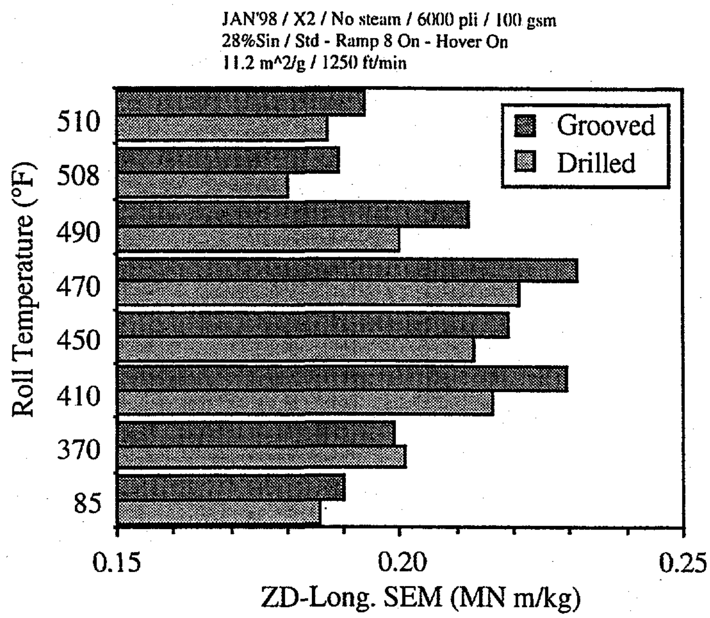



Figure 34. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using the standard 10-inch shoe with ramps #8 on and with the post-nip "hover press" on for both a drilled and a grooved blanket and without steam preheating.

Figures 35 through 38 show these values compared to the wet pressing controls. At this freeness, ramp #8 resulted in an increase of critical temperature of about 60°F over the ramp off case. As at the higher freeness, the "hover press" seemed to encourage rewet, see Figure 35. The increase in press dryness of impulse drying over wet pressing was about 6 percentage points. Comparing the paper physical properties of the impulse dried samples to the wet pressed controls, the impulse dried samples have marginally better properties.

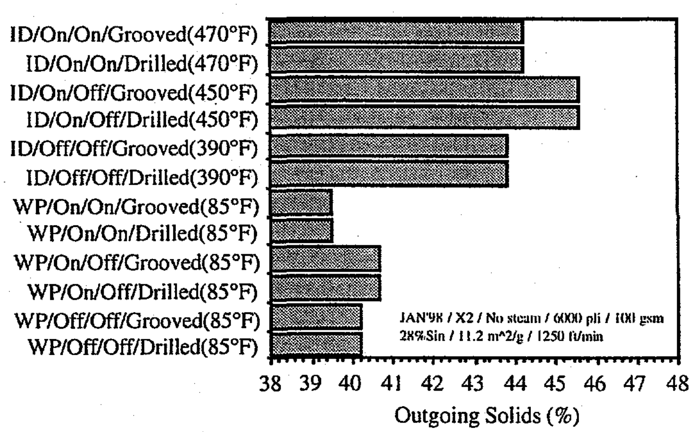



Figure 35. Outgoing solids of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

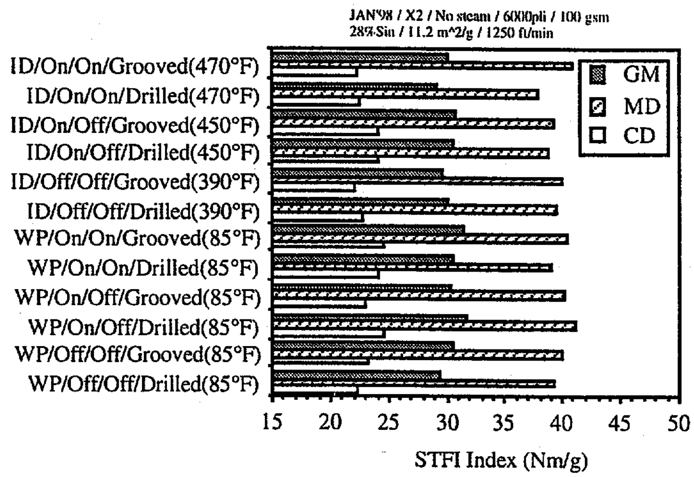



Figure 36. CD, MD, and GM STFI compression index of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

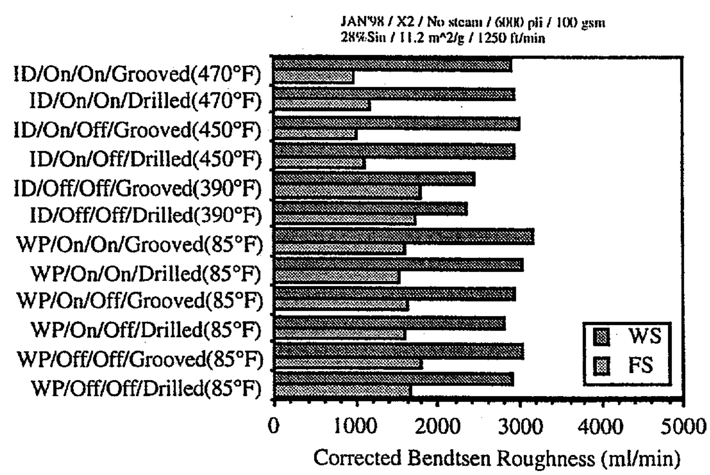



Figure 37. Corrected Bendtsen Roughness of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

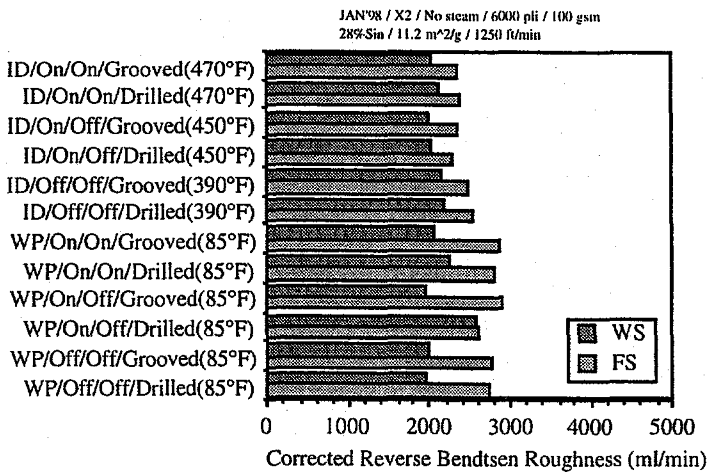



Figure 38. Corrected Reverse Bendtsen Roughness of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

Figures 39 and 40 show the zd-specific elastic modulus as a function of press roll surface temperature for two of the press shoe pressure profiles at a freeness of 460 ml CSF and a machine speed of 2500 ft/min. As in the two previous cases, the grooved blanket consistently resulted in a higher modulus than did the blind-drilled blanket. Based on Figures 39 and 40, the critical temperatures were determined and outgoing solids and paper physical properties reported at these conditions.

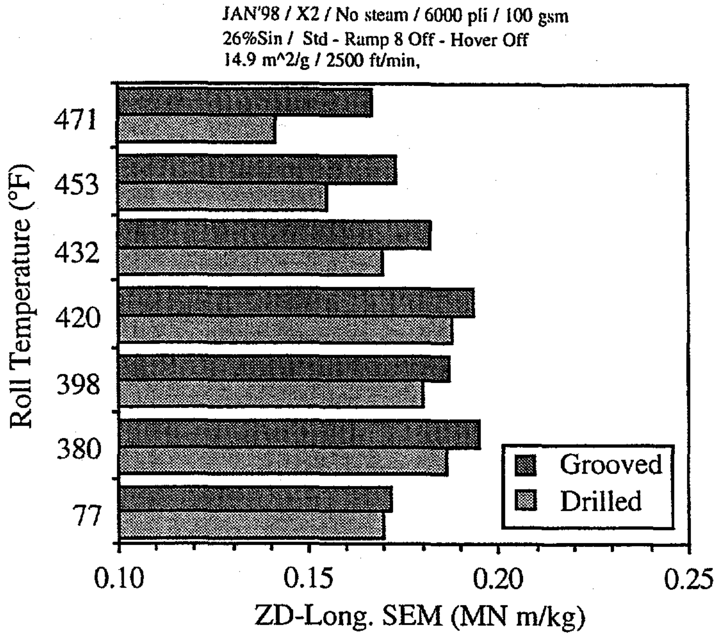



Figure 39. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using the standard 10-inch shoe with ramps #8 off and with the post-nip "hover press" off for both a drilled and a grooved blanket and without steam preheating.

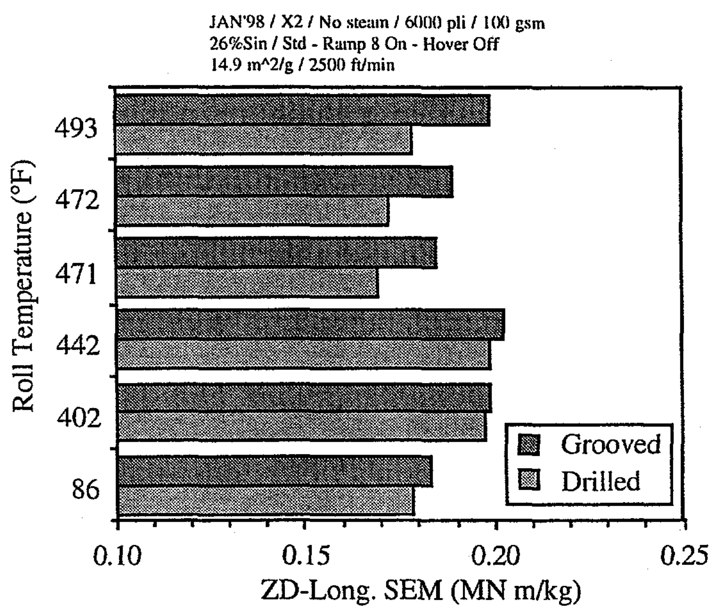



Figure 40. Out-of-plane specific elastic modulus as a function of press roll surface temperature for impulse drying using the standard 10-inch shoe with ramps #8 on and with the post-nip "hover press" off for both a drilled and a grooved blanket and without steam preheating.

Figures 41 through 44 show these values as compared to the wet pressing controls. At this increased machine speed, the ramp #8 resulted in an increase of critical temperature of about 22°F over the ramp off case. The increase in press dryness of impulse drying over wet pressing was about 3 percentage points. Comparing the paper physical properties of the impulse dried samples to the wet pressed controls, produced sheets of marginally better properties.

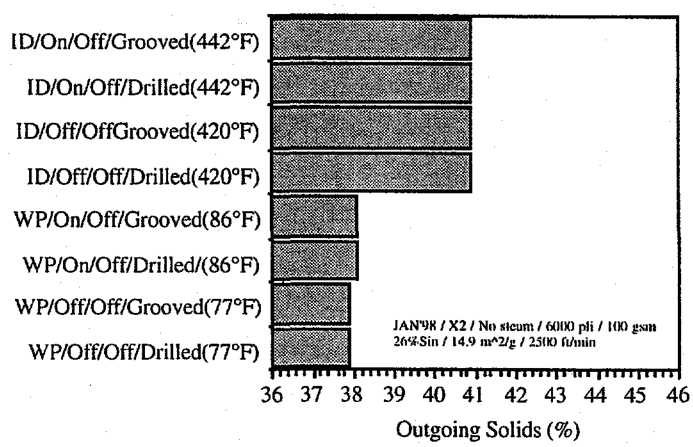



Figure 41. Outgoing solids of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

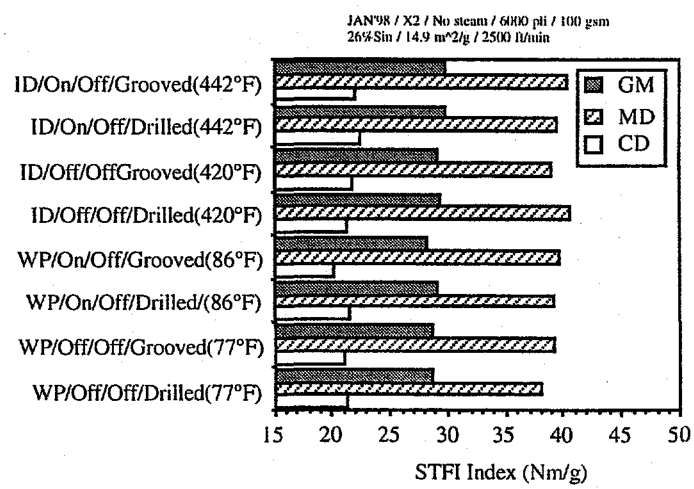
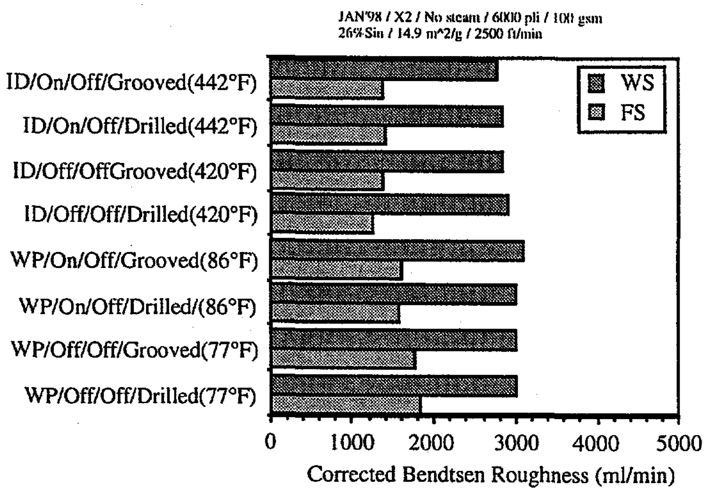
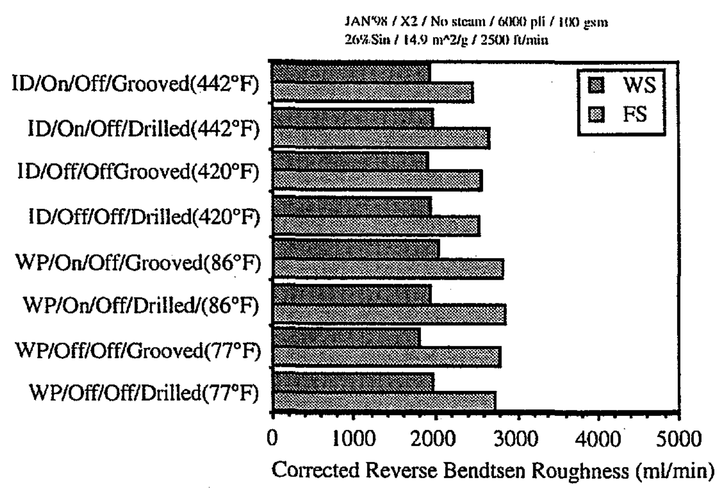



Figure 42. CD, MD, and GM STFI compression index of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.




<u>Figure 43.</u> Corrected Bendtsen Roughness of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.




<u>Figure 44.</u> Corrected Reverse Bendtsen Roughness of paper impulse dried at the critical temperature as compared to that paper wet pressed under the same pressing conditions using the standard 10-inch shoe and various ramp profiles for both a drilled and a grooved blanket and without steam preheating.

## E. COMPARISON OF SUMMER AND WINTER EXPERIMENTS

Table 3 summarizes the impulse drying critical temperatures that were determined in the pilot experiments that were conducted in the Summer of 1997 and the Winter of 1998. A few differences are particularly interesting. It is noted that the critical impulse drying temperature of the July 1997 Standard 10-inch shoe (with no ramp) was about 70°F lower that the critical impulse drying temperature for the January 1998 Standard 10-inch shoe with Ramp #8 and the "hover press" both being unpressurized. There are a number of factors that contribute to these differences. These are differences in ingoing solids, freeness (and hydrodynamic specific surface), and small differences in the pressure profiles. Based on previous laboratory simulations, it is expected that a decrease in ingoing solids would decrease the critical impulse drying temperature. Likewise, an increase in hydrodynamic specific surface and a corresponding decrease in freeness would also result in a decrease in critical impulse drying temperature. As these trends were not observed, the differences in pressure profile were considered. Referring to Figures 3, the Standard 10 inch shoe pressure dropped the last 100 psi in less than 1 inch. Referring to Figure 24, the Standard 10-inch shoe with the unpressurized Ramp and hover dropped the last 100 psi in just over 2 inches. Hence, the unpressurized Ramp and hover profiles would be expected to result in some reduction in the net pressure difference between the inside and outside of the web as it leaves the impulse dryer. This effect could have resulted in the observed increase in critical impulse drying temperature. As the ingoing temperatures for all cases were about the same (105°F), the pressure profile was most probably the cause of the observed difference. Hence, an attempt to impulse dry the January 1998 furnishes with a standard 10-inch shoe, would have produced an even lower critical temperature than was observed in August 1997.

The remaining critical impulse drying temperature data appears to be internally consistent. Based on the analysis in the previous paragraph, it is concluded that the 4-inch long ramp is probably adequate in length for future experiments on the Beloit X4 pilot paper machine.

Table 3. Critical Impulse Drying Temperatures

| Case<br><br>Date, Freeness, P.M. Speed | Specific Surface,<br><br>$m^2/g$ | Ingoing Solids,<br><br>% | Shoe Press Configuration | Critical Impulse Drying Temperature, °F | |
|---|---|---|---|---|---|
| | | | | Blind Drilled | Grooved |
| Jul'97<br>570 ml CSF<br>1250 ft/min | na | 30.0 | Std - No Ramp | na | 328 |
| Aug'97<br>570 ml CSF<br>1250 ft/min | 3.20 | 32.2 | Short -Ramp 4 | na | 424 |
| | 4.07 | 31.5 | Short -Ramp 5 | na | 408 |
| Jan'98<br>540 ml CSF<br>1250 ft/min | 6.63 | 24.6 | Std - Ramp 8 Off -Hover Off | 370 | 398 |
| | | | Std - Ramp 8 On -Hover Off | 421 | 421 |
| | | | Std - Ramp 8 On -Hover On | 422 | 422 |
| Jan'98<br>458 ml CSF<br>1250 ft/min | 11.16 | 27.5 | Std - Ramp 8 Off -Hover Off | 390 | 390 |
| | | | Std - Ramp 8 On -Hover Off | 450 | 450 |
| | | | Std - Ramp 8 On -Hover On | 470 | 470 |
| Jan'98<br>460 ml CSF<br>2500 ft/min | 14.97 | 26.1 | Std - Ramp 8 Off -Hover Off | 420 | 420 |
| | | | Std - Ramp 8 On -Hover Off | 442 | 442 |

In the January 1998 experiments, there was a consistent difference between the specific elastic modulus of paper produced with the grooved blanket and the blind drilled blanket. In almost all cases (see Figures 27, 32, and 39), paper wet pressed or impulse dried on the grooved side was stronger than those wer pressed or impulse dried on the blind drilled side. This was interpreted as resulting from higher amounts of rewet or lower press solids on the blind drilled side which would reduce web densification and strength. This would be consistent with the hypothesis that the blind drilled blanket did not provide as much of a path for loss of water from the felt while the paper web and felt are in the nip. With this in mind, physical property development will be compared between the various cases based entirely on data from the grooved blanket side of the web. Tables 4 and 5 list the outgoing solids, Bendtsen roughness of the heated side, as well as the CD and GM STFI compression indices for the wet pressed controls as well as the impulse dried samples at the appropriate critical temperatures. It should be noted that samples for outgoing solids measurements were always taken across the entire web. Hence, for the January 1998 experiments, the tabulated outgoing solids slightly overstates the outgoing solids for the blind drilled blanket side of the web and understates the outgoing solids for the grooved blanket side of the web.

Referring to Table 4, attention is focused on the following cases: Short-Ramp 4, Short-Ramp 5, and Std-Ramp 8 On-Hover Off. In these cases, outgoing solids was improved over wet pressing by between 4 and 13%. Similarly, surface smoothness improved by between 22 and 51%. Examination of Table 5 shows corresponding improvements to CD STFI Index of between 3 and 20%, and improvements to GM STFI Index of between 0.7 and 17%. Clearly, impulse drying was beneficial.

Table 4. Outgoing Solids and Bendtsen Roughness: Improvement of Impulse Drying Compared to Wet Pressing with a Standard 10-Inch Press Shoe.

| Case | Shoe Press Configuration | Outgoing Solids, % | | | TS-Bendtsen Roughness, ml/min | | |
|---|---|---|---|---|---|---|---|
| Date, Freeness, P.M. Speed | | WP | ID | % incr. | WP | ID | % decr. |
| JUL'97 570 ml CSF 1250 ft/min | Std - No Ramp | 43.4 | 43.5 | +0.2 | 1135 | 632 | +44.3 |
| Aug'97 570 ml CSF 1250 ft/min | Short -Ramp 4 | 44.0 | 48.1 | +10.8 | 1140 | 550 | +51.5 |
| | Short -Ramp 5 | 44.2 | 47.8 | +10.1 | 870 | 620 | +45.4 |
| Jan'98 540 ml CSF 1250 ft/min | Std - Ramp 8 Off -Hover Off | 42.8 | 45.2 | +5.6 | 1740 | 1340 | +23.0 |
| | Std - Ramp 8 On -Hover Off | na | 44.7 | +4.4 | na | 1250 | +28.2 |
| | Std - Ramp 8 On -Hover On | na | 41.7 | -2.6 | na | 1330 | +23.6 |
| Jan'98 458 ml CSF 1250 ft/min | Std - Ramp 8 Off -Hover Off | 40.2 | 43.8 | +9.0 | 1780 | 1780 | +00.0 |
| | Std - Ramp 8 On -Hover Off | 40.7 | 45.6 | +13.4 | 1600 | 1000 | +43.8 |
| | Std - Ramp 8 On -Hover On | 39.5 | 44.2 | +10.0 | 1580 | 990 | +44.4 |
| Jan'98 460 ml CSF 2500 ft/min | Std - Ramp 8 Off -Hover Off | 37.9 | 40.9 | +7.9 | 1770 | 1370 | +22.6 |
| | Std - Ramp 8 On -Hover Off | 38.1 | 40.9 | +7.9 | 1600 | 1380 | +22.0 |

Table 5. CD and GM STFI Compression Strength Indices: Improvement of Impulse Drying Compared to Wet Pressing with a Standard 10-Inch Press Shoe.

| Case<br><br>Date, Freeness, P.M. Speed | Shoe Press Configuration | CD STFI Index, Nm/g | | | GM STFI Index, Nm/g | | |
|---|---|---|---|---|---|---|---|
| | | WP | ID | % incr. | WP | ID | % incr. |
| Jul'97<br>570 ml CSF<br>1250 ft/min | Std - No Ramp | 19.7 | 22.8 | +15.7 | 25.6 | 28.2 | +10.2 |
| Aug'97<br>570 ml CSF<br>1250 ft/min | Short -Ramp 4 | 19.9 | 23.4 | +18.8 | 26.1 | 30.1 | +17.6 |
| | Short -Ramp 5 | 22.7 | 23.7 | +20.3 | 28.0 | 28.9 | +12.9 |
| Jan'98<br>540 ml CSF<br>1250 ft/min | Std - Ramp 8 Off -Hover Off | 21.2 | 21.0 | -0.9 | 27.0 | 26.9 | -0.4 |
| | Std - Ramp 8 On -Hover Off | na | 22.8 | +7.5 | na | 27.4 | +1.5 |
| | Std - Ramp 8 On -Hover On | na | 21.1 | -0.5 | na | 26.2 | -3.0 |
| Jan'98<br>458 ml CSF<br>1250 ft/min | Std - Ramp 8 Off -Hover Off | 23.4 | 22.1 | -5.6 | 30.6 | 29.7 | -2.9 |
| | Std - Ramp 8 On -Hover Off | 23.0 | 24.2 | +3.4 | 30.4 | 30.8 | +0.7 |
| | Std - Ramp 8 On -Hover On | 24.5 | 22.2 | -5.1 | 31.4 | 30.1 | -1.6 |
| Jan'98<br>460 ml CSF<br>2500 ft/min | Std - Ramp 8 Off -Hover Off | 21.1 | 21.8 | +3.3 | 28.8 | 29.1 | +1.0 |
| | Std - Ramp 8 On -Hover Off | 20.1 | 22.0 | +4.3 | 28.2 | 29.8 | +3.5 |