Institute of Paper Science and Technology

THE EFFECT OF BOX PLANT PROCESS VARIABLES ON THE EDGE CRUSH TEST OF CORRUGATED BOARD

Project 3749

Final Report

To

The Containerboard & Kraft Paper Group

of

The American Paper Institute

January 15, 1993

Atlanta, Georgia

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
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IPST Project 3749 for
Containerboard & Kraft Paper Group

The Effect of Box Plant Process Variables on the Edge Crush Test of Corrugated Board

I. Summary and Conclusions.

The recent adoption of Alternate Item 222 and Rule 41 has accelerated the marketplace's interest in compressive strength performance packaging. The Edge Crush Test (ECT) of the corrugated board has been shown to be the most important combined board property controlling box compressive strength. The ECT has been shown to be related primarily to the cross direction edge crush strength of the linerboard and the medium, and to the quality of the box plant converting operations.

The objective of this project was to evaluate the effect of selected box plant process variables on the ECT of corrugated board. The study considered the effect on both the average ECT and the ECT variability as they influence compliance with Item 222 and Rule 41, and as they influence the consistency of package compressive strength performance.

The experiment included the process variables of combined board crushing, single-face bond strength, leaning flutes, high/low flutes, and single-facer pressure roll cutting of the linerboard. The following major conclusions are supported by the data presented in this report.

1. A lower single-face pin adhesion bond strength, a greater angle of leaning flutes, a greater percentage of high/low flutes, and crushing of the combined board all adversely affect the average Edge Crush Test (ECT). While the effect of the double-face pin adhesion bond strength was not evaluated in this study, there is no reason to suspect that its effect would not be identical to that observed for single-face bond strength.

2. Moderate increases in the pressure roll cutting of the linerboard improved the average ECT. It is hypothesized that this effect can be explained by the decoupling of the stress/strain differences between the linerboard and medium under compression loading. It is not recommended that a box plant use pressure roll cutting to improve the average ECT. Such an

action would be detrimental to the ability of the box to contain and protect the packaged product. The result does indicate that pressure roll cutting should not be a process variable to be included in a box plant ECT improvement strategy. It should be maintained at the same good quality level as was done under the old mullen specifications.

3. None of the process variables affect the within sample ECT standard deviation value when the defect occurs uniformly throughout the combined board. However, localized defects, such as nonuniform crushing or variable bond strength will produce a higher effective ECT standard deviation due to the combination of different average ECT populations.

4. No variable interaction effects were found. The effect of the variables are additive and can be modeled by a multiple linear regression equation. The equation is presented in the report. It indicates that the order of influence of the process variables studied, from greatest to least effect, is crushing, bond strength, high/low flutes, and leaning flutes.

5. The degree of crushing determined by caliper measurements in a box plant is not a sensitive quality control method. The medium has a large caliper recovery property and most of the recovery occurs in less than one minute after crushing. A possible better quality control method would be to measure actual clearances at the pinch points in the box plant process.

6. The documented adverse effect of high/low flutes on the average ECT may justify the installation of a continuously measuring high/low gauge monitor on corrugators. Such a gauge was developed at IPST and is available.

7. The documented adverse effect of low bond strength on the average ECT indicates that the adhesive application systems on the corrugator should be kept in good working order. This includes keeping a uniform adhesive application rate in the cross machine direction, eliminating glue station roll run-out problems that will cause machine direction bond strength cycles, and controlling the adhesive properties and the glue station mechanics to avoid adhesive film defects such as mottle and ringing.

8. The influence of the box plant process variables discussed above on the ECT may explain part of the difficulty in developing a universal equation relating

ECT to the crush strength of the linerboard and medium.

II. Introduction.

The recent adoption of Alternate Item 222 and Rule 41 has accelerated the marketplace's interest in compressive strength performance packaging. The Edge Crush Test (ECT) of the corrugated board has been shown to be the most important combined board property controlling box compressive strength (1). The ECT has been shown to be related primarily to the cross direction edge crush strength of the linerboard and the medium (2, 3), and to the quality of the box plant converting operations (4, 5, 6, 7). These referenced studies have evaluated the effect of single variables,and not the combined effect of the several variables.

The objective of this project was to evaluate the effect of selected box plant process variables on the ECT of corrugated board. The study considered the effect on both the average ECT and the ECT variability as they influence compliance with Item 222 and Rule 41, and as they influence the consistency of package compressive strength performance.

The experiment included the process variables of combined board crushing, single-face bond strength, leaning flutes, high/low flutes, and single-facer pressure roll cutting of the linerboard. A complete factorial experimental design was used so that any significant interactive effects between the process variables could be detected.

III. Experimental Methods.

The experimental corrugated board used in this experiment was produced on the IPST 14-inch wide, pilot corrugator, at commercial speeds. All of the board was fabricated from a single roll of commercial corrugating medium and a single roll of commercial linerboard. Material from the same linerboard roll was used for both the single-face linerboard and the double-face linerboard. A standard, two-phase, 25% solids adhesive was used. The containerboard materials used were nominal 42 lb/msf linerboard and nominal 26 lb/msf medium. The corrugated board was C-flute.

The samples for each of the experimental conditions were equally distributed over the length of the corrugator run. This was done to avoid a bias in the data due to possible machine direction cycles of material crush strength. This procedure incorporated any such cycles into the uncertainty of the prediction model estimates, rather than into erroneous correlations for the variables.

The techniques used to change the levels of the process variables studied were the same conditions that would exist in a commercial box plant. The single-face bond strength was changed by varying the adhesive application rate. The magnitude of the high/low flutes was changed by adjusting the medium web tension and the upper corrugating roll pressure. The degree of leaning flutes was changed by passing the single-faced web through a roll nip with the flute axis parallel to the roll axis. Pressure roll cutting of the linerboard was changed by changing the gap between the lower corrugating roll and the pressure roll. Crushing was varied by passing the singlewall board through a hard rubber covered roll nip of known gap, with the flute axis perpendicular to the roll axis.

TAPPI standard test methods were followed for all of the combined board physical tests. The steel platen method was used for the caliper measurements. The high/low flutes were measured using the IPST laser flute height tester. The degree of pressure roll cutting was quantified by the mullen test values of the singlewall board. The average ECT value for each experimental condition is based on 10 replicate measurements. All of the samples were preconditioned and conditioned according to TAPPI methods prior to testing.

IV. Experimental Results.

The experimental design included three levels of single-face bond strength, three levels of high/low flutes, two levels of leaning flute, two levels of pressure roll cutting, and six levels of crushing. A full factorial experimental design was used resulting in a total of 216 sample conditions. The average quantitative values for all of these process levels and the average experimental ECT are shown in Table A. The detailed data for each of the 216 conditions are shown in Appendix A.

The objective of this study was to determine the effect of these process variables over a range representative of poor to excellent commercial quality. It was not the intent to extend the study to materials so poor in

TABLE A

EXPERIMENTAL DESIGN - FULL FACTORIAL

- SINGLE-FACE PIN ADHESION, LB.

  84.6 = 42.0 lb/in AVERAGE ECT.
  59.2 (70%) = 39.5 lb/in AVERAGE ECT.
  38.6 (46%) = 38.6 lb/in AVERAGE ECT.

- HIGH/LOW FLUTES, % AT OR ABOVE 4 MILS.

  0.2 = 40.4 lb/in AVERAGE ECT.
  3.8 = 39.6 lb/in AVERAGE ECT.
  18.0 = 38.5 lb/in AVARAGE ECT.

- LEANING FLUTE, ANGLE FROM VERTICAL.

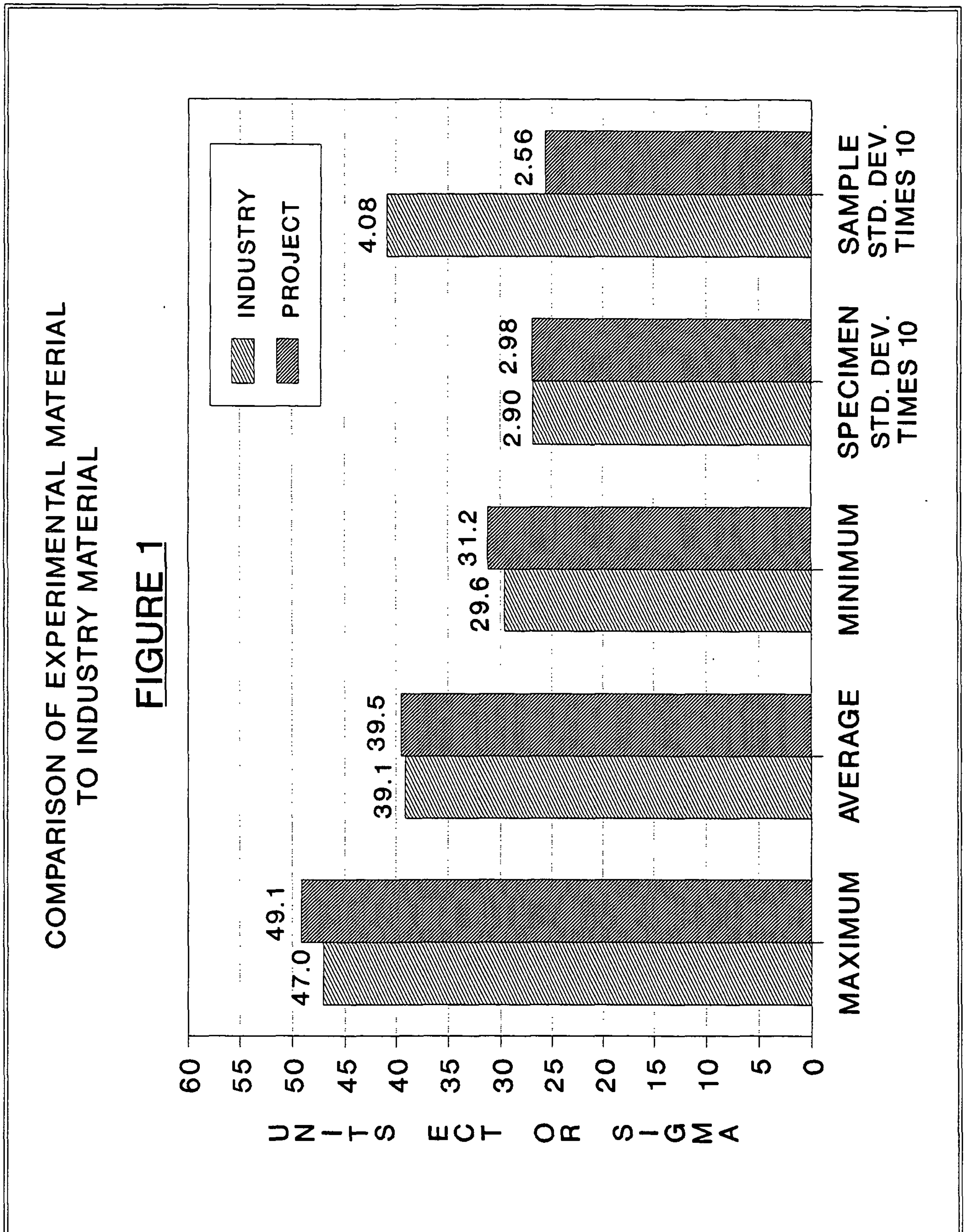
  1.7 = 40.2 lb/in AVERAGE ECT.
  21.1 = 39.0 lb/in AVERAGE ECT.

- PRESSURE ROLL CUTTING, PSI MULLEN.

  235 = 38.8 lb/in AVAREAGE ECT.
  218 (93%) = 40.3 lb/in AVERAGE ECT.

- ACTUAL CRUSHING, MILS.

  0 = 42.8 lb/in AVERAGE ECT.
  8 = 40.5 lb/in AVERAGE ECT.
  15 = 39.9 lb/in AVERAGE ECT.
  25 = 38.3 lb/in AVERAGE ECT.
  35 = 38.4 lb/in AVERAGE ECT.
  50 = 37.2 lb/in AVERAGE ECT.



COMPARISON OF EXPERIMENTAL MATERIAL TO INDUSTRY MATERIAL

FIGURE 1

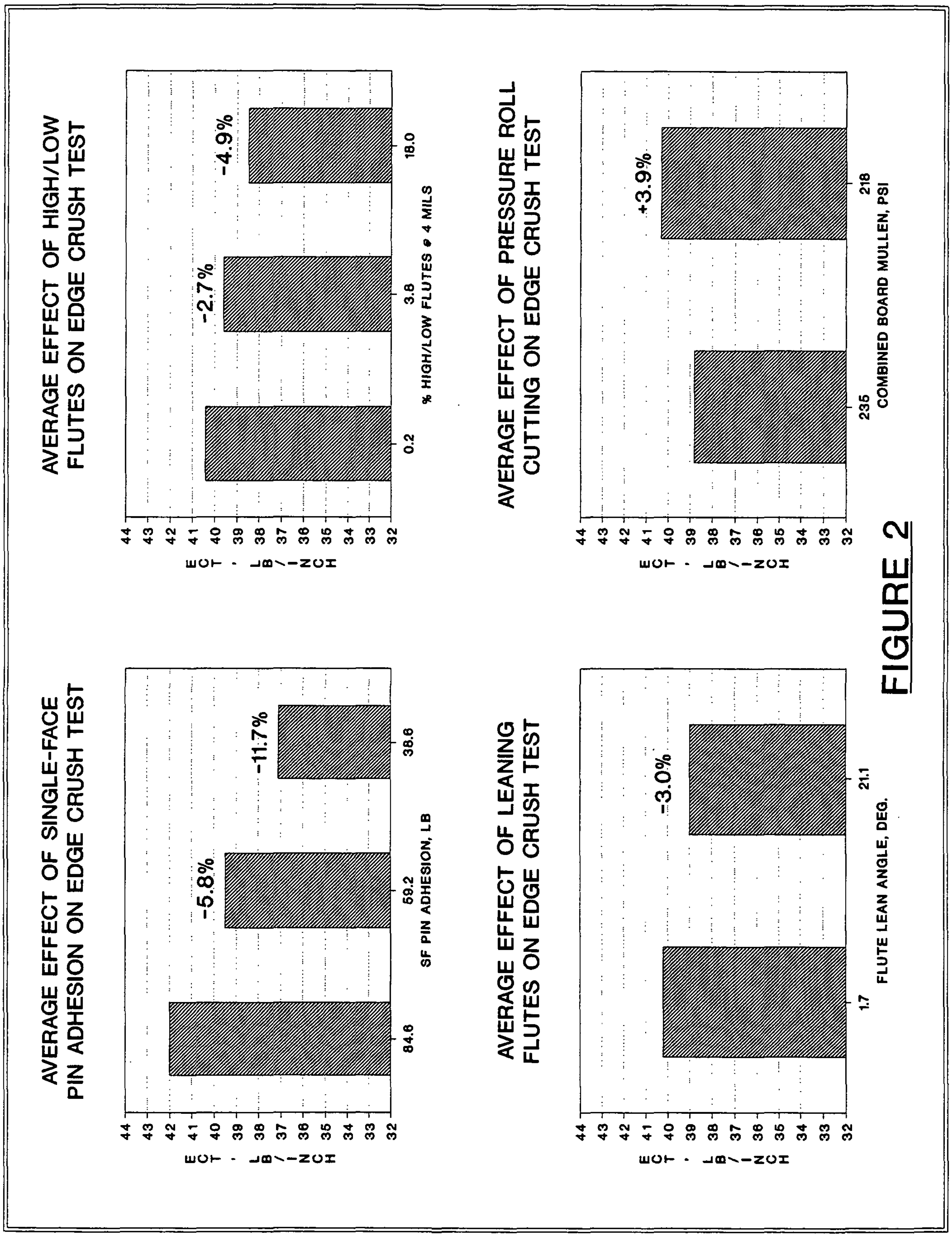

AVERAGE EFFECT OF HIGH/LOW FLUTES ON EDGE CRUSH TEST
ECT - LB/INCH
% HIGH/LOW FLUTES @ 4 MILS
0.2
3.8
18.0
-2.7%
-4.9%
AVERAGE EFFECT OF PRESSURE ROLL CUTTING ON EDGE CRUSH TEST
COMBINED BOARD MULLEN, PSI
235
218
+3.9%
AVERAGE EFFECT OF SINGLE-FACE PIN ADHESION ON EDGE CRUSH TEST
SF PIN ADHESION, LB
84.6
59.2
38.6
-5.8%
-11.7%
AVERAGE EFFECT OF LEANING FLUTES ON EDGE CRUSH TEST
FLUTE LEAN ANGLE, DEG.
1.7
21.1
-3.0%
44
43
42
41
40
39
38
37
36
35
34
33
32

FIGURE 2

quality as to be noncommercial in nature just to force a correlation. The ECT levels obtained in this study are compared to industry ECT data in Figure 1 (2, 8).

The ECT levels produced in this experiment reflected the commercial levels in average, minimum and maximum, and in the standard deviation of specimen test values within a given sample condition. The linerboard and medium materials were held constant in the experiment and the range of ECT levels achieved, therefore, reflects only the influence of the process variables. The commercial data ECT range includes the influence of both rollstock crush strength variability and the influence of the process variables. It can be concluded from this that the ECT range of this study achieved slightly broader process ranges that exist in commercial production, and that the experimental objective was met. It should be noted that the sample average ECT standard deviation for the commercial product was significantly greater than that for the experimental material. A comparison of these standard deviation values to the respective range values indicates that the experimental data have a reasonable normal distribution shape, while the commercial data are somewhat skewed.

The average effects of the process variables of single-face pin adhesion, high/low flutes, leaning flutes and pressure roll cutting of the linerboard are shown in Figure 2. Over the ranges of the variables shown in Table A, a lower single-face pin adhesion reduced the average ECT by 11.7%, increased percentage of high/low flutes @ 4 mils, or greater reduced the average ECT by 4.9%; increased leaning flutes decreased the average ECT by 3.0%; and increased pressure roll cutting, as indicated by reduced mullen strength, increased the average ECT by 3.9%. It is hypothesized that the improved ECT observed with the pressure roll cutting may be attributed to a decoupling of the stress/strain imbalance between the linerboard and the medium (9).

The double-back pin adhesion bond strength was not included as a separate variable in this study. However, there is no reason to believe that its effect would be different than that observed for the single-face pin adhesion bond strength. A bond effect is a bond effect. It is, therefore, suggested that the effect of the double-back bond strength would be equal to that observed for the single-face bond and that it can be quantitatively treated as such for box plant ECT quality control strategies. The adverse effect of a lower bond strength on the ECT is in agreement with prior published studies (4, 5).

While increased pressure roll cutting was favorable for increasing the average ECT, it is not recommended that the box plant use this technique for improving the ECT. The integrity of the linerboard facing is important to maintaining the integrity of the corrugated package in order to contain and protect the product being packaged. The significance of this finding is that the box plant need not directly include this variable in the ECT process control improvement strategy. The box plant should continue to view good pressure roll cutting control in the same manner as was done under the Item 222/Rule 41 mullen specification and certification.

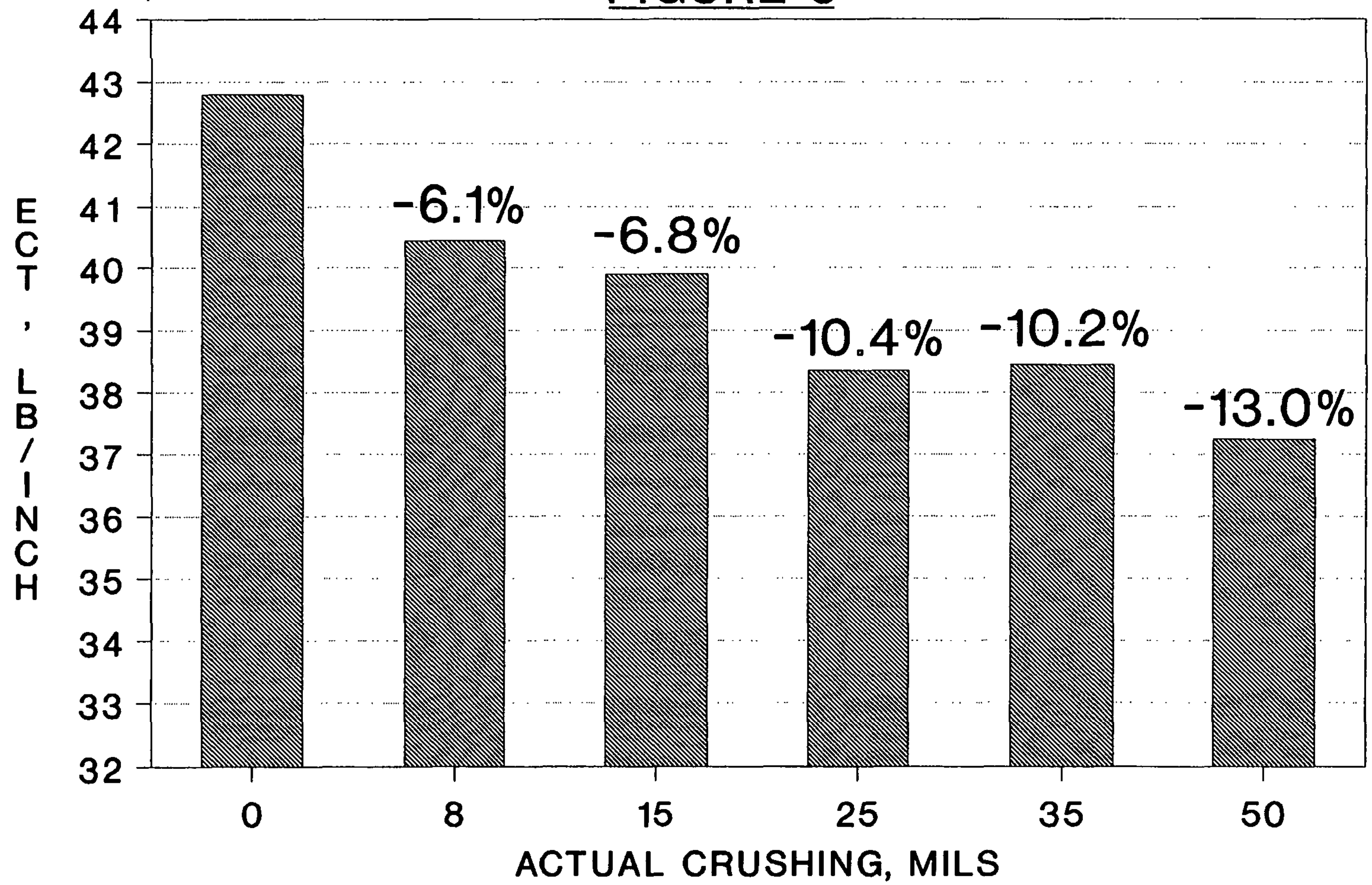
The effect of combined board crushing on the average ECT is shown in Figure 3. An actual 50 mil crushing produced an average ECT reducing of 13.0%. These results are not consistent with a prior published study that reported an increase in average ECT with crushing (7), but are consistent in trend with other published studies (5, 6). A typical stress/strain curve for flat crush is shown in Figure 4 (7, 10). The curve shows an initial elastic region followed by a region of continuing strain at a reduced stress. The material then enters a nonelastic region until flat crush failure occurs. The subsequent rapid increase in stress represents the direct crushing of the linerboard against the completely crushed medium. The range of crushing investigated in this experiment represented approximately 50% of the total strain range prior to actual flat crush failure.

Combined board caliper measurements are frequently used in box plants as a method for controlling actual crush occurring in the process. Figure 5 shows that the measured crush is significantly less than the actual crush due to the ability of the fluted medium to recover in caliper. An actual crush of 23 mils resulted in a measured crush of only 3 mils. An actual crush of 44 mils resulted in a measured crush of only 7 mils. These results are consistent with the observations of prior published studies (5, 11). What is even more significant is that almost all of the caliper recovery occurred within one minute of the actual crushing. This recovery speed is too fast to make box plant caliper measurements a sensitive tool for judging actual crushing.

The leaning flute defect also resulted in a combined board caliper loss of 21 mils, on average. The data were analyzed to determine whether there was an interaction effect between caliper loss due to crushing and caliper loss due to leaning flutes. The results are shown in Figure 6. The data show that the measured crush of the leaning flute and nonleaning flute samples as identical with respect to the actual crushing. The two lines in the top graph of Figure 6 are statistically parallel. The

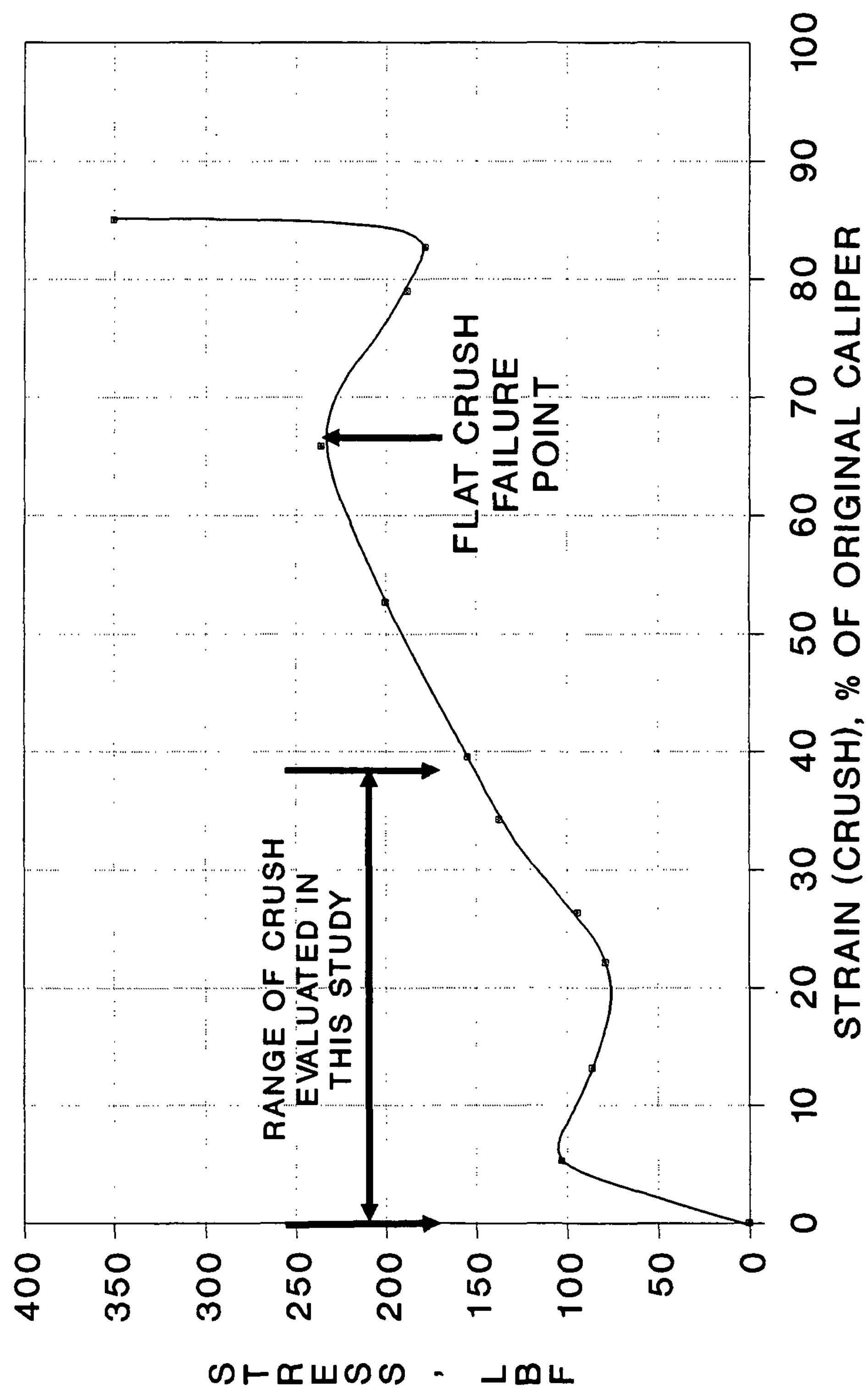
AVERAGE EFFECT OF CRUSHING ON EDGE CRUSH TEST

FIGURE 3



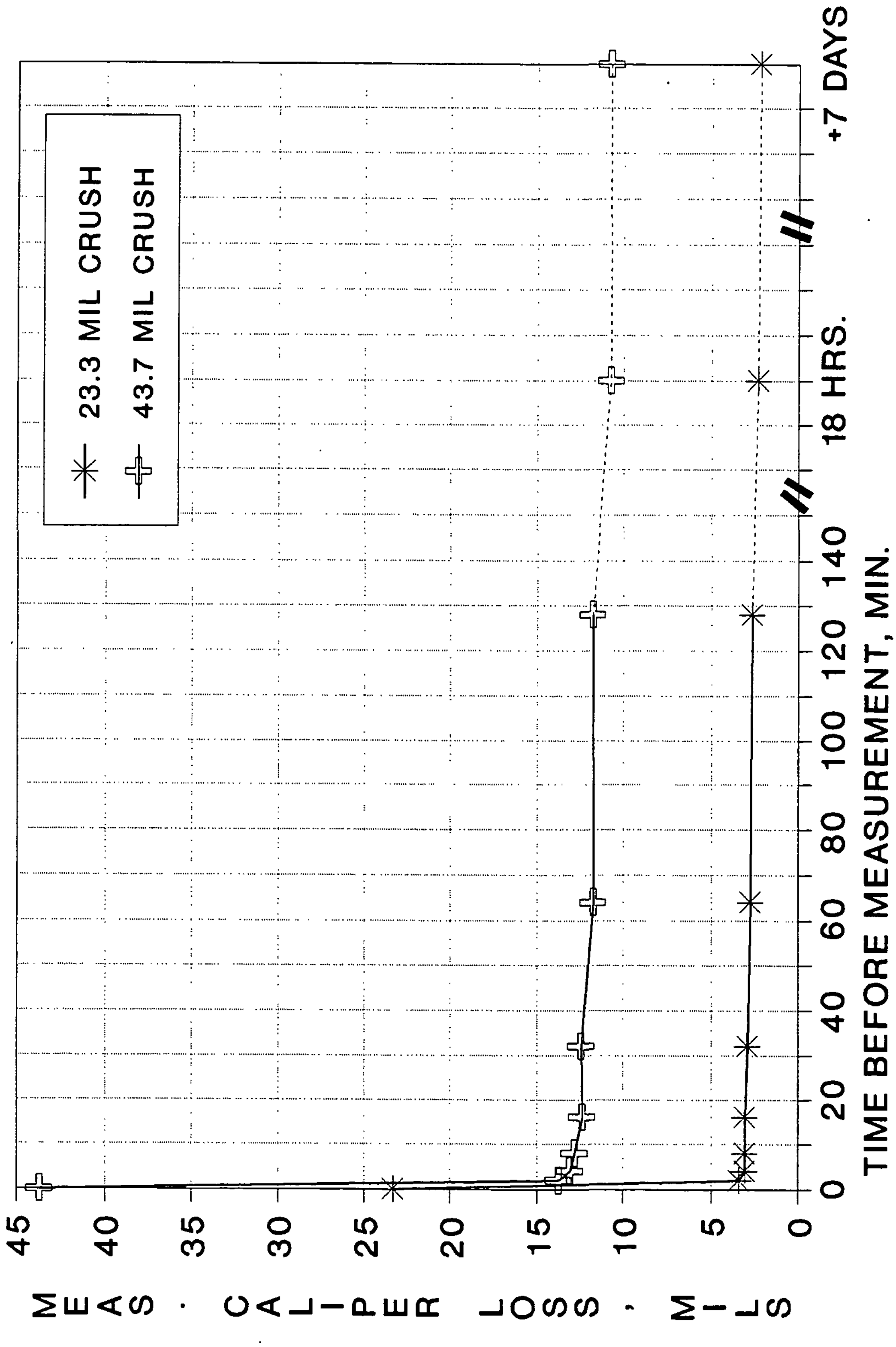
TYPICAL CORRUGATED BOARD FLAT CRUSH
STRESS/STRAIN CURVE FOR A-FLUTE
26 LB/MSF MEDIUM (7, 10)

FIGURE 4



EFFECT OF RECOVERY TIME ON MEASURED CALIPER AFTER CRUSHING

FIGURE 5



ACTUAL CRUSHING TO MEASURED CRUSHING

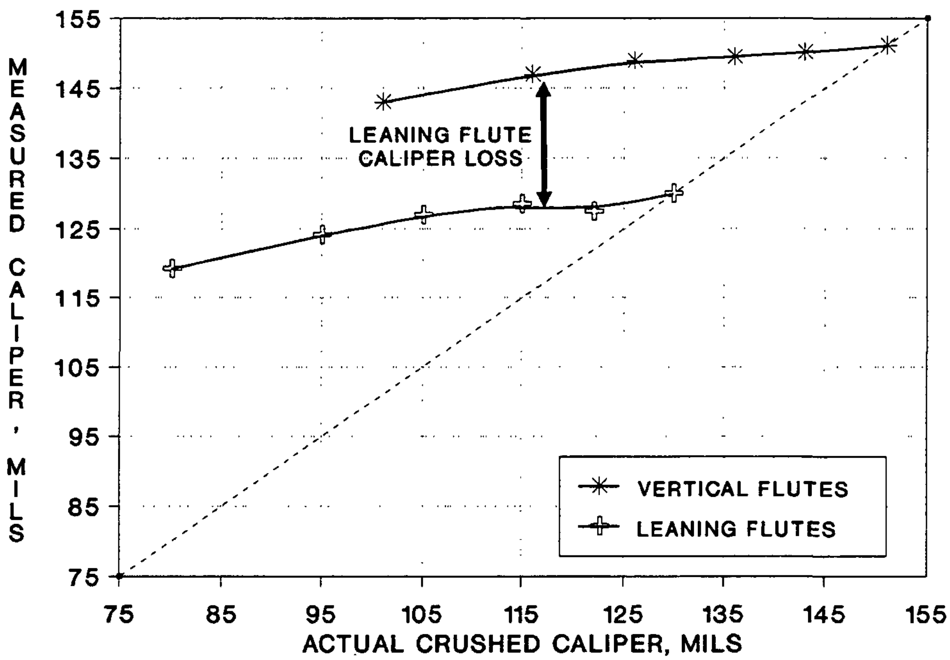
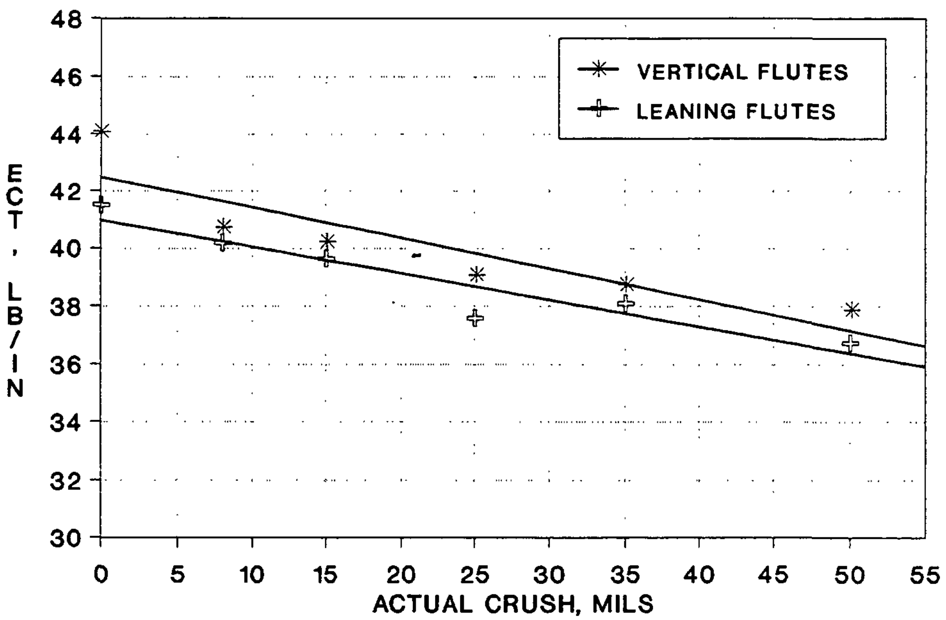


FIGURE 6

EVALUATION OF INTERACTION EFFECTS BETWEEN FLUTE LEAN AND CRUSHING



bottom graph of Figure 6 shows that the loss in ECT due to crushing was identical for both sets of samples, except for the constant offset due to the leaning flute defect. The two regression lines are statistically parallel. These results also demonstrate a second weakness of box plant combined board caliper measurements as a sensitive quality control tool. Caliper measurements, alone, do not differentiate between crushing and leaning flutes.

Multiple regression analysis was performed on the 216 data points. The analysis showed no statistically significant interactions between any of the variables. The best correlation was obtained with a linear multiple regression model. This indicates that the effect of the five process variables, on the average ECT, is independent and additive. The regression equation is given in Figure 7, and a plot of the calculated ECT, using the regression equation, and the measured ECT is shown in Figure 8. The r-squared correlation coefficient was 0.750, and the average, absolute error of the estimated ECT values was 1.52 lb/in. The average 95% confidence limit of the measured ECT values was 1.85 lb/in. This indicates that the regression equation results are as good as can be statistically expected based on the experimental uncertainty of the measured, average ECT.

The regression equation shown in Figure 7 was used to generate the sensitivity plots shown in Figure 9. The pressure roll cutting is not included since it is not a tool that should be used in a box plant to control the average ECT quality. An attempt was made to keep the variable ranges shown on a comparable magnitude basis. The variable ranges shown in Figure 9 are based on a 20% change for crushing and single-face pin adhesion, a 20 percentage point increase in high/low flutes, and a 20 degree increase in leaning flute angle.

The results show that actual crushing is the largest factor, 8.7% average ECT reduction, followed by the single-face (or double-face) pin adhesion bond strength with a 5.5% reduction in average ECT. The comparable high/low flute effect is 2.3%, and the leaning flute effect is 1.7%. The total effect of all five variables at the maximum range shown in Figure 9 is 18.2% average loss in ECT. These loses would have to be compensated for by increased medium or linerboard starting crush strength in order to maintain a constant compression strength performance in the corrugated board.

The compliance probability for Item 222/Rule 41 certification involves both the average ECT and the ECT standard deviation (12). Variability in ECT will also

MULTIPLE LINEAR REGRESSION EQUATION FOR PREDICTING ECT BASED ON BOX PLANT PROCESS VARIABLES

$$\begin{aligned} ECT = {} & 33.71 - 0.0397(LF) + 0.150(SFPA) - 0.0534(H/L) \\ & - 0.134(ACT.\ CRUSH) - 0.130(\%\ MULLEN\ LOSS) \end{aligned}$$

$n = 216 \qquad r^2 = 0.750$

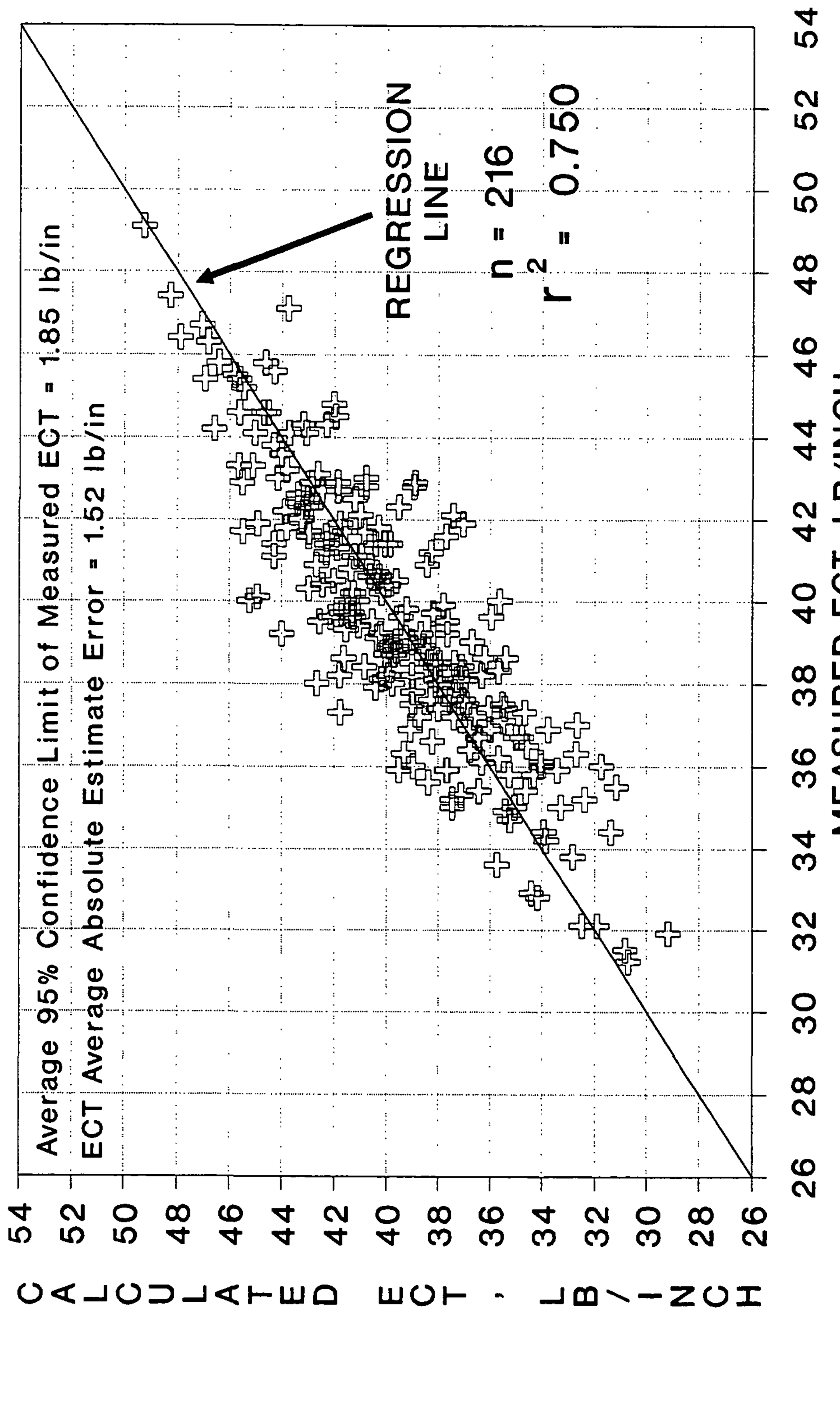
LF = LEANING FLUTE ANGLE, DEGREES.
SFPA = SINGLE-FACE PIN ADHESION, LB.
H/L = HIGH/LOW FLUTES AT 4 MIL OR MORE, %.
ACT. CRUSH = ACTUAL CRUSH OCCURRING, MILS.

$$\%\ MULLEN\ LOSS = \left(\frac{(ACTUAL - HIGHEST)}{HIGHEST}\right)(100)$$

FIGURE 7

COMPARISON OF CALCULATED ECT
TO OBSERVED ECT

FIGURE 8



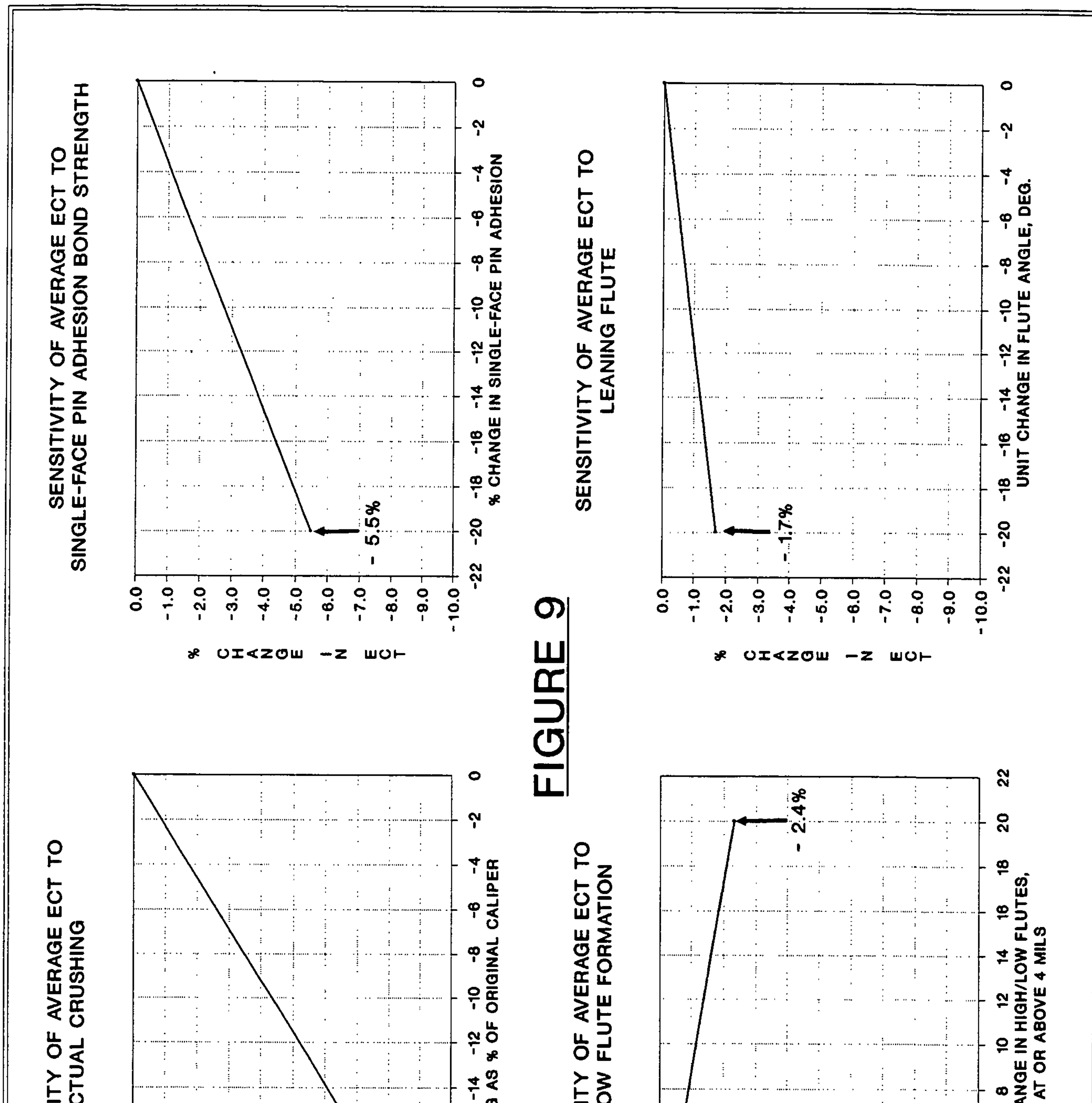

SENSITIVITY OF AVERAGE ECT TO ACTUAL CRUSHING
- 8.7%
CRUSHING AS % OF ORIGINAL CALIPER
% CHANGE IN ECT
SENSITIVITY OF AVERAGE ECT TO SINGLE-FACE PIN ADHESION BOND STRENGTH
- 5.5%
% CHANGE IN SINGLE-FACE PIN ADHESION
SENSITIVITY OF AVERAGE ECT TO HIGH/LOW FLUTE FORMATION
- 2.4%
UNIT CHANGE IN HIGH/LOW FLUTES, % AT OR ABOVE 4 MILS
SENSITIVITY OF AVERAGE ECT TO LEANING FLUTE
- 1.7%
UNIT CHANGE IN FLUTE ANGLE, DEG.

FIGURE 9

result in variable package compressive strength performance. The ECT standard deviation is plotted against the average ECT in Figure 10 for the 216 data points. The regression line is statistically flat indicating no correlation between the two parameters. This indicates that the reduction in average ECT due to the process variables studied does not change the observed standard deviation, provided the defect is evenly and uniformly present throughout the entire sample being tested. The observed standard deviation would increase if the defect was not constant over the entire sample. This is due to the fact that the sample would consist of two or more populations with different average values.

The following is an example of the effect of combined populations on Item 222/Rule 41 ECT certification compliance probability. The example is based on the crushing variable. Assume that a 30,000 box, 32 lb/msf ECT grade, C-flute construction order is being run on a corrugator following a B-flute order. The operator forgets to adjust the double-backer rider roll setting when going from B-flute to C-flute. The first 10,000 sheets are crushed 35 mils before the dry end crew measures a 4.4 mil lower than expected caliper for the grade. The wet end machine tender remembers that he forgot to adjust the rider roll, slaps his forehead, and makes the adjustment. The next 10,000 sheets are run, and the crew sees that the caliper is still running 1.6 mils lower than standard. These sheets were, then, actually crushed 15 mils. The rider roll is again adjusted, and the final 10,000 sheets are run to the standard caliper and without excessive crushing.

Since actual crushing reduces the average ECT, the three actual crushing levels of 35, 15, and 0 mils (measured crush of 4.4, 1.7, and 0 mils) result in populations with three different ECT averages. The 35 mil crushed board averages 31.9 lb/in ECT; the 15 mil crushed board averages 34.4 lb/in ECT; and the zero crushed board averages 36.4 lb/in ECT. Since the crushing does not affect the ECT standard deviation, each of the three populations has the same ECT standard deviation of 2.69 lb/in. The ECT distributions for the three populations are shown in the top graph of Figure 11 and are all normal in shape.

However, the compliance with Item 222/Rule 41 ECT certification is based on all 30,000 boxes in the order. The combined distribution of the three populations is shown in the bottom graph of Figure 11. To the eye, the population appears to be a normal distribution with an average ECT of 34.2 lb/in. The ECT standard deviation,

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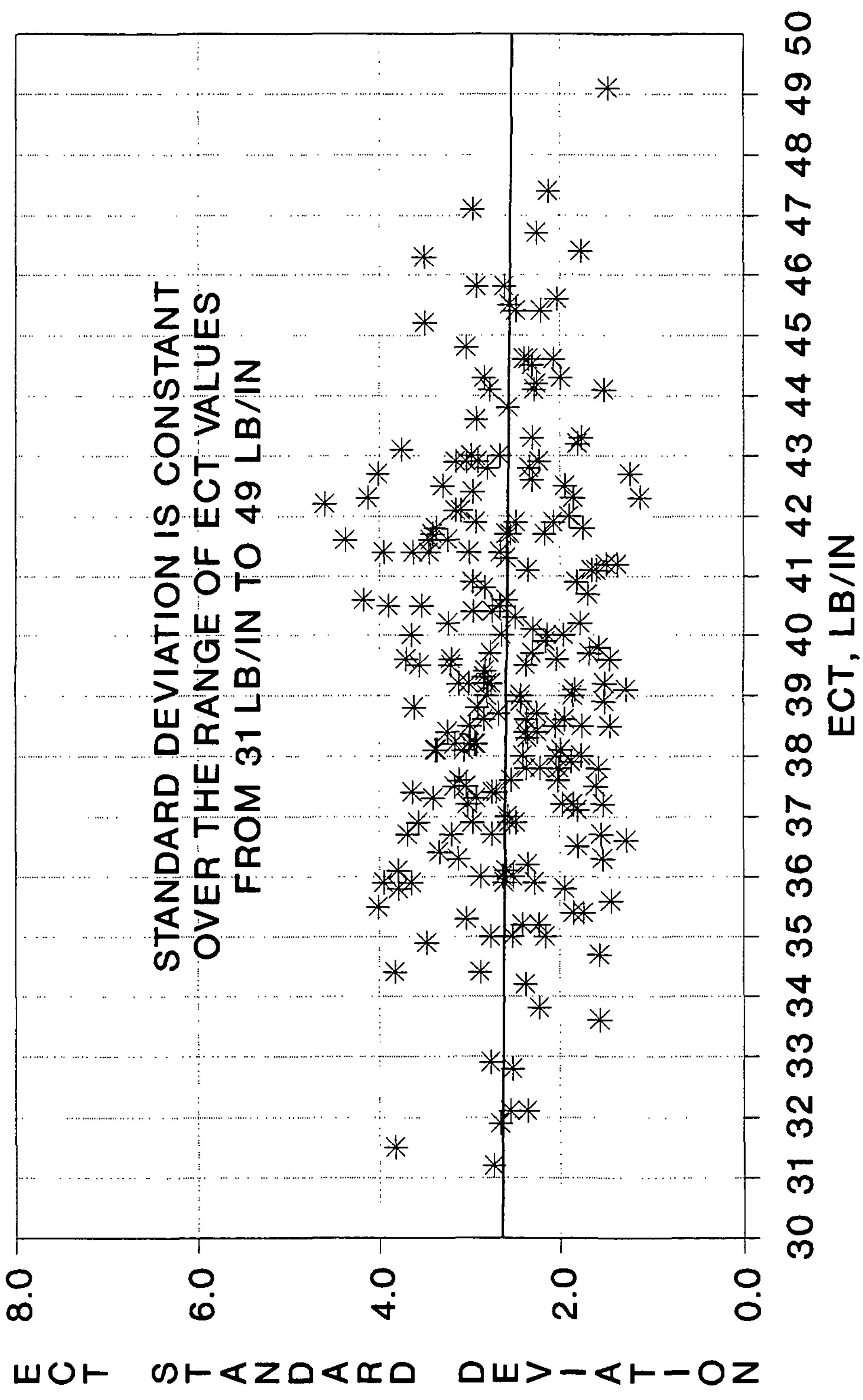
RELATIONSHIP OF AVERAGE ECT TO
ECT STANDARD DEVIATION

FIGURE 10



EXAMPLE OF MULTIPLE DEFECT SITUATION
ON ECT DISTRIBUTION FOR THREE DIFFERENT
CRUSH LEVELS EQUALLY REPRESENTED

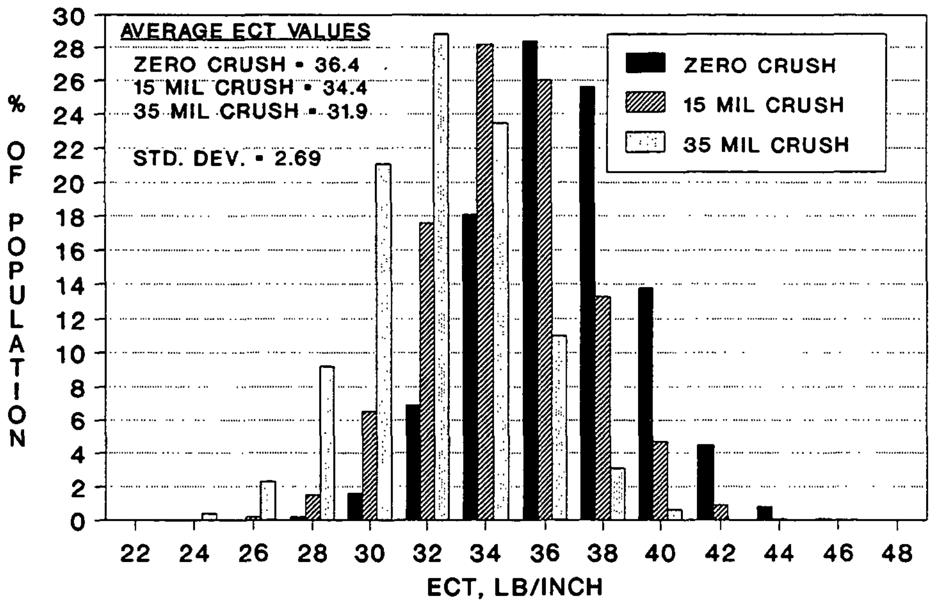
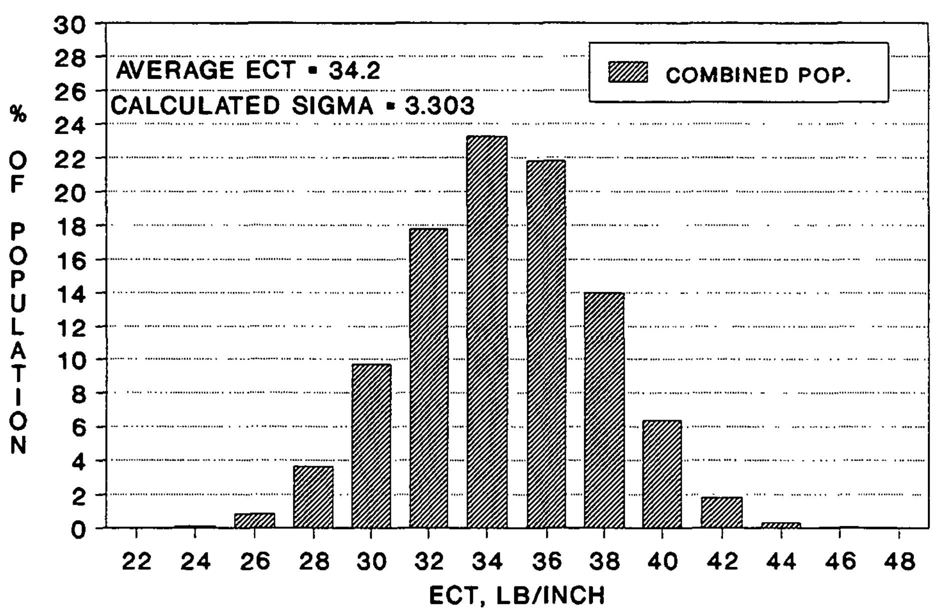


FIGURE 11

EXAMPLE OF MULTIPLE DEFECT SITUATION
ON ECT DISTRIBUTION FOR THREE DIFFERENT
CRUSH LEVELS EQUALLY REPRESENTED



however, is no longer 2.69, but 3.03. This is the effect of combining the three populations.

The average ECT and the ECT standard deviation values can be used to statistically predict the expected Item 222/Rule 41 compliance probability (6). The compliance probability calculations are based on an assumed unbiased sampling from the entire population and are shown in Figure 12. The zero crushed boxes would just achieve a 100% compliance probability. The 15 mil crushed boxes would have a 86% compliance probability, and the 35 mil crushed boxes would have a 10% compliance probability. The compliance probability for the entire population would be 71%, even though the average ECT is equal to that of the 15 mil crushed boxes. The reduction in the compliance probability from 86% to 71% is due to the higher ECT standard deviation, 3.03 versus 2.69.

The same principles described above will also hold for other examples of combined populations. Some other examples that might be expected in a box plant would be localized crushing or high/low flutes occurring in a MD cycle on the corrugator due to a loping roll of medium or to vibration in the single-facer roll stack. Variation in the bond strength due to such factors as nonuniform CD adhesive application rates, an out-of-round adhesive doctor roll, or mottled or ringed adhesive patterns on the glue applicator roll would cause similar ECT multi-population situations.

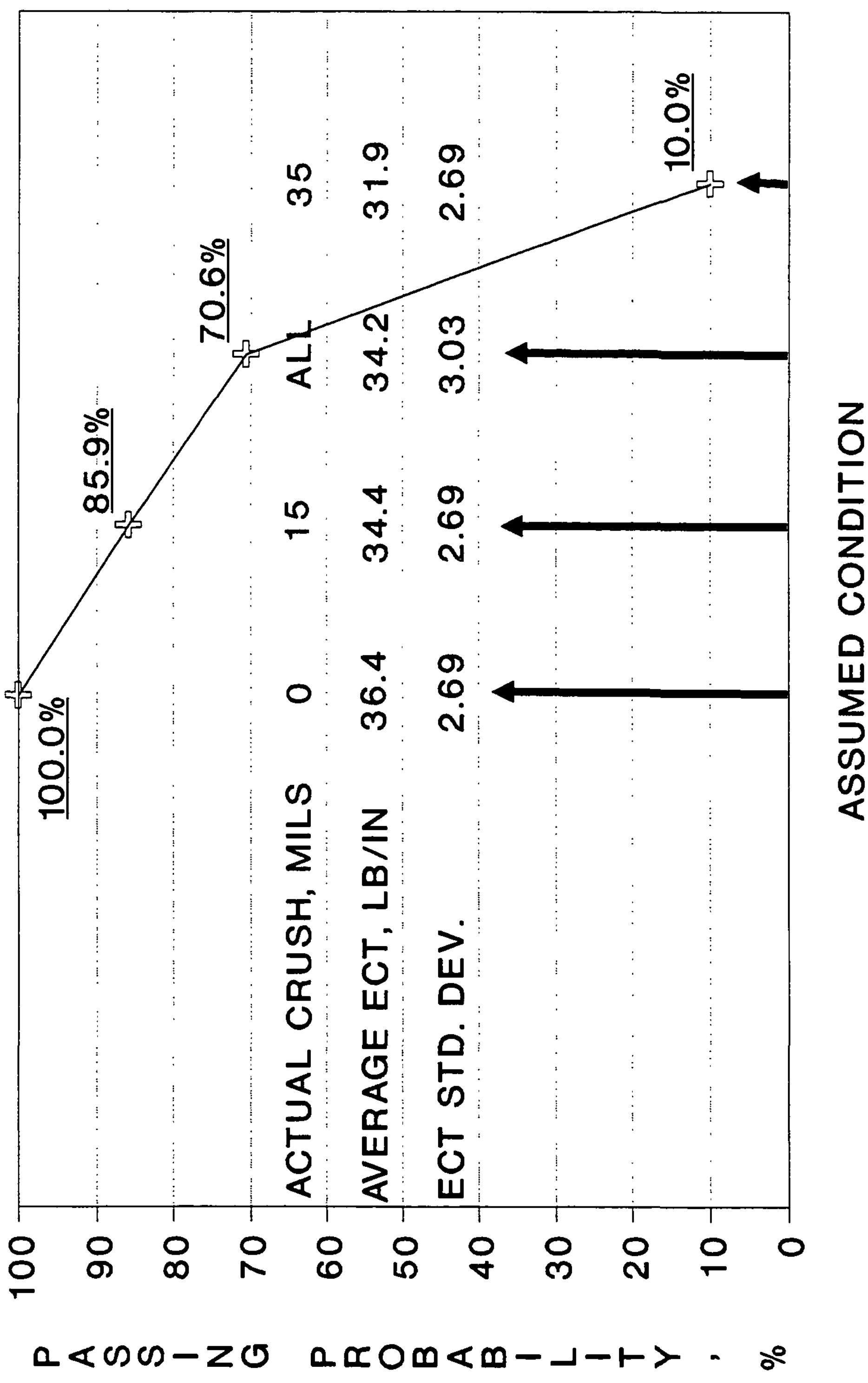
V. Practical Applications.

The ECT of corrugated board is critical to box compressive strength, and is now an alternative specification parameter for Item 222/Rule 41. The ECT has been shown to be determined by the cross machine direction compressive strength of the linerboard and medium and by the quality of the box plant converting processes.

Any excessive loss in ECT due to the converting will result in reduced box compression strength and a reduced probability of Item/Rule compliance, unless the strength of the incoming containerboard is increased to account for the excessive box plant effects. Such a condition could place the box plant in an adverse competitive situation in the marketplace. The converse is also true; a box plant with excellent converting quality may be able to adjust the incoming paperboard material requirements downward and become more competitive. We now live in a "world without basis weight."

THEORETICAL EXAMPLE OF EFFECT OF COMBINED DEFECTS ON ITEM/RULE ECT COMPLIANCE (5/6 & 20/24)

FIGURE 12



The results of this study can assist box plant personnel in developing effective quality control strategies for ECT. It quantitatively defines the most important process variables influencing the ECT. The order of the variables, in decreasing quantitative effect, is actual crushing, corrugator single-face and double-face bond strength, high/low flute formation, and leaning flutes, see Figure 9. Defects such as blisters and fractured flutes are not listed here since they are not variables that can be viewed in terms of degree of quality. Blisters or fracture are either present or not present. If they are present, the board is just not acceptable for compression packaging. Pressure roll cutting is not included since its effect should not be used to influence the ECT.

Caliper measurements of the combined board are not a sensitive method for determining the crushing that has occurred. Spring back of the medium flute structure occurs in less than one minute. A better approach would be to measure the actual gap clearances at the nip points in the process.

Programs to reduce starch adhesive consumption, while a valid objective, should be viewed critically with respect to loss in ECT. Such starch savings are easy to follow in the cost accounting procedures, but the potential ECT loss and its cost in terms of lower compression performance, which is harder to track by accounting methods, may well overshadow the starch savings.

The high/low flute formation is a difficult measurement to make in a current box plant environment. IPST developed a continuous reading, on-line, high/low gauge for use on corrugators. The cost justification for the installation of the gauge should now be considered against the potential ECT savings.

The degree of leaning flute can be easily measured in a box plant by the use of a magnified, flute angle template.

The issue of ECT quality involves both the average ECT and the ECT variability. It is important that any ECT measurement procedures be designed to sample throughout the order so as to get a true representation of the ECT variability. Samples should be equally distributed in the cross machine direction to pick up any CD bias, and equally distributed in the machine direction to pick up any MD cycles. Control charts or other process control methods should track both the ECT average and the ECT variability (range or standard deviation).

A box plant produces many different grades of combined board. A useful technique for normalizing the data over all grades is to use the following two ratios. Equation 1 quantifies the corrugator ECT process quality independent of the starting containerboard crush levels. The goal is to obtain as high a Corrugator Efficiency Ratio as possible.

Corr.Eff. = (Sheet ECT)/(Sum Crush) (Eq.1)

Corr. Eff. = Corrugator Efficiency Ratio.
Sheet ECT = ECT of sheets off corrugator.
Sum Crush = Linerboard crush + draw factor(medium crush). This can be Ring Crush or STFI Crush.

Equation 2 is the ratio of the finished box ECT to the corrugator sheet ECT. This ratio represents the ECT efficiency of the box converting process. This ratio should be as close to 1.0 as possible.

Con.Eff. = (Box ECT)/(Sheet ECT) (Eq.2)

Con.Eff. = Converting process efficiency.
Box ECT = ECT of finished boxes.

VI. Conclusions.

The following major conclusions are supported by the data presented in this report.

1. A lower single-face pin adhesion bond strength, a greater angle of leaning flutes, a greater percentage of high/low flutes, and crushing of the combined board all adversely affect the average Edge Crush Test (ECT). While the effect of the double-face pin adhesion bond strength was not evaluated in this study, there is no reason to suspect that its effect would not be identical to that observed for single-face bond strength.

2. Moderate increases in the pressure roll cutting of the linerboard improved the average ECT. It is hypothesized that this effect can be explained by the decoupling of the stress/strain differences between the linerboard and medium under compression loading. It is not recommended that a box plant use pressure roll cutting to improve the average ECT. Such an action would be detrimental to the ability of the box

to contain and protect the packaged product. The result does indicate that pressure roll cutting should not be a process variable to be included in a box plant ECT improvement strategy. It should be maintained at the same good quality level as was done under the old mullen specifications.

3. None of the process variables affect the within sample ECT standard deviation value when the defect occurs uniformly throughout the combined board. However, localized defects such as nonuniform crushing or variable bond strength will produce a higher effective ECT standard deviation due to the combination of different average ECT populations.

4. No variable interaction effects were found. The effect of the variables is additive and can be modeled by a multiple linear regression equation. The equation is presented in the report. It indicates that the order of influence of the process variables studied, from greatest to least effect, is crushing, bond strength, high/low flutes, and leaning flutes.

5. The degree of crushing determined by caliper measurements in a box plant is not a sensitive quality control method. The medium has a large caliper recovery property, and most of the recovery occurs in less than one minute after crushing. A possible better quality control method would be to measure actual clearances at the pinch points in the box plant process.

6. The documented adverse effect of high/low flutes on the average ECT may justify the installation of a continuously measuring high/low gauge on corrugators. Such a gauge was developed at IPST and is available.

7. The documented adverse effect of low bond strength on the average ECT indicates that the adhesive application systems on the corrugator should be kept in good working order. This includes keeping a uniform adhesive application rate in the cross machine direction, eliminating glue station roll runout problems that will cause machine direction bond strength cycles, and controlling the adhesive properties and the glue station mechanics to avoid adhesive film defects such as mottle and ringing.

8. The influence of the box plant process variables discussed above on the ECT may explain part of the difficulty in developing a universal equation relating ECT to the crush strength of the linerboard and medium.

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APPENDIX A

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIGINAL	CALIPER mils ACTUAL CRUSH	CALIPER mils MEASURED CRUSH	EDGE CRUSH TEST lb/in AVERAGE	EDGE CRUSH TEST lb/in STD. DEV.
238	2.0	98.4	133	0	0	155.7	155.7	155.7	47.4	2.13
						155.7	143	150.0	44.2	2.26
						155.7	136	150.0	43.3	1.77
						155.7	126	148.8	43.8	2.57
						155.7	116	148.3	41.6	4.38
						155.7	101	143.9	42.1	3.16
240	1.4	87.3	132	7	2	151.9	151.9	151.9	45.8	2.62
						151.9	143	149.8	40.0	3.64
						151.9	136	148.4	41.4	2.66
						151.9	126	148.4	40.3	2.50
						151.9	116	148.8	38.6	2.85
						151.9	101	146.2	38.8	3.61
246	1.0	88.5	124	29	11	149.5	149.5	149.5	45.5	2.56
						149.5	143	149.7	40.1	2.30
						149.5	136	149.2	39.2	2.80
						149.5	126	147.0	38.0	2.04
						149.5	116	147.0	39.7	1.68
						149.5	101	142.3	36.3	1.54

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIG-INAL	CALIPER mils ACT-UAL CRUSH	CALIPER mils MEAS-URED CRUSH	EDGE CRUSH TEST lb/in AVER-AGE	EDGE CRUSH TEST lb/in STD. DEV.
225	1.8	61.7	139	0	0	154.1	154.1	154.1	41.7	3.41
						154.1	143	149.9	40.5	3.53
						154.1	136	149.2	39.4	2.83
						154.1	126	150.0	38.7	2.26
						154.1	116	148.5	38.8	2.92
						154.1	101	144.3	36.7	2.75
240	1.5	65.1	130	15	3	148.6	148.6	148.6	42.5	3.30
						148.6	143	149.8	41.4	3.95
						148.6	136	151.1	40.8	2.84
						148.6	126	149.9	38.7	2.68
						148.6	116	146.6	39.2	3.12
						148.6	101	142.1	39.0	2.81
248	1.8	48.4	125	35	19	150.2	150.2	150.2	39.8	1.58
						150.2	143	151.1	38.5	3.00
						150.2	136	150.5	38.5	1.76
						150.2	126	150.2	36.9	2.56
						150.2	116	147.0	37.3	2.93
						150.2	101	141.2	37.0	2.58

Appendix A

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIG-INAL	CALIPER mils ACT-UAL CRUSH	CALIPER mils MEAS-URED CRUSH	EDGE CRUSH TEST lb/in AVER-AGE	EDGE CRUSH TEST lb/in STD. DEV.
232	0.8	33.8	133	0	0	153.7	153.7	153.7	42.8	2.81
						153.7	143	151.6	37.6	2.02
						153.7	136	148.6	37.2	3.02
						153.7	126	149.3	35.8	1.95
						153.7	116	147.6	34.4	3.82
						153.7	101	145.1	32.1	2.55
235	2.0	51.3	135	9	3	150.6	150.6	150.6	42.5	1.94
						150.6	143	151.1	38.1	3.36
						150.6	136	149.5	39.1	1.83
						150.6	126	148.1	38.0	2.41
						150.6	116	148.4	37.2	1.97
						150.6	101	146.0	36.5	1.81
237	1.4	33.6	122	41	23	150.1	150.1	150.1	42.1	3.10
						150.1	143	148.8	36.7	3.20
						150.1	136	148.2	37.1	1.81
						150.1	126	146.7	32.8	2.53
						150.1	116	146.3	33.8	2.23
						150.1	101	144.4	31.5	3.82

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIG-INAL	CALIPER mils ACT-UAL CRUSH	CALIPER mils MEAS-URED CRUSH	EDGE CRUSH TEST lb/in AVER-AGE	EDGE CRUSH TEST lb/in STD. DEV.
235	20.0	83.8	142	0	0	133.3	133.3	133.3	42.9	3.04
						133.3	122	128.4	43.6	2.93
						133.3	115	127.6	44.1	1.52
						133.3	105	128.0	41.9	2.49
						133.3	95	126.4	41.4	3.01
						133.3	80	120.7	40.9	2.98
230	15.6	78.2	136	7	2	131.1	131.1	131.1	44.1	2.78
						131.1	122	128.7	43.2	1.81
						131.1	115	130.3	42.3	1.13
						131.1	105	128.1	39.3	2.84
						131.1	95	127.6	39.2	1.51
						131.1	80	120.4	36.6	1.28
235	15.7	74.5	132	29	11	129.7	129.7	129.7	44.1	2.28
						129.7	122	129.3	40.9	1.82
						129.7	115	129.4	37.3	3.40
						129.7	105	127.9	37.9	1.88
						129.7	95	126.2	36.9	2.97
						129.7	80	120.8	35.3	3.04

Appendix A

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIG-INAL	CALIPER mils ACT-UAL CRUSH	CALIPER mils MEAS-URED CRUSH	EDGE CRUSH TEST lb/in AVER-AGE	EDGE CRUSH TEST lb/in STD. DEV.
220	25.1	59.8	141	0	0	127.7	127.7	127.7	39.5	2.37
						127.7	122	126.4	38.2	3.01
						127.7	115	128.6	41.7	2.55
						127.7	105	125.7	35.9	2.28
						127.7	95	121.1	39.2	3.01
						127.7	80	116.5	38.6	2.37
229	22.2	58.8	139	15	3	129.6	129.6	129.6	42.9	3.16
						129.6	122	128.0	38.4	3.25
						129.6	115	128.9	38.2	3.17
						129.6	105	125.8	38.9	2.44
						129.6	95	124.2	38.1	3.07
						129.6	80	118.1	34.7	1.57
236	22.2	41.1	133	35	19	130.1	130.1	130.1	38.5	1.46
						130.1	122	127.1	37.5	3.17
						130.1	115	129.0	39.6	3.70
						130.1	105	127.6	35.4	1.74
						130.1	95	125.5	35.0	2.53
						130.1	80	122.8	34.4	2.89

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIGINAL	CALIPER mils ACTUAL CRUSH	CALIPER mils MEASURED CRUSH	EDGE CRUSH TEST lb/in AVERAGE	EDGE CRUSH TEST lb/in STD. DEV.
238	27.4	29.5	133	0	0	126.5	126.5	126.5	38.1	3.38
						126.5	122	125.0	38.2	2.93
						126.5	115	125.4	38.6	1.95
						126.5	105	123.6	36.0	2.52
						126.5	95	119.1	36.3	3.13
						126.5	80	117.7	31.2	2.74
231	23.0	44.2	133	9	3	125.7	125.7	125.7	42.3	1.85
						125.7	122	127.0	38.2	2.95
						125.7	115	124.5	38.4	2.25
						125.7	105	123.0	36.4	3.34
						125.7	95	123.2	37.4	2.75
						125.7	80	116.2	35.2	2.23
242	23.4	28.8	127	41	23	127.6	127.6	127.6	37.5	3.04
						127.6	122	124.9	36.7	1.55
						127.6	115	126.2	34.2	2.38
						127.6	105	126.0	32.1	2.36
						127.6	95	119.6	35.5	4.01
						127.6	80	115.9	31.9	2.66

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb		HIGH/LOW FLUTES %		CALIPER mils			EDGE CRUSH TEST lb/in	
		SF	DF	@3 MILS	@4 MILS	ORIGINAL	ACTUAL CRUSH	MEASURED CRUSH	AVERAGE	STD. DEV.
219	2.7	98.1	135	0	0	153.2	153.2	153.2	49.1	1.48
						153.2	143	149.0	46.4	1.77
						153.2	136	149.3	45.4	2.49
						153.2	126	151.0	44.6	2.35
						153.2	116	146.8	45.6	2.03
						153.2	101	142.2	41.6	3.24
236	2.8	75.5	129	24	5	148.8	148.8	148.8	45.8	2.93
						148.8	143	152.6	42.2	4.60
						148.8	136	152.2	41.7	2.17
						148.8	126	149.1	41.7	2.59
						148.8	116	144.9	40.6	4.18
						148.8	101	141.5	41.2	1.38
233	1.0	89.8	124	27	9	153.2	153.2	153.2	46.3	3.50
						153.2	143	148.2	45.2	3.49
						153.2	136	149.6	44.6	2.40
						153.2	126	148.2	44.3	1.99
						153.2	116	144.9	42.7	1.24
						153.2	101	139.5	41.4	3.45

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIG-INAL	CALIPER mils ACT-UAL CRUSH	CALIPER mils MEAS-URED CRUSH	EDGE CRUSH TEST lb/in AVER-AGE	EDGE CRUSH TEST lb/in STD. DEV.
219	1.7	61.3	134	0	0	151.5	151.5	151.5	47.1	2.97
						151.5	143	150.9	43.1	3.75
						151.5	136	150.2	39.7	2.31
						151.5	126	150.1	40.7	1.70
						151.5	116	147.9	39.0	1.86
						151.5	101	144.0	41.9	2.94
213	2.7	63.5	133	18	4	150.1	150.1	150.1	43.0	2.67
						150.1	143	153.1	42.0	1.90
						150.1	136	149.5	41.2	1.50
						150.1	126	150.0	41.1	1.61
						150.1	116	146.3	40.5	3.90
						150.1	101	141.9	39.5	3.21
225	1.2	59.8	118	37	24	148.1	148.1	148.1	44.5	2.31
						148.1	143	147.6	40.2	1.78
						148.1	136	149.0	40.5	2.67
						148.1	126	149.5	37.8	2.01
						148.1	116	144.7	41.6	3.43
						148.1	101	139.6	38.3	2.36

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIG-INAL	CALIPER mils ACT-UAL CRUSH	CALIPER mils MEAS-URED CRUSH	EDGE CRUSH TEST lb/in AVER-AGE	EDGE CRUSH TEST lb/in STD. DEV.
203	0.6	45.6	129	3	1	150.5	150.5	150.5	44.3	2.84
						150.5	143	150.6	39.6	1.46
						150.5	136	149.9	39.1	1.28
						150.5	126	147.9	37.5	1.61
						150.5	116	146.8	35.9	3.95
						150.5	101	145.5	36.2	2.36
221	1.4	44.3	131	18	6	149.7	149.7	149.7	43.0	2.99
						149.7	143	149.9	38.9	1.52
						149.7	136	148.2	37.8	1.58
						149.7	126	149.0	35.9	3.64
						149.7	116	145.9	36.1	3.76
						149.7	101	141.6	35.8	3.78
220	1.3	43.9	122	41	22	149.9	149.9	149.9	40.4	2.75
						149.9	143	147.3	38.5	2.05
						149.9	136	147.2	38.1	1.99
						149.9	126	146.5	36.9	2.49
						149.9	116	147.3	34.9	3.47
						149.9	101	141.8	35.9	2.62

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIG-INAL	CALIPER mils ACT-UAL CRUSH	CALIPER mils MEAS-URED CRUSH	EDGE CRUSH TEST lb/in AVER-AGE	EDGE CRUSH TEST lb/in STD. DEV.
218	21.4	88.1	145	0	0	132.7	132.7	132.7	46.7	2.26
						132.7	122	129.7	45.4	2.21
						132.7	115	128.8	44.6	2.07
						132.7	105	128.7	42.4	2.97
						132.7	95	125.3	44.8	3.04
						132.7	80	121.0	41.4	3.62
222	20.8	72.7	136	24	5	131.2	131.2	131.2	41.1	2.36
						131.2	122	128.6	42.3	4.13
						131.2	115	131.2	39.6	2.03
						131.2	105	128.3	42.8	2.34
						131.2	95	126.0	39.6	3.21
						131.2	80	121.2	35.0	2.16
227	15.6	80.1	133	27	9	131.9	131.9	131.9	43.3	2.31
						131.9	122	128.4	41.8	3.37
						131.9	115	129.2	42.9	2.23
						131.9	105	129.3	40.0	2.65
						131.9	95	124.9	40.2	3.24
						131.9	80	120.6	39.7	2.78

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIGINAL	CALIPER mils ACTUAL CRUSH	CALIPER mils MEASURED CRUSH	EDGE CRUSH TEST lb/in AVERAGE	EDGE CRUSH TEST lb/in STD. DEV.
206	19.6	68.8	137	0	0	133.4	133.4	133.4	41.9	2.07
						133.4	122	128.9	42.6	2.31
						133.4	115	133.7	40.4	2.97
						133.4	105	130.7	40.0	1.96
						133.4	95	127.0	38.0	1.77
						133.4	80	122.5	39.9	2.16
225	19.2	60.9	137	18	4	131.2	131.2	131.2	42.7	4.01
						131.2	122	129.6	41.1	1.66
						131.2	115	131.1	41.8	1.75
						131.2	105	130.0	36.0	2.64
						131.2	95	125.9	39.2	2.76
						131.2	80	121.6	40.0	2.14
218	16.5	60.8	129	37	24	131.4	131.4	131.4	41.3	2.60
						131.4	122	128.2	40.6	2.60
						131.4	115	128.8	38.7	2.37
						131.4	105	130.1	35.6	1.45
						131.4	95	125.4	37.6	2.54
						131.4	80	121.1	36.7	3.68

COMBINED BOARD TEST DATA

BURST psi	FLUTE ANGLE deg.	PIN ADHESION lb SF	PIN ADHESION lb DF	HIGH/LOW FLUTES % @3 MILS	HIGH/LOW FLUTES % @4 MILS	CALIPER mils ORIG-INAL	CALIPER mils ACT-UAL CRUSH	CALIPER mils MEAS-URED CRUSH	EDGE CRUSH TEST lb/in AVER-AGE	EDGE CRUSH TEST lb/in STD. DEV.
200	25.2	39.4	137	3	1	128.7	128.7	128.7	39.5	3.55
						128.7	122	125.6	39.0	2.43
						128.7	115	126.2	37.2	1.53
						128.7	105	123.8	37.2	1.85
						128.7	95	122.1	37.4	3.63
						128.7	80	116.5	36.1	2.60
214	23.6	35.1	133	18	6	128.8	128.8	128.8	42.9	2.82
						128.8	122	127.0	37.4	2.71
						128.8	115	126.6	38.4	2.38
						128.8	105	125.4	33.6	1.57
						128.8	95	121.8	32.9	2.77
						128.8	80	117.3	35.2	2.42
206	22.9	33.6	126	41	22	129.1	129.1	129.1	37.6	3.12
						129.1	122	125.5	37.8	2.22
						129.1	115	127.6	35.4	1.85
						129.1	105	122.8	35.0	2.77
						129.1	95	122.8	36.9	3.56
						129.1	80	115.0	36.0	2.89