Institute of Paper Science and Technology

Single-Facer Green Bond Formation

Project 3748

Final Report

to the

Containerboard and Kraft Paper Group

of the

American Forest and Paper Association

February 15, 1993

Atlanta, Georgia

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
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By
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I. Summary and Conclusions.

The structure of corrugated board, as it impacts on the functional strength performance of the package, depends on the integrity of the fluted shape and the firm bonding of the medium to the linerboard facings. The bonding involves the application of a starch adhesive to the tips of the fluted medium and the subsequent application and contact of the linerboard facings to the adhesive coated flute tips. A combination of heat, pressure and time is then used to set the adhesive and achieve the final bond.

The single-facer bond is under pressure only in the nip between the lower corrugating roll and the pressure roll in the single-facer. The single-faced board exiting this nip must remain in contact, without additional external pressure forces, until the final bond is formed. This bonding is known as the "green bond", and is extremely weak upon exiting the single-facer nip. Any separation of this green bond is permanent and the bond can not be reformed during the remainder of the corrugating process. Such a separation results in corrugated board defects commonly referred to as "blisters", loose edges", "fluff-out", and "loose bond".

The objective of this study was to characterize the green bond strength development under actual corrugating conditions over the bonding time range of 10 to 150 milliseconds, and to determine the independent effects of the five process variables of the linerboard temperature, the linerboard moisture content, the medium temperature, the medium moisture content, and the bonding time.

The data presented in this report support the following conclusions concerning the single-face green bond development.

1. Higher medium and linerboard temperatures and moisture contents at the point of entering the single-facer roll stack are beneficial to the rate of the green bond strength development.

2. The medium characteristic has more of an effect than the linerboard characteristics, and moisture content has more of an effect than temperature on the rate of the green bond strength development.

3. The order of importance, based on a per degree temperature change or a per percent moisture change, is medium moisture content, linerboard moisture content, medium temperature, and linerboard temperature.

4. There is a practical upper limit on the temperature and moisture levels. An excessive temperature will crystallize the starch and produce a brittle bond. Excessively high moisture levels can result in fluff-out and blisters.

5. The rate of green bond strength development is linear with time once the bond starts to form.

6. The results of this project are consistent with the results from the previous project, (1, 2). The previously reported induction time barrier of 19 ms before a measurable green bond strength is achieved now appears to be an artifact of the preconditioning capacity of the IPST pilot single-facer at high corrugating speeds, and not an inherent function of the mechanism of the green bond formation itself.

7. Higher moisture content averages in the medium and linerboard rollstock will be beneficial to an increased rate of green bond formation. The higher average must be consistent with uniform moisture profiles.

8. The preconditioning equipment on the single-facer needs to be kept in good operating condition. Adjustments to the steaming and preheating need to occur simultaneously with changes in the single-facer speed in order to minimize the probability of bond defects.

II. Introduction.

The structure of corrugated board, as it impacts on the functional strength performance of the package, depends on the integrity of the fluted shape and the firm bonding of the medium to the linerboard facings. This bonding involves two forms, the double-back bond and the single-face bond. Both bonds involve the application of a starch adhesive to the tips of the fluted medium and the subsequent application and contact of the linerboard facings to the adhesive coated flute tips. A combination of heat, pressure and time is then used to set the adhesive and achieve the final bond. Failure to achieve a uniformly strong final bond has a large adverse effect on the strength of the corrugated board.

The double-backer bond is formed under continuous pressure of the hot plates and belt in the double-backer section of the corrugator. The single-facer bond, on the other hand, is under pressure only in the nip between the lower corrugating roll and the pressure roll in the single-facer. The single-faced board exiting this nip must remain in contact, without additional external pressure forces, until the final bond is formed. This bonding is known as the "green bond", and is extremely weak upon exiting the single-facer nip, (1, 2). Any separation of this green bond is permanent and the bond can not be reformed during the remainder of the corrugating process. Such a separation results in corrugated board defects commonly referred to as "blisters", loose edges", "fluff-out", and "loose bond".

Over the years, there have been many studies on the nature and development of this green bond. Most of these studies have involved inferences based on examination of the final cured bond or have involved studies of the green bond under non-corrugating conditions, (3-13). One published study evaluated the strength of the green bond under actual corrugating conditions, over the bonding time range of 19 to 150 milliseconds after exiting the pressure roll nip in the single-facer. In that study, the bonding time was varied by changing the corrugator speed. The change in corrugator speed also affected the preconditioning levels of the linerboard and medium. The study, therefore, did not allow the complete separation of the effects of bonding time and the linerboard and medium temperature and moisture content, (1, 2).

The objective of this study was to characterize the green bond strength development under actual corrugating conditions over the bonding time range of 10 to 150 milliseconds, and to determine the independent effects of the five process variables of the linerboard temperature, the linerboard moisture content, the medium temperature, the medium moisture content, and the bonding time.

III. Experimental Techniques.

All of the experiments were done on the Institute of Paper Science & Technology, IPST, pilot single-facer. The material used was commercial 42 lb/msf linerboard and commercial 26 lb/msf medium. The same recycled linerboard was used in all of the experiments. Two different mediums were used, one being recycled and one being virgin. Each of the three materials was supplied at two different moisture content levels, with the rolls being produced within one reel of production on the paper machine in order to keep other process conditions constant. The corrugating was done using C-flute rolls and the standard IPST 25% solids, two-phase, starch adhesive.

The green bond strength was measured by the use of a debonding wedge devise located on the exit side of the nip between the lower corrugating roll and the pressure roll, Figure 1. The medium web width was two inches wider than the linerboard web width. This allowed the linerboard to pass between the wedge edges while the medium contacted the wedge. The curved design of the wedge edges produced an upward thrust on the medium. The linerboard was free to follow the medium, provided the

Wedge Devise

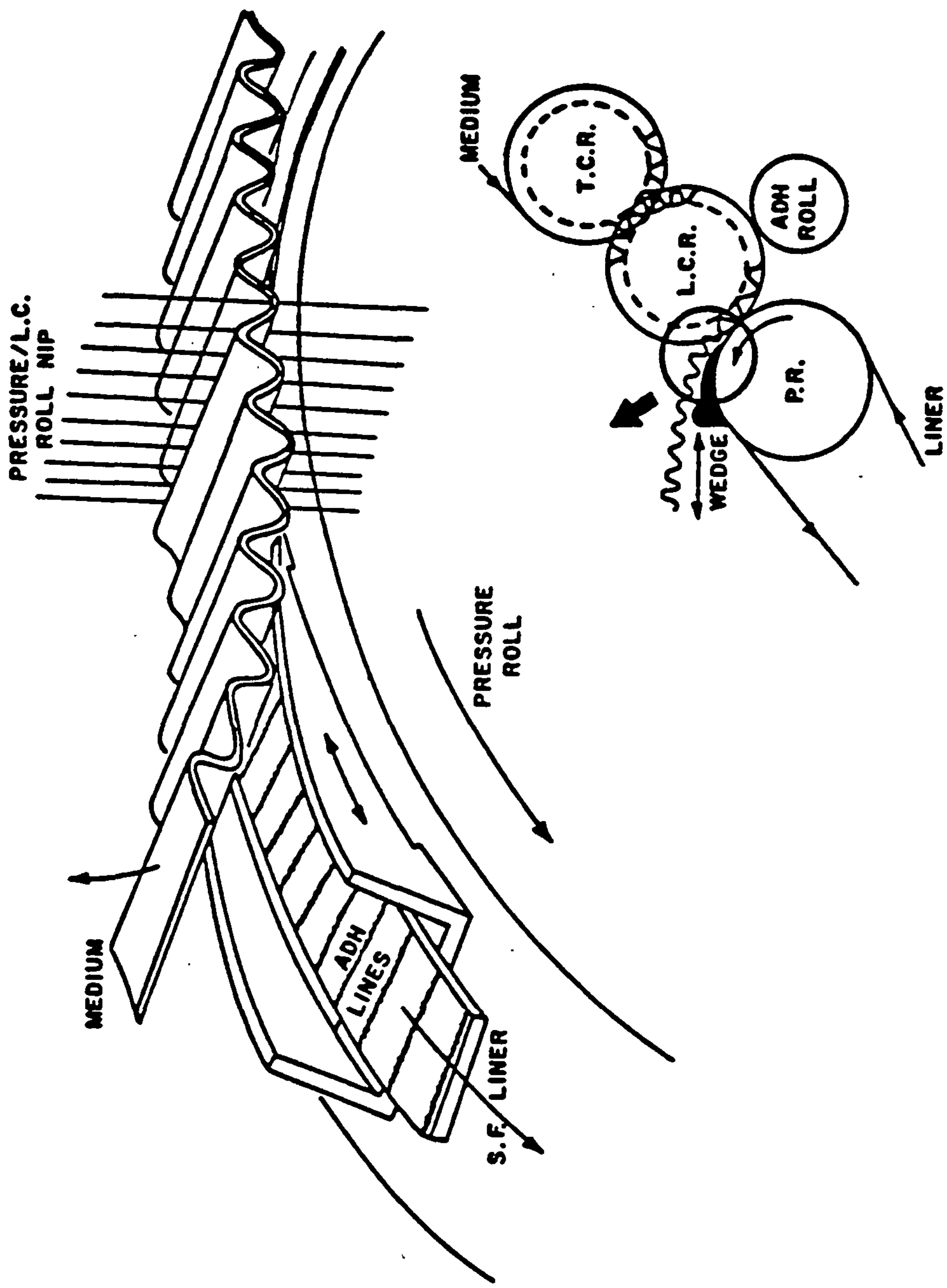


FIGURE 1

green bond was strong enough to support the weight of the linerboard. A strong green bond strength resulted in no separation of the linerboard from the medium. As the green bond strength became weaker, the linerboard would start to separate from the medium at the edges up to the point of complete debonding. The amount of separation was used as a measurement of the green bond strength. The wedge was supported by a holder which allowed it to be positioned at varying distances, ranging from 1 to 6 inches from the pressure roll nip. The holder was designed to angle the wedge as it was relocated so as to maintain the same single-faced web contact angle, and, therefore the same applied force, at all distances.

A schematic drawing of the IPST pilot single-facer is shown in Figure 2. The temperature and moisture content of both the medium and linerboard were measured continuously by gauges located at the single-facer enter points for the two webs. The preconditioning levels were varied to change the temperatures and moisture contents of the entering materials.

Two end point criteria were used for the experiments. One was the percent bonded area at a speed of 500 fpm. The second was the fastest speed possible, below 500 fpm, at which 100% delamination occurred.

IV. Experimental Results.

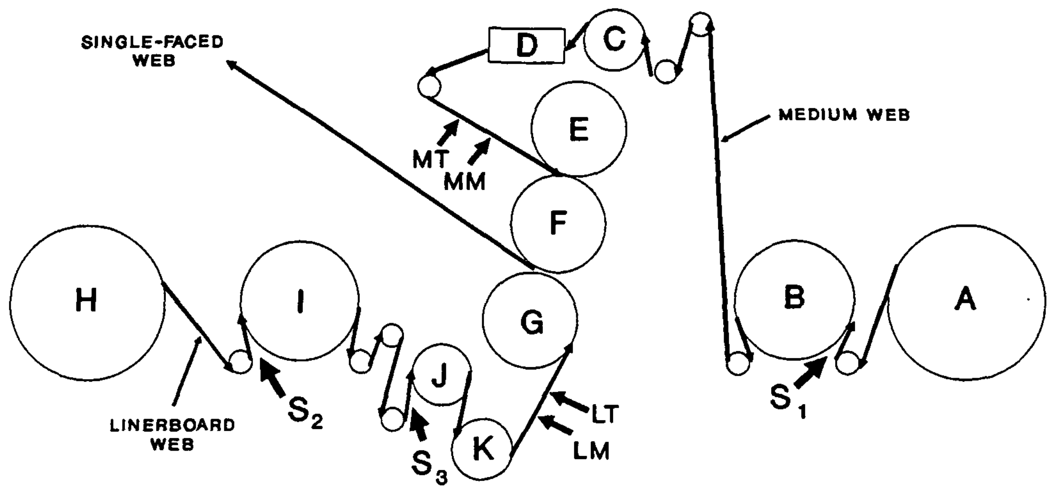
The detailed experimental data for the 63 different experimental conditions are given in the Appendix. Twenty three of the conditions achieved a speed of 500 fpm and forty of the conditions exhibited 100% delamination at speeds less than 500 fpm. This indicates that the desired experimental sensitivity range was achieved.

The bonding rate data for the virgin and recycled mediums are shown in Figure 3. Each data point represents the maximum speed obtained at 100% debonding for the identical preconditioning levels. The statistical analysis of the data shows that the two materials are not different in bonding potentials. The data for the two materials can, therefore, be pooled for the purpose of data analysis.

The ability of the preconditioning tools on the IPST pilot single-facer to independently change the temperature and the moisture content of the containerboard was studied in a screening experiment prior to conducting the actual bonding experiments. The purpose was to assist in designing the final experimental conditions. The evaluation included linerboard and medium steam shower usage, the linerboard secondary preheater usage, the steam pressure in the preheaters, and

SCHEMATIC OF IPST SINGLE-FACER
NOT TO SCALE

FIGURE 2



B, E, F, G, I, J, K, = 150 psi STEAM

WEB DISTANCES:

OUTFEED A TO INFEED B = 8 ft. - 0 in.
OUTFEED B TO INFEED C = 8 ft. - 6 in.
OUTFEED D TO F/G NIP = 5 ft. - 0 in.
OUTFEED H TO INFEED I = 8 ft. - 0 in.
OUTFEED I TO INFEED J = 6 ft. - 6 in.
OUTFEED K TO F/G NIP = 2 ft. - 0 in.

LEGEND:

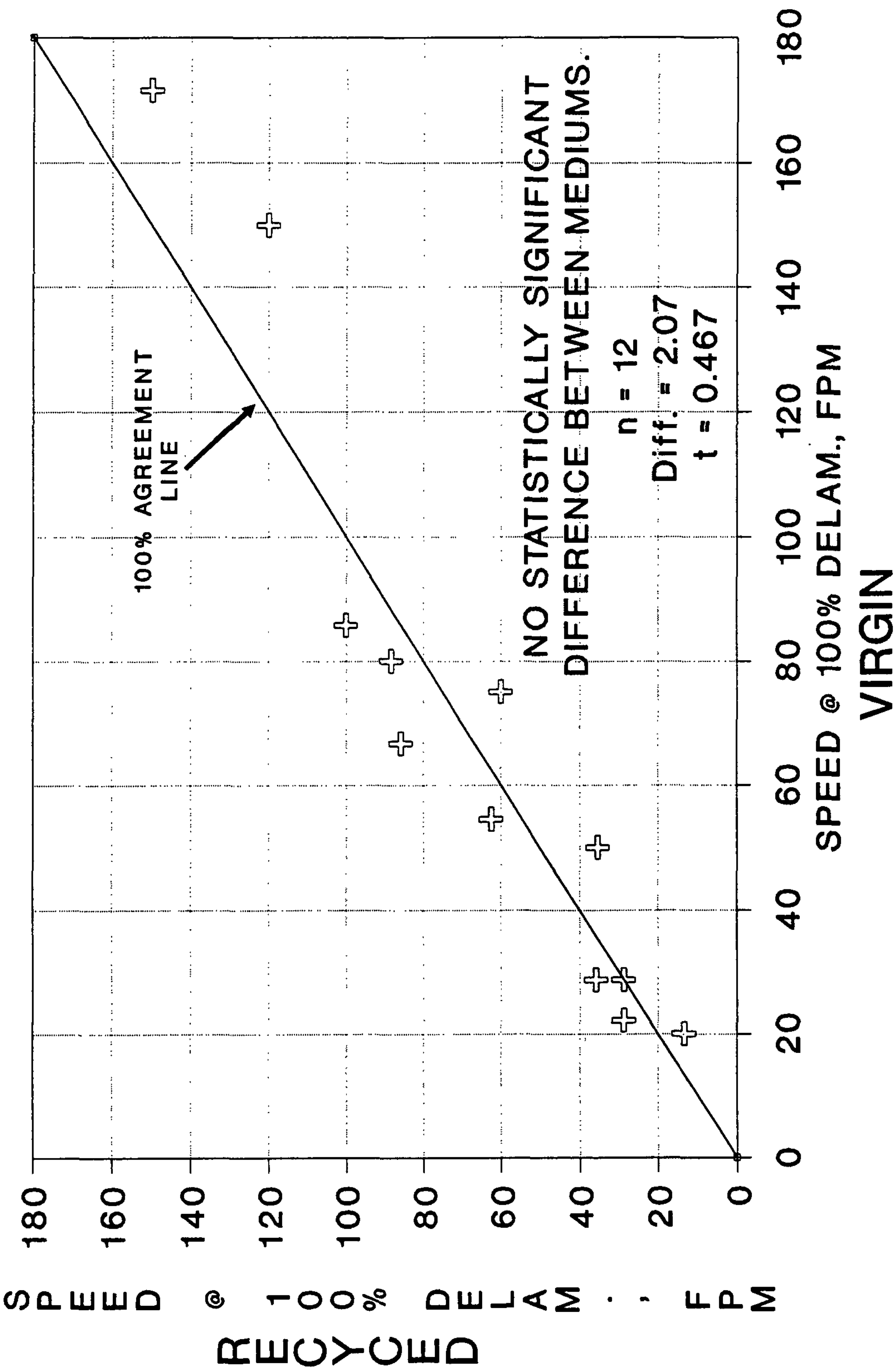
A = MEDIUM ROLL.
B = MEDIUM PREHEATER, 24 in. DIAMETER.
C = MEDIUM GAYLORD SHOWER.
D = MEDIUM STEAM BOX PRECONDITIONER.
E = UPPER CORRUGATING ROLL, 12 in. DIAMETER.
F = LOWER CORRUGATING ROLL, 12 in. DIAMETER.
G = PRESSURE ROLL, 12 in. DIAMETER.
H = LINERBOARD ROLL.
I = LINERBOARD PREHEATER, 30 in. DIAMETER.
J = LINERBOARD PREHEATER, 8.5 in. DIAMETER.
K = LINERBOARD PREHEATER, 8.5 in. DIAMETER.
S = STEAM SHOWERS.
MT = MEDIUM TEMPERATURE SENSOR.
MM = MEDIUM MOISTURE SENSOR.
LT = LINERBOARD TEMPERATURE SENSOR.
LM = LINERBOARD MOISTURE SENSOR.

PRECONDITIONING LEVELS:

MATERIAL	NORMAL	SUBNORMAL
LINERBOARD	S_2, I, S_3, J, K, G.	I, G.
MEDIUM	S_1, B, C, D, E, F.	S_1, B, E, F.

COMPARISON OF VIRGIN AND RECYCLED MEDIUM BONDING RATES

FIGURE 3



speed. The preheater wraps were not changed due to the difficulty of making such adjustments on the IPST corrugator. It would have been necessary to stop the corrugator for prolonged periods of time to adjust the wrap. It was decided that achieving a steady state operation on the corrugator was more critical to the experiment than achieving wrap changes.

The screening experiment results are shown in Figure 4, where moisture content is plotted against temperature. Both the medium and linerboard exhibited a shift to lower temperatures and higher moisture contents as the speed increased from 500 fpm to 800 fpm. The shift was approximately 30 deg. F. and 1% moisture content for the linerboard, and 15 deg. F. and 1% moisture content for the medium. The following observations apply to the operation of the IPST pilot single-facer used in this study. Changes to the preheater wraps may have produced different results. The linerboard exhibited a relatively flat moisture content over a wide range of temperatures at a given speed. This indicates that it is difficult to change the linerboard moisture at the single facer, but wide variation in temperature can be achieved. The medium, on the other hand, exhibited a pronounced "L' shaped relationship. A large moisture content range was observed at temperatures above approximately 170 deg. F. Below that temperature, the moisture curve was flat, and similar to the linerboard curve. Both observations suggest that the control of the incoming containerboard rollstock moisture content could be a key element in achieving the desired temperature/moisture relationship in the single-facer bonding zone.

The actual range of temperature/moisture relationships achieved in the bonding experiment are shown in Figure 5 for both the linerboard and medium. The medium temperatures ranged from 132 to 211 deg. F., and the moisture content ranged from 0.76% to 9.68%. The linerboard temperature ranged from 135 to 284 deg. F., and the moisture content ranged from 4.48% to 10.88%. Both show the scattered relationship needed to provide a reasonably valid statistical basis for regression analysis of the data. Figure 6 shows the relation between the medium and the linerboard for both temperature and moisture content. Again, the scattered pattern of data supports the validity for the use of statistical regression analysis techniques.

The multiple linear regression equation for the maximum speed at 100% delamination limiting case data points is given in Figure 7, and the plot of measured speed at 100% delamination versus the equation calculated speed is shown in Figure 8. The regression equation has a relatively low R-Squared value of 0.361 and the best fit regression line exhibits a significant angle to the 100% agreement line. This indicates that there is an addition factor related to the green bond strength measurements that is not accounted for by the variables shown. One possibility is the effect of crystallization of the bond

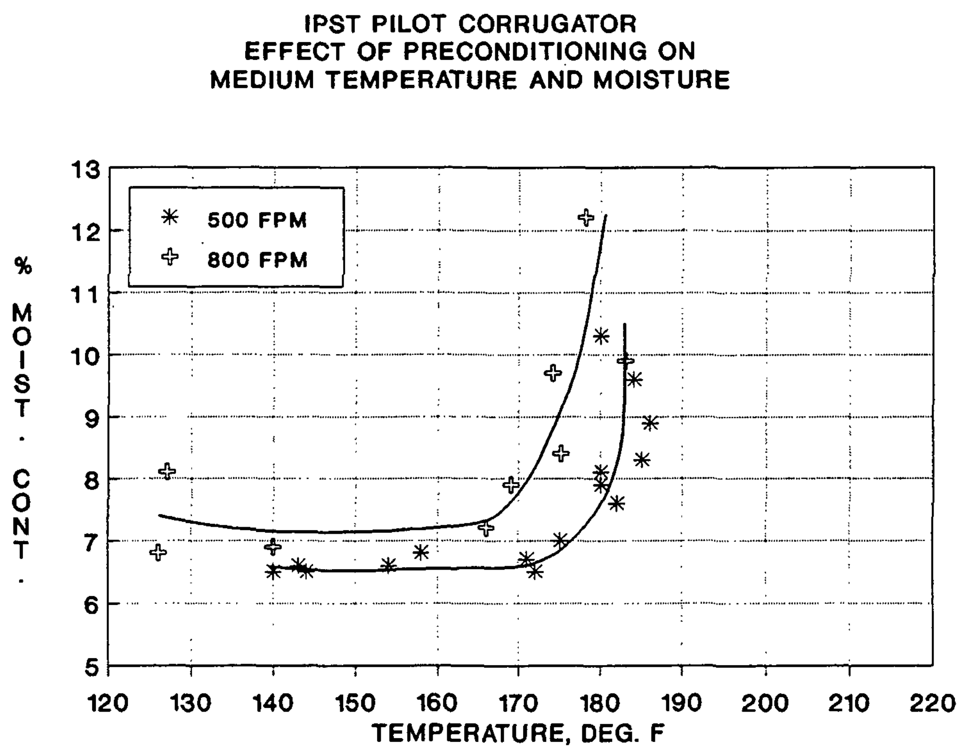
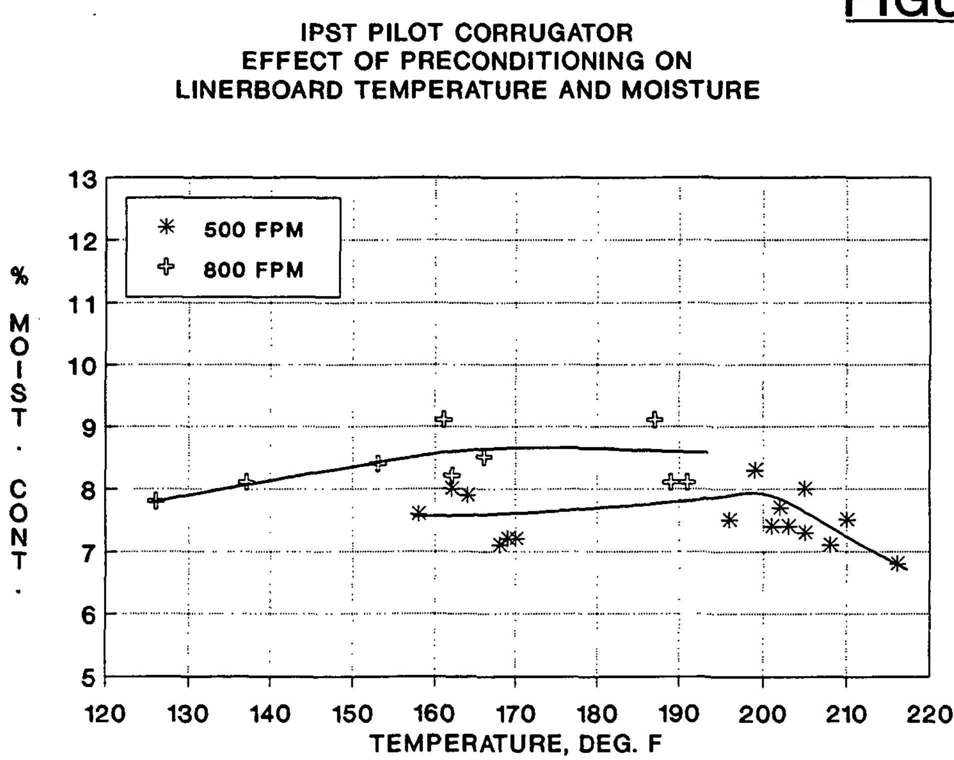

IPST PILOT CORRUGATOR
EFFECT OF PRECONDITIONING ON
MEDIUM TEMPERATURE AND MOISTURE
500 FPM
800 FPM
% MOIST. CONT.
13
12
11
10
9
8
7
6
5
120
130
140
150
160
170
180
190
200
210
220
TEMPERATURE, DEG. F

FIGURE 4


IPST PILOT CORRUGATOR
EFFECT OF PRECONDITIONING ON
LINERBOARD TEMPERATURE AND MOISTURE
500 FPM
800 FPM
% MOIST. CONT.
13
12
11
10
9
8
7
6
5
120
130
140
150
160
170
180
190
200
210
220
TEMPERATURE, DEG. F

MEDIUM TEMPERATURE AND MOISTURE LEVELS ACHIEVED IN EXPERIMENT AT END POINT

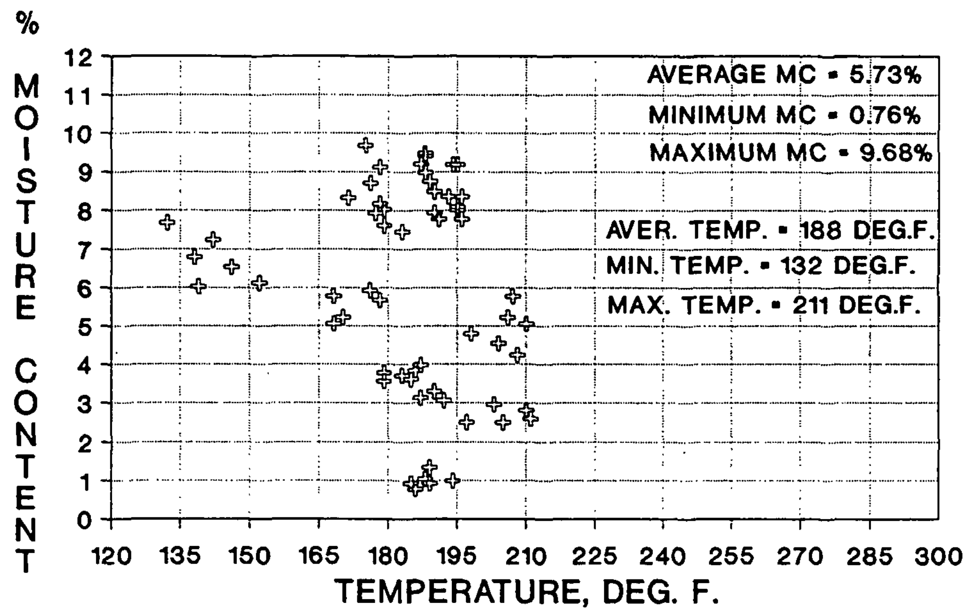
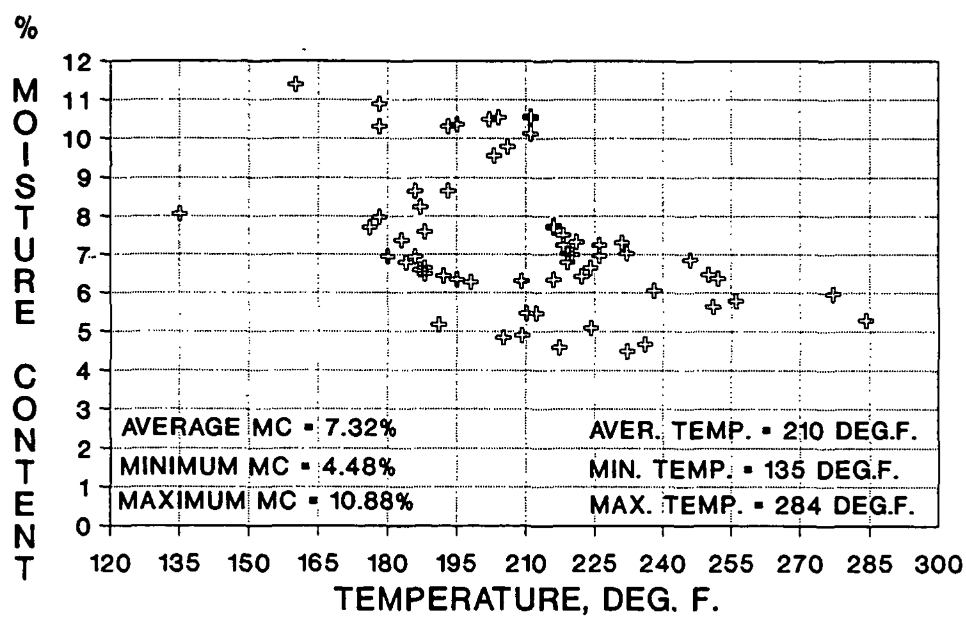


FIGURE 5

LINERBOARD TEMPERATURE AND MOISTURE LEVELS ACHIEVED IN EXPERIMENT AT END POINT



LINERBOARD AND MEDIUM TEMPERATURE ACTUAL EXPERIMENTAL LEVELS

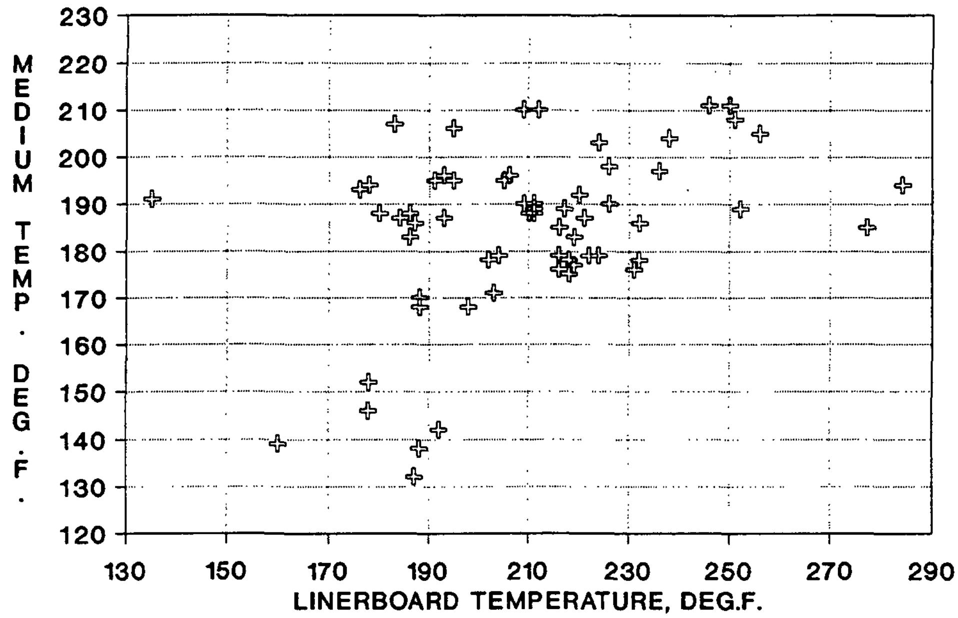
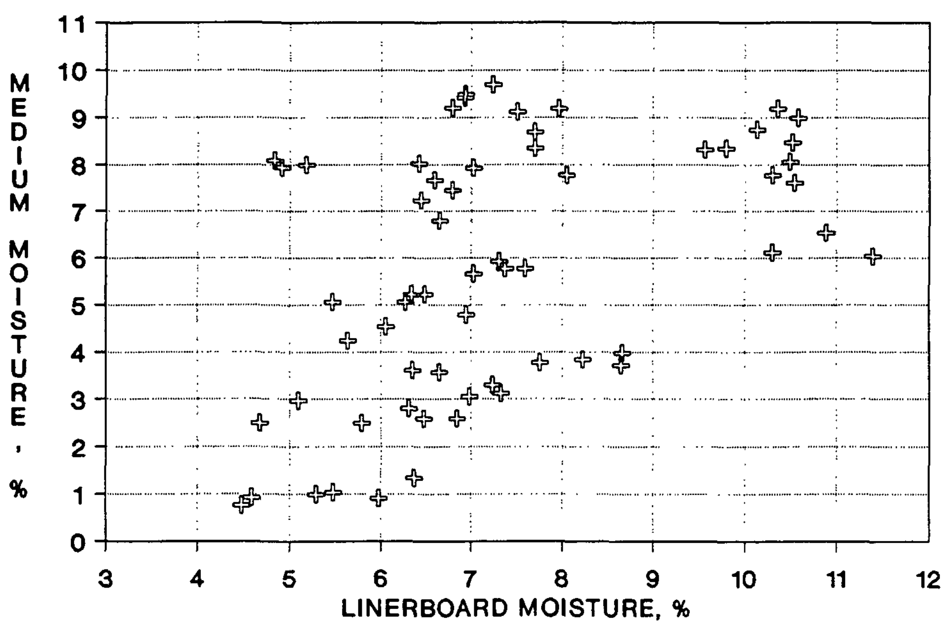


FIGURE 6

LINERBOARD AND MEDIUM MOISTURE ACTUAL EXPERIMENTAL LEVELS



MULTIPLE LINEAR REGRESSION EQUATION
SPEED LIMITED DATA

FIGURE 7

SPEED = 42.33 + 0.525(LB TEMP.) - 0.711(MED. TEMP.)
+ 15.70(LB MOIST.) + 21.69(MED. MOIST.)
+ 14.68(WEDGE POS.)

$r^2 = 0.361$

$n = 40$

SPEED = MAXIMUM SPEED AT 100% DEBONDING, FPM.

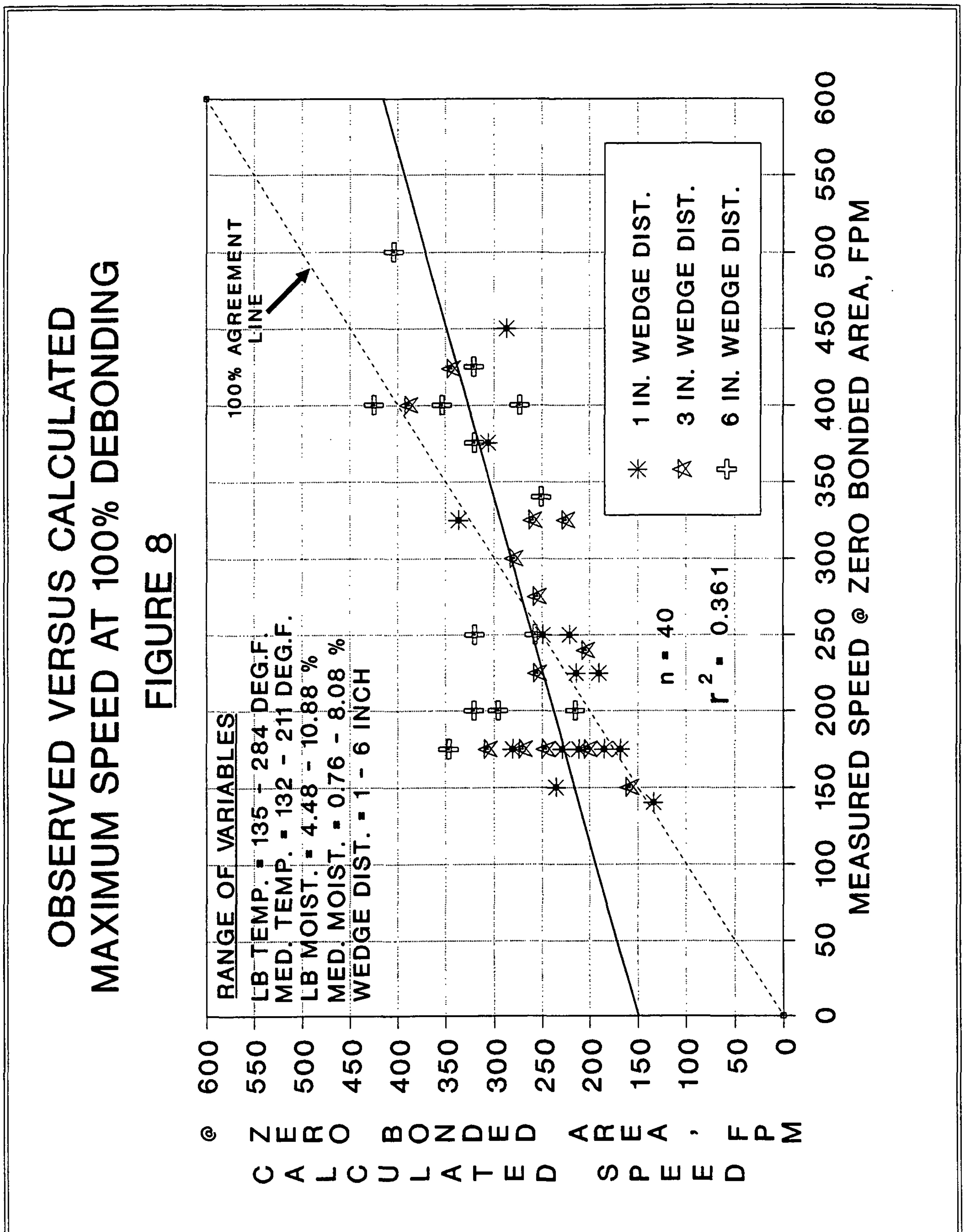
LB TEMP. = LINERBOARD TEMPERATURE, DEG.F.

MED. TEMP. = MEDIUM TEMPERATURE, DEG.F.

LB MOIST. = LINERBOARD MOISTURE CONTENT, %.

MED. MOIST. = MEDIUM MOISTURE CONTENT, %.

WEDGE POS. = DISTANCE OF WEDGE LEADING EDGE FROM PRESSURE ROLL NIP.


OBSERVED VERSUS CALCULATED
MAXIMUM SPEED AT 100% DEBONDING
FIGURE 8
RANGE OF VARIABLES
LB TEMP. = 135 - 284 DEG.F.
MED. TEMP. = 132 - 211 DEG.F.
LB MOIST. = 4.48 - 10.88 %
MED. MOIST. = 0.76 - 8.08 %
WEDGE DIST. = 1 - 6 INCH
100% AGREEMENT LINE
n = 40
r 2 = 0.361
1 IN. WEDGE DIST.
3 IN. WEDGE DIST.
6 IN. WEDGE DIST.
0 50 100 150 200 250 300 350 400 450 500 550 600
MEASURED SPEED @ ZERO BONDED AREA, FPM
CALCULATED SPEED @ ZERO BONDED AREA, FPM

MULTIPLE LINEAR REGRESSION EQUATION
BOND LIMITED DATA AT 500 FPM
FIGURE 9

$$\% \text{ BOND} = 0.461(\text{LB TEMP.}) + 0.544(\text{MED. TEMP.}) + 3.939(\text{LB MOIST.}) + 6.059(\text{MED. MOIST.}) + 0.474(\text{BOND TIME}) - 257.7$$

$$r^2 = 0.806$$

$$n = 23$$

% BOND = PERCENT BONDED AREA.
LB TEMP. = LINERBOARD TEMPERATURE, DEG.F.
MED. TEMP. = MEDIUM TEMPERATURE, DEG.F.
LB MOIST. = LINERBOARD MOISTURE CONTENT, %.
MED. MOIST. = MEDIUM MOISTURE CONTENT, %.
BOND TIME = BONDING TIME BEFORE WEDGE, ms.

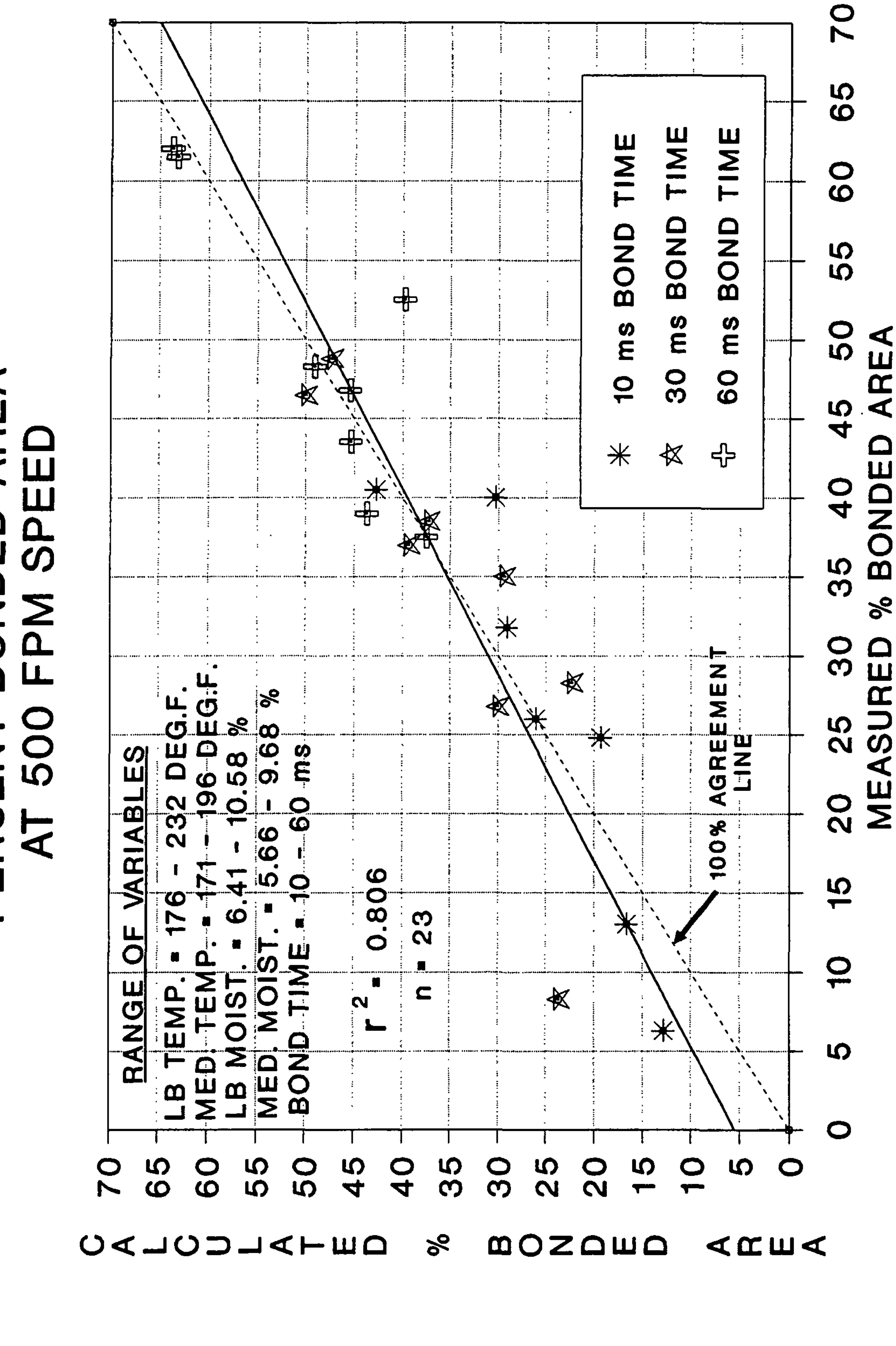

OBSERVED VERSUS CALCULATED
PERCENT BONDED AREA
AT 500 FPM SPEED
RANGE OF VARIABLES
LB TEMP. = 176 - 232 DEG.F.
MED. TEMP. = 171 - 196 DEG.F.
LB MOIST. = 6.41 - 10.58 %
MED. MOIST. = 5.66 - 9.68 %
BOND TIME = 10 - 60 ms
r² = 0.806
n = 23
100% AGREEMENT LINE
10 ms BOND TIME
30 ms BOND TIME
60 ms BOND TIME
MEASURED % BONDED AREA
CALCULATED % BONDED AREA
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70

FIGURE 10

due to an excessively high linerboard temperature at slow speed, (1, 2). It should also be noted that this set of data represents subnormal commercial performance at the single-facer, and, therefore, of limited, quantitative, commercial significance. The regression equation does indicate qualitative directions of higher linerboard temperature, higher linerboard moisture, lower medium temperature, higher medium moisture, and longer bonding times as being favorable for stronger green bond strengths.

The experimental conditions that achieved a speed of 500 fpm, and which were rated by the percent bond at that speed, are more representative of expected commercial performance. That is, the preconditioning was closer to normal levels. The multiple linear regression equation for this portion of the data is shown in Figure 9, and the calculated bonded area at 500 fpm is shown plotted against the observed values in Figure 10. A much better correlation agreement was obtained with this set of data as indicated by the R-Squared value of 0.806, and by the regression line being statistically equivalent to the 100% agreement line in Figure 10. As with the previous subnormal conditioning level data, these data indicate that a higher linerboard temperature, a higher linerboard moisture content, a higher medium moisture content, and longer bonding times are favorable for improving the green bond strength. This regression analysis, however, indicates that a higher medium temperature is also favorable. It is believed that this regression equation is a more valid representation of the physical reality of actual commercially acceptable single-facer operations. The remainder of the data analysis is, therefore, based on the equation shown in Figure 9.

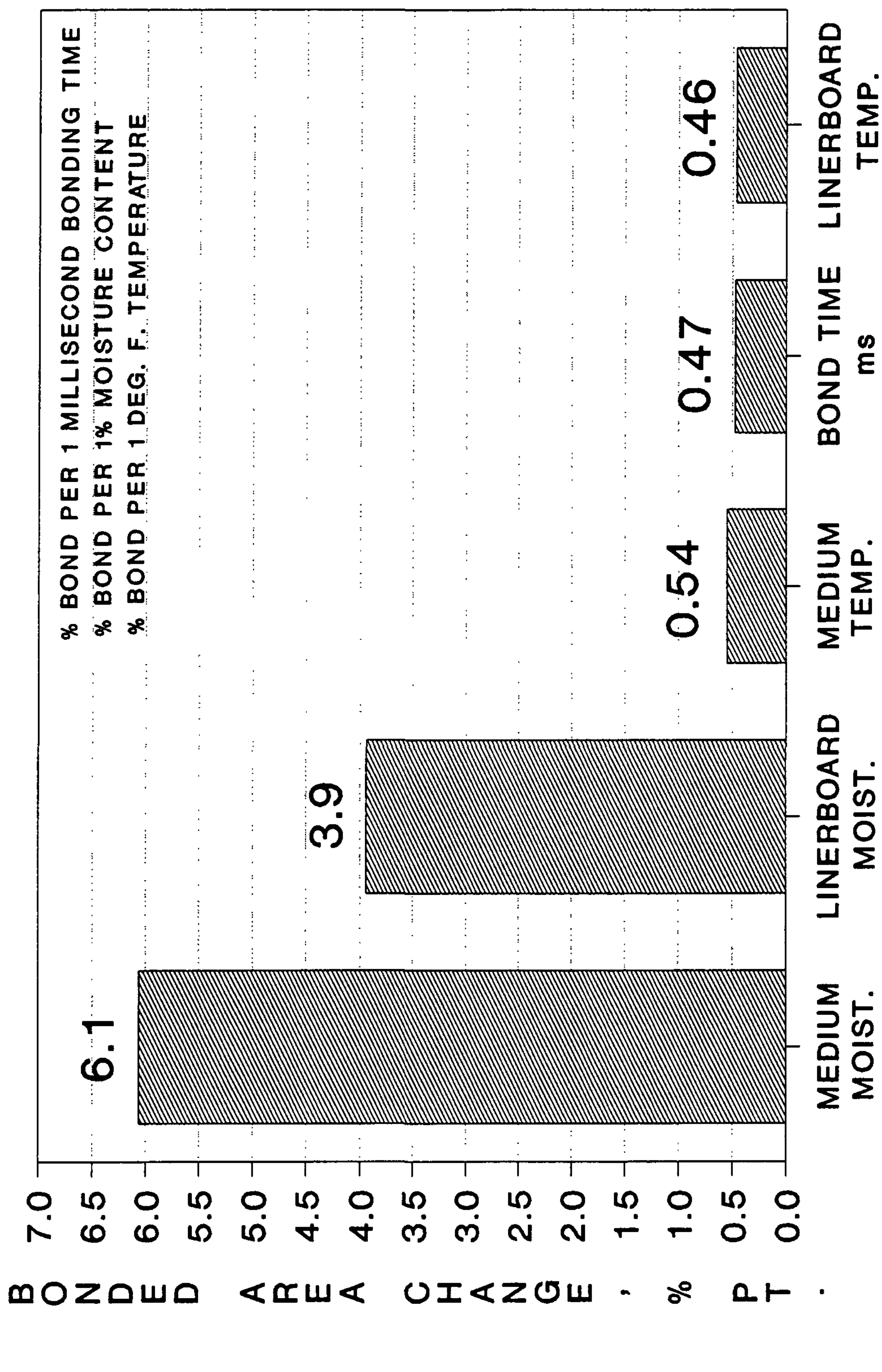
The constants shown in the regression equation represent the unit change in bonded area per unit change in the respective variable. The comparison of these slope values for the five variables is shown in Figure 11. Based on this interpretation, the moisture content effect is, on average, ten times the effect of temperature. The medium moisture content is 56% greater in effect than the linerboard moisture content. The medium temperature effect is only slightly greater than the linerboard temperature effect, and both are approximately equal to the bonding time effect.

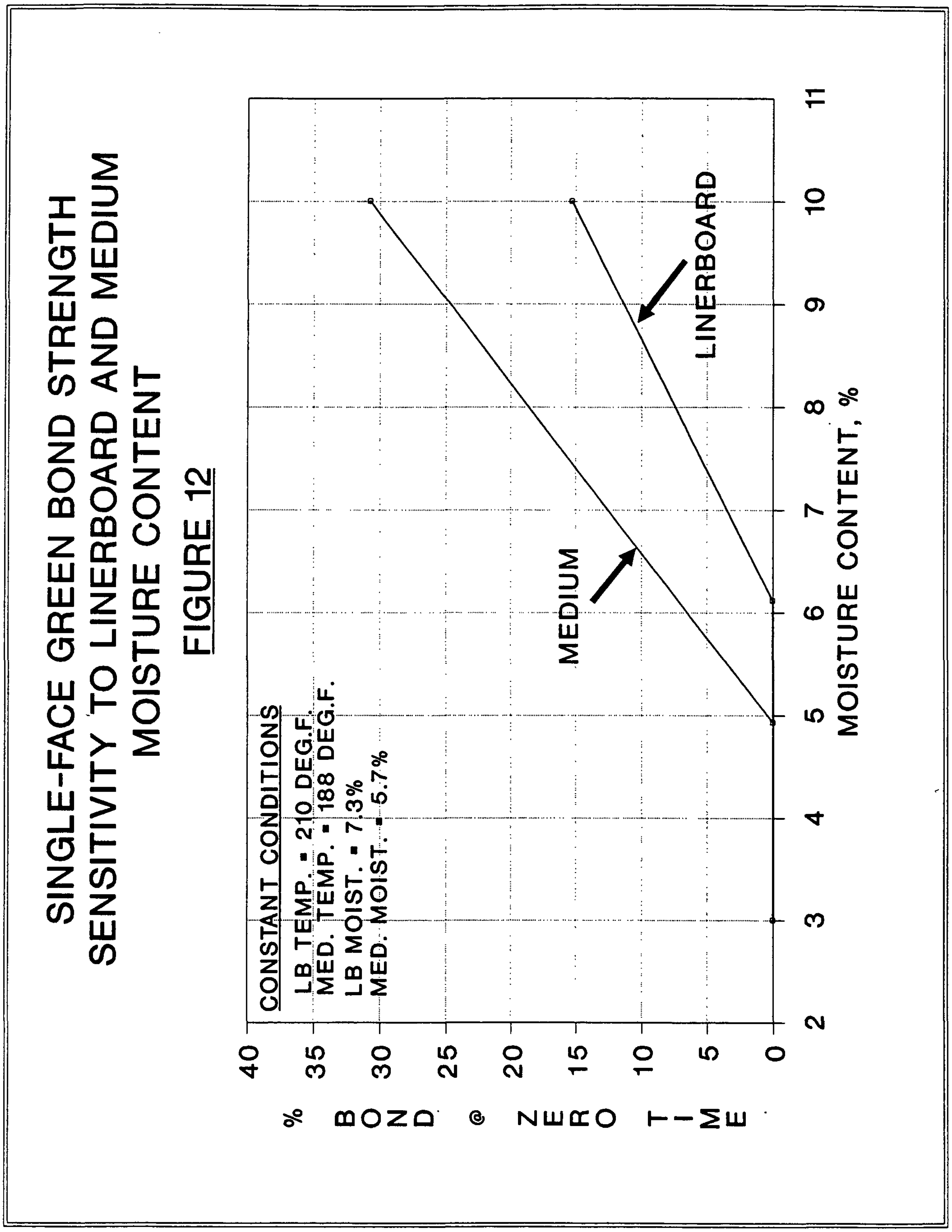
The sensitivity analysis of the regression equation variables shown in Figure 9 can be based on two different extrapolated limiting cases. The first case is the calculated bonding time at the zero bonded area limit, and the subsequent rate of bond strength increase. The second case is the calculated bonding time necessary to achieve a 100% bonded area.

Figure 12 shows the calculated effect of moisture content on the percent bonded area at zero bonding time, (ie; at the pressure roll nip) for both the medium and the linerboard. The

BONDED AREA CHANGE AT 500 FPM SPEED PER UNIT CHANGE IN VARIABLES

FIGURE 11




SINGLE-FACE GREEN BOND STRENGTH
SENSITIVITY TO LINERBOARD AND MEDIUM
MOISTURE CONTENT
FIGURE 12
CONSTANT CONDITIONS
LB TEMP. = 210 DEG.F.
MED. TEMP. = 188 DEG.F.
LB MOIST. = 7.3%
MED. MOIST. = 5.7%
MEDIUM
LINERBOARD
% BOND @ ZERO TIME
MOISTURE CONTENT, %
0
5
10
15
20
25
30
35
40
2
3
4
5
6
7
8
9
10
11

other variable levels were set at the average levels observed in the experiment, and held constant at the levels shown in Figure 12 for the calculations. The intercept of the calculated line will, of course, change if the assumed values of the other variables are changed, but the slope will remain the same. With the assumed variable levels, the green bond will have a measurable strength leaving the pressure roll nip if medium moisture contents are above 5%. The corresponding critical moisture content for the linerboard is 6%. Again, these are the moisture content levels of the webs entering the single-facer roll stack and not the initial rollstock moisture levels.

A similar plot for web temperature is shown in Figure 13. The medium critical temperature is 176 deg. F. for the assumed constants shown for the other variables in the equation. The critical linerboard temperature is 200 deg. F.

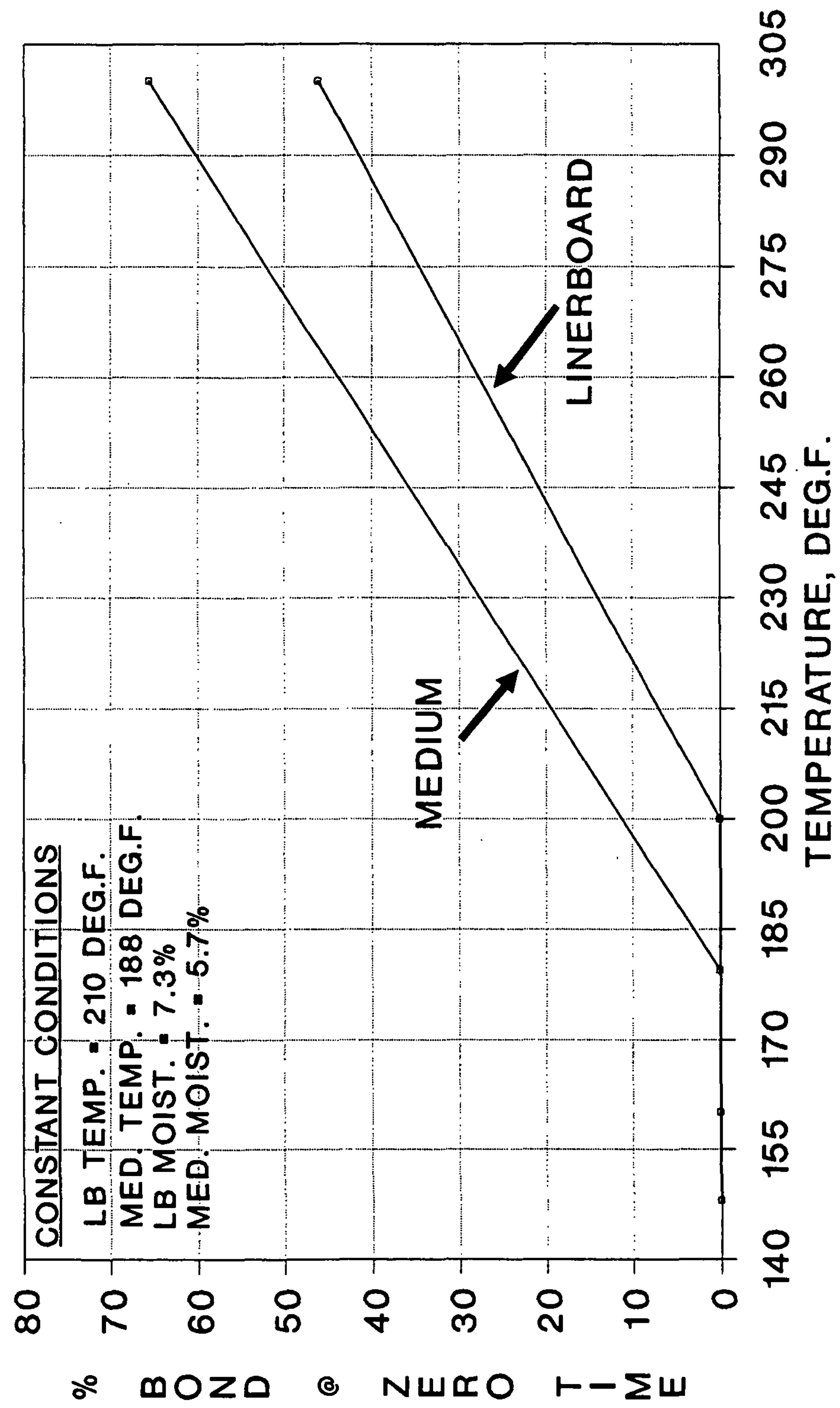
The sensitivity plot for bonding time is shown in Figure 14. The regression equation predicts that a minimum bond development time of 18 ms is required to obtain a measurable bond strength when the linerboard web temperature is 202 deg. F., when the medium web temperature is 180 deg. F., and when the linerboard and medium moisture contents are 5.8% and 5.2%, respectively. This 18 ms bond development time will increase if the assumed temperatures and/or moisture contents are reduced, and will decrease if they are increased. In fact, a measurable green bond strength immediately after exiting the pressure roll nip would be expected if the linerboard and medium have suitably high temperatures and moisture contents.

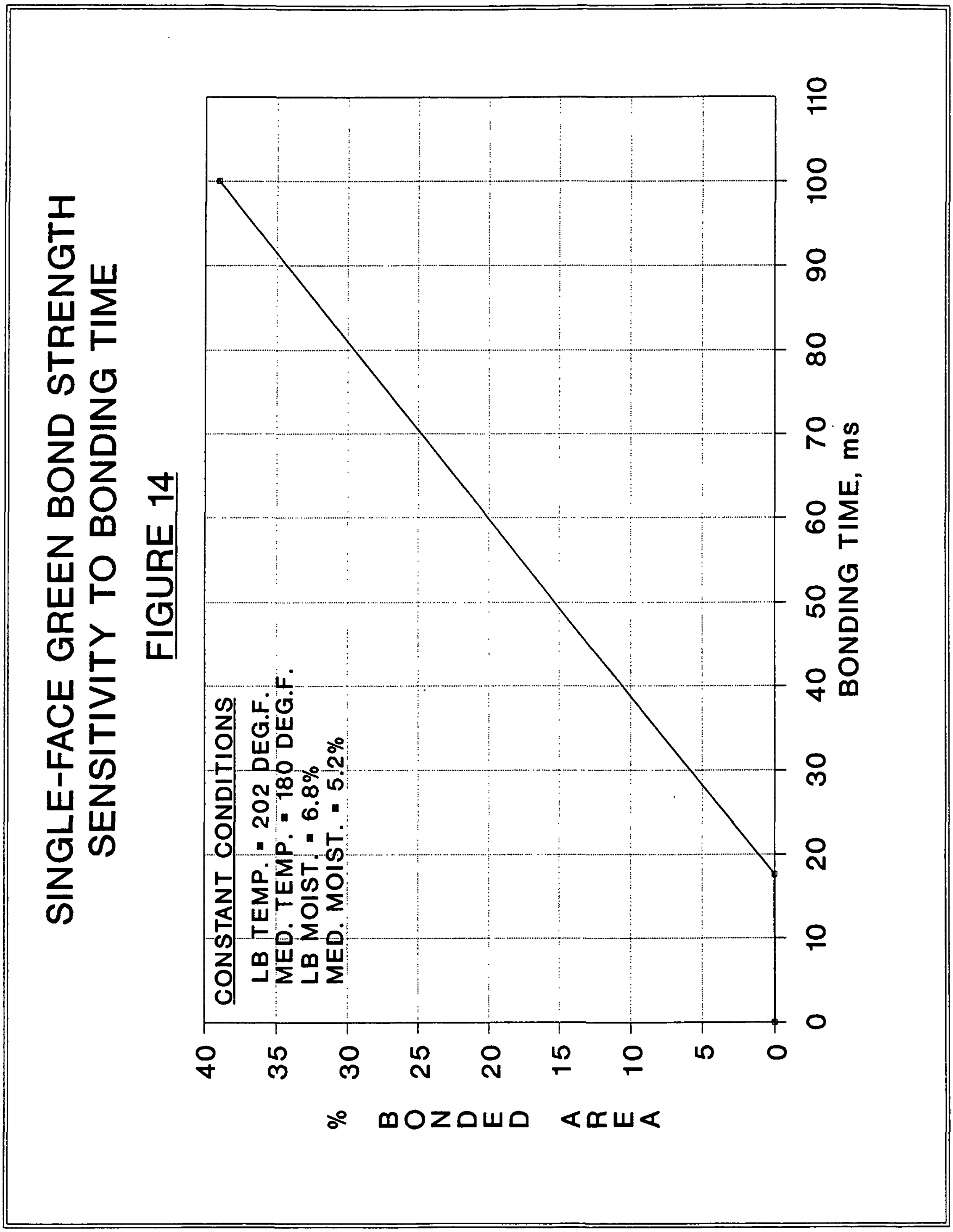
The prior CKPG project in the area of green bond strength development indicated an induction time barrier at 19 ms, (1, 2). These results are consistent with the results from this study. However, it now appears that this observed barrier is a function of the maximum preconditioning capacity of the IPST pilot single-facer under high corrugating speeds, and not an inherent function of the mechanism of the green bond formation itself.

The regression equation shown in Figure 9 was used to predict bond development times required to achieve a 100% bonded area. Seven different combinations of temperature and moisture content levels were used for the analysis, and the selected values are shown in Figure 15. The "Worst" case scenario represents the lowest values observed during the actual experiment, but not necessarily within the same trial run. The "Average" condition represents the actual average experimental values observed for all of the runs. The "Best" condition represents the highest temperatures and moisture contents actually measured during the experiment, but not necessarily within the same specific trial run. The last four conditions

SINGLE-FACE GREEN BOND STRENGTH SENSITIVITY TO LINERBOARD AND MEDIUM TEMPERATURE

FIGURE 13




SINGLE-FACE GREEN BOND STRENGTH
SENSITIVITY TO BONDING TIME
FIGURE 14
CONSTANT CONDITIONS
LB TEMP. = 202 DEG.F.
MED. TEMP. = 180 DEG.F.
LB MOIST. = 6.8%
MED. MOIST. = 5.2%
% BONDED AREA
0
5
10
15
20
25
30
35
40
BONDING TIME, ms
0
10
20
30
40
50
60
70
80
90
100
110

MAGNITUDE OF EFFECT COMPARISON OF VARIABLES

CONDITION	LINER TEMP.	MEDIUM TEMP.	LINER MOIST.	MEDIUM MOIST.
"WORST"	135	132	4.48	0.76
"AVERAGE"	210	188	7.32	5.73
"BEST"	285	211	10.88	9.68
LINER TEMP.	250	188	7.32	5.73
MEDIUM TEMP.	210	226	7.32	5.73
LINER MOIST.	210	188	8.63	5.73
MEDIUM MOIST.	210	188	7.32	7.04

FIGURE 15

represent a 20% increase in the numerical average values for each of the four equation variables.

The resultant calculated minimum bonding times required to achieve a 100% bonded area are shown in Figure 16. A lower bonding time indicates an improved green bond formation rate. The total range covered by the "Best" to "Worst" conditions was 200% of the "Average" condition bonding time. The 20% increases in the temperature or moisture content levels, from that of the "Average" condition, reduced the predicted bonding time to a 100% bonded area by values ranging from 6% to 23%. With this method of calculation, the temperature effect is greater than the moisture content effect, and the medium conditioning levels are more effective than those of the linerboard. These results are not inconsistent with those presented in Figure 11. The reason why the temperature appears more significant than moisture content in Figure 16 is that a 20% increase in a temperature of 210 deg. F. is a 42 unit change, while a 20% increase in a 6.0% moisture content is only a 1.2 unit change. Both methods of analysis, Figures 11 & 16, indicate that the medium temperature and moisture content has more of an effect than that of the linerboard, respectively.

It needs to be kept in mind that there is an upper limit to the beneficial temperature effects and an upper limit to the beneficial moisture effect. Excessively high temperatures can cause the starch adhesive to crystalize and produce a weak, brittle bond, (1, 2). Practical experiences also indicate that excessively high moisture content levels can result in poor bonding and blisters.

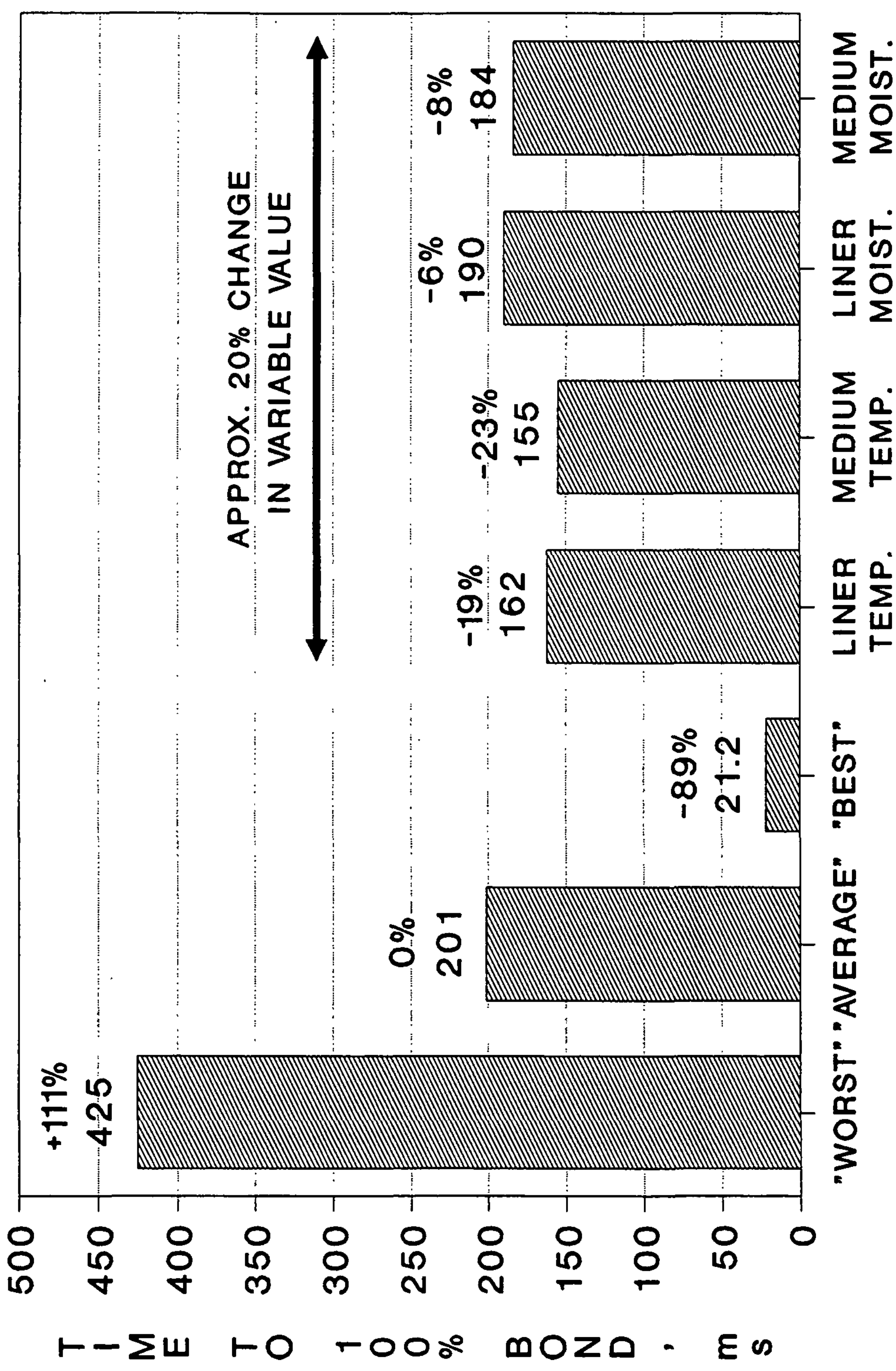
V. Practical Applications.

The results of this study reinforce the need to control the preconditioning on the corrugator, especially during speed changes. Failure to increase the preconditioning of both the medium and the linerboard simultaneously with significant speed increases on the single-facer will increase the risk of single-face bond defects occurring. The operation of the steam showers is particularly important since a higher moisture content is more beneficial to the rate of bond strength development. The preheater wrap is also important since a higher temperature is also beneficial.

Linerboard and medium rollstock with a higher average moisture content should be beneficial in achieving a rapid rate of green bond development in the single-facer. The higher average moisture content needs to be consistent with uniform moisture profiles.

MAGNITUDE OF EFFECT COMPARISON OF VARIABLES

FIGURE 16



VI. Conclusions.

The data presented in this report support the following conclusions concerning the single-face green bond development.

1. Higher medium and linerboard temperatures and moisture contents at the point of entering the single-facer roll stack are beneficial to the rate of the green bond strength development.

2. The medium characteristics have more of an effect than the linerboard characteristics, and moisture content has more of an effect than temperature on the rate of the green bond strength development.

3. The order of importance, based on a per degree temperature change or a per percent moisture change, is medium moisture content, linerboard moisture content, medium temperature, and linerboard temperature.

4. There is a practical upper limit on the temperature and moisture levels. An excessive temperature will crystallize the starch and produce a brittle bond. Excessively high moisture levels can result in fluff-out and blisters.

5. The rate of green bond strength development is linear with time once the bond starts to form.

6. The results of this project are consistent with the results from the previous project, (1, 2). The previously reported induction time barrier of 19 ms before a measurable green bond strength is achieved now appears to be an artifact of the preconditioning capacity of the IPST pilot single-facer at high corrugating speeds, and not an inherent function of the mechanism of the green bond formation itself.

7. Higher moisture content averages in the medium and linerboard rollstock will be beneficial to an increased rate of green bond formation. The higher average must be consistent with uniform moisture profiles.

8. The preconditioning equipment on the single-facer needs to be kept in good operating condition. Adjustments to the steaming and preheating need to occur simultaneously with changes in the single-facer speed in order to minimize the probability of bond defects.

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APPENDIX

APPENDIX
Project 3748
Single-face Green Bond

Run No.	P.C. Code	Wedge Dist. (in.)	Liner Temp. Deg. F	Liner Moist Cont. %	Medium Temp. Deg. F	Medium Moist Cont. %	Speed @ 100% Delam. (fpm)	Bonded Area @ 500fpm %	Bond Time (ms)
Recycled Medium and Recycled Linerboard									
1	LLLL	1	232	4.48	186	0.76	140	-	35.7
		3	217	4.59	189	0.92	150	-	100.0
		6	210	5.47	188	1.03	200	-	150.0
2	LLHL	1	236	4.67	197	2.49	175	-	28.6
		3	224	5.09	203	2.96	240	-	62.5
		6	209	6.30	210	2.80	340	-	88.2
3	HLHL	1	256	5.78	205	2.49	225	-	22.2
		3	250	6.46	211	2.59	325	-	46.2
		6	246	6.84	211	2.59	400	-	75.0
4	HLLL	1	277	5.97	185	0.91	175	-	28.6
		3	284	5.28	194	0.98	175	-	85.7
		6	252	6.36	189	1.33	250	-	120.0
5	MLMM	1	232	7.02	178	5.66	-	6.3	10.0
		3	232	7.02	178	5.66	-	28.3	30.0
		6	231	7.30	176	5.91	-	37.5	60.0
6	LLHH	1	180	6.93	188	9.41	-	13.0	10.0
		3	186	6.93	188	9.48	-	35.0	30.0
		6	184	6.79	187	9.19	-	52.5	60.0

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Run No.	P.C. Code	Wedge Dist. (in.)	Liner Temp. Deg. F	Liner Moist Cont. %	Medium Temp. Deg. F	Medium Moist Cont. %	Speed @ 100% Delam. (fpm)	Bonded Area @ 500fpm %	Bond Time (ms)
7	LLLH	1	188	6.64	138	6.79	375	-	13.3
		3	192	6.43	142	7.23	425	-	35.3
		6	187	6.58	132	7.66	500	-	60.0
8	LHLH	1	178	10.30	152	6.11	325	-	15.4
		3	178	10.88	146	6.53	400	-	37.5
		6	160	11.38	139	6.02	400	-	75.0
9	HHHH	1	211	10.58	188	8.98	-	40.5	10.0
		3	211	10.52	190	8.47	-	46.5	30.0
		6	211	10.13	189	8.74	-	62.0	60.0
10	HHLL	1	224	6.64	179	3.56	175	-	28.6
		3	216	6.34	185	3.61	175	-	85.7
		6	216	7.75	179	3.77	250	-	120.0
11	LHLL	1	187	8.22	186	3.84	150	-	33.3
		3	186	8.64	183	3.71	175	-	85.7
		6	193	8.65	187	3.98	200	-	150.0
12	MHMM	1	204	10.54	179	7.60	-	26.0	10.0
		3	202	10.49	178	8.16	-	38.5	30.0
		6	203	9.56	171	8.31	-	46.8	60.0

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Run No.	P.C. Code	Wedge Dist. (in.)	Liner Temp. Deg. F	Liner Moist Cont. %	Medium Temp. Deg. F	Medium Moist Cont. %	Speed @ 100% Delam. (fpm)	Bonded Area @ 500fpm %	Bond Time (ms)
13	MMMM	1	218	7.50	178	9.11	-	31.8	10.0
		3	218	7.23	175	9.68	-	37.0	30.0
		6	216	7.69	176	8.69	-	48.3	60.0
14	MMMH	1	219	6.78	183	7.44	-	24.8	10.0
		3	222	6.41	179	8.01	-	26.8	30.0
		6	219	7.02	177	7.92	-	39.0	60.0
15	MMML	1	251	5.63	208	4.24	250	-	20.0
		3	238	6.05	204	4.53	325	-	46.2
		6	226	6.94	198	4.78	425	-	70.6
Virgin Medium and Recycled Linerboard									
16	LLLL	1	209	4.91	190	7.93	175	-	28.6
		3	205	4.83	195	8.08	175	-	85.7
		6	191	5.17	195	7.99	175	-	171.4
17	LLHL	1	212	5.46	210	5.05	225	-	22.2
		3	195	6.33	206	5.22	275	-	54.5
		6	183	7.36	207	5.76	375	-	80.0
18	LLHH	1	135	8.04	191	7.77	450	-	11.1
		3	176	7.69	193	8.35	-	8.3	30.0
		6	178	7.96	194	9.18	-	43.5	60.0

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Run No.	P.C. Code	Wedge Dist. (in.)	Liner Temp. Deg. F	Liner Moist Cont. %	Medium Temp. Deg. F	Medium Moist Cont. %	Speed @ 100% Delam. (fpm)	Bonded Area @ 500fpm %	Bond Time (ms)
19	LLLH	1	198	6.26	168	5.05	250	-	20.0
		3	188	6.48	170	5.22	300	-	50.0
		6	188	7.58	168	5.76	400	-	75.0
20	HHHH	1	193	10.30	196	7.77	-	40.0	10.0
		3	206	9.79	196	8.35	-	48.8	30.0
		6	195	10.36	195	9.18	-	61.5	60.0
21	HHLL	1	220	6.98	192	3.05	175	-	28.6
		3	226	7.23	190	3.29	225	-	66.7
		6	221	7.32	187	3.12	200	-	150.0

L = Low Numerical Value Planned.
M = Medium Numerical Value Planned.
H = High Numerical Value Planned.