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A Comparative examination of the physical properties of recycled, high-performance and virgin-kraft linerboards and combined boards

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A Comparative Examination of the Physical Properties of Recycled, High-Performance and Virgin-Kraft Linerboards and Combined Boards

By
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CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

The M.S. degree thesis of Jeffrey D. Vilenski

has been examined and approved

by the thesis committee as satisfactory

for the thesis requirements for the

Master of Science Degree

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Dr. Daniel Goodwin	**Date**
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Jeffrey D. Vilenski Date

Acknowledgments

There were many individuals who made this endeavor a success. First, I wish to thank my committee members. Especially, I appreciate the efforts of Vern Kauffman who nurtured my interest in corrugated and helped me develop this thesis topic. This research is indebted to the Southern Container Corporation which provided me with samples for testing. Also, I extend my gratitude to John Siy who helped with testing, and Jim Bodenstedt who gave me the incentive to complete this project on time.

Abstract

The most recent advances in corrugated quality involve the use of recycled linerboard. Recycled linerboard has improved by both enhancing the quality of the source pulp and refinements in the recycling process itself. This examination compared both linerboard and combined board using 100% recycled pulp, virgin-kraft material, as well as a high-performance material.

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Glossary

Combined Board (CB)

- Linerboard and mediums combined (converted) into finished corrugated.

Corrugated Medium

- A sheet of corrugating material that has been softened with steam and pressed into the wave shape known as flutes.

Die Cut

- A cut made with a die. This technique is employed when non-perpendicular cuts are needed, and/or exacting tolerances.

High-Performance

- Also known as high ring-crush liners. Paper using increased refining and chemical additives to increase performance without increasing weight.

Linerboard (LB)

- Paper used for the flat outer facings of combined corrugated.

Regular Slotted Container (RSC)

- Container with all flaps the same depth and the two outer flaps are one-half the container's width so that they meet at the center of the box.

Introduction

Introduction

Although the fundamentals of both corrugated design and board manufacture have remained unchanged since their origins over 100 years ago, technology has enhanced the capabilities of corrugated exponentially. Developments in adhesives, inks, waxes and other coatings have contributed to an array of new applications. Breakthroughs in printing and corrugator techniques have reduced board crush and increased productivity. The most recent advances in corrugated quality involve the use of recycled linerboard (LB) and the resulting combined board (CB). Recycled board has improved by both enhancing the quality of the source pulp and refinements in the recycling process itself.

Problem Statement

These advances seem to show evidence of increased performance on a purely observational level, but from a measurable and statistical view point, how do these new recycled CBs perform? In particular, how do these advanced recycling techniques improve corrugated characteristics as compared to standard kraft and high-performance CBs?

Background (Need for the Study)

An understanding of the physical properties of a given LB is extremely important for both corrugated manufacturers and users. Over-packaging or under-packaging result from a lack of understanding of the strengths and weaknesses of the paper employed. The variables that typically merit investigation include internal tear, vertical compression strength, tensile strength, and caliper. Users constantly grapple with these variables, debating for example, "Can we substitute 35 pound high-density board for straight 42 pound basis weight kraft?" Currently, the newest issue to face purchasers is "Can we downgrade from 35 pound high-density LB to CB using recycled liners?"

Significance

A few studies do exist that compare the qualities of recycled LB and virgin kraft LB. However, these studies were conducted in the 1970's and early to middle 1980's which voids them as being valid indicators of current CB output due to advances in technology. Further, the literature review has demonstrated that no independent and practical research has been published that applies to the current concerns of manufacturers, buyers, or users of corrugated products.

This endeavor will increase the body of knowledge in the area of both LB and CB performance characteristics. Manufacturers will better understand their own products, as well as gain a more informed view of their competitor's goods. Users and buyers will become more informed about their packaging choices and be able to maximize their efforts.

Nature of the Study

This study compares the physical properties of three different types of LB: recycled, high-performance, and virgin kraft. The analysis allows for two differences to be examined. First, it will show if recent technological enhancements in the recycling and fabrication processes enhance the physical properties of the LB and CB. Second, because all three LB types would be made into CB by the same company under essentially equal conditions, a fair comparison can be made about the vertical compression strength of each. This study involves correlational research.

Literature Review

Currently, high-performance and recycled LB are increasing in usage. In fact, recycled LB capacity will more than double between 1993 and 1996 (Pace, p. 8). It is interesting that only a few documents are available comparing high-performance, recycled and kraft LB and CB. Although research does exist which evaluates each of these materials, these studies typically isolate and examine variables which cannot be controlled in real-life, including moisture and temperature. As a practical (versus a theoretical) examination this thesis is not able to draw upon many of the existing references.

However, an influential study was performed in 1975 by J. W. Koning, Jr. and W. D. Godshall. The study *Repeated Recycling of Corrugated Containers and its Effect on Strength Properties* was one of the earliest studies examining the properties of recycled LB. The authors concluded that in general, the strength and performance of CB lowered when recycled fiber was used. Further, it was determined that the greatest decrease in performance occurred between the virgin material and the first recycling process rather than between subsequent recycles.

Additional research was provided by R. A. Horn in his work titled "What are the Effects of Recycling on Fibre and Paper Properties?" His testing demonstrated that as the number of recycles increased, the length of the LB fibers decreased.

This research, in part, lead to "Recycled Fibers in Corrugated Fiberboard Containers" by D. J. Fahey and D. W. Bormett. In this examination, pulp combinations and process variables were studied to understand how they affect both the recyclability and physical properties of CB. It was determined that the strength properties of LB and CB decreased as the percentage of recycled fiber increased which mirrored the findings of Koning and Godshall.

In addition to the previous analyses, the foundation material provided in sources such as the *Fibre Box Handbook* and the reference volumes by George G. Maltenfort lead to the article by Alfred H. McKinlay titled "Commodity or Performance Specified? Corrugated Boxes." This composition explored many of the issues discussed in this thesis, including the ability of a corrugated user or supplier to substitute LB grades. McKinlay explained why it was important to understand the distribution environment to make an informed decision regarding LB and CB selection. He also detailed the value of knowing the differences between high-performance and kraft LBs.

This thesis builds upon the work of McKinlay by actually evaluating the three primary alternatives for LB and CB (kraft, high-performance and recycled) and associating specific performance data with them. This work will further encourage a more informed corrugated selection-process.

Design of the Study

Hypothesis

The hypothesis is that recycled LB will not demonstrate physical properties exceeding those of virgin kraft. Similarly, high-performance CB will not out-perform virgin kraft CB according to vertical compression tests. This is essentially contrary to the conventional wisdom within the corrugated industry.

Assumptions

Even though both accuracy and consistency have been considered, this research contains numerous opportunities to introduce error, and therefore some sweeping, albeit justified, assumptions are required.

Little within the corrugated environment can be controlled. For example, dimensional tolerances are typically ± 3/16 inch. Moisture content is even more difficult to govern. Corrugated board is at the mercy of the weather in terms of humidity in the plant, on the delivery truck, and at the end-user's site.

The first assumption of this thesis is that the moisture content of all three LBs and CBs are approximately equal. Sufficient time was allowed for the samples to reach the same environmental conditions to decrease variability. Also, each test was completed at approximately the same time for each paper grade to insure similar conditions.

The second assumption in this research is that the LB and the subsequent CB were formed under the same conditions. Due to the nature of the corrugated manufacture at Southern Container Corporation (which is similar to most other operations), it is almost impossible to have each material type created at the same time, under identical conditions. One can only make the determination that under the parameters of corrugated acceptability, the samples should be considered the same. Also, since the LB was not from the same lot as the resulting CB, this brings into question whether or not the sample LB is representative of the paper used in the CB. Once again, with the wide range of acceptability within the corrugated industry, these small variances should not be particularly important.

Scope and Limitations

This research will determine within limited test parameters, if 100% recycled LB and CB perform at a level which is competitive with either high-performance or virgin kraft materials.

Influencing factors which are not included in this testing include moisture, time, printing, coatings, wax impregnation, or different adhesives. These were not included because this thesis attempts to provide direction for both corrugated users and providers on a general, practical level only.

An Edge Crush Test was not performed as part of this study because the test of the compression strength of the RSCs essentially examine the same physical characteristics.

Procedure

The testing which was conducted in this research included or was influenced by the following American Society for Testing and Materials Test Standards:

ASTM D 528-87	Standard Test Method for Machine-Direction of Paper and Paperboard
ASTM D 585-86	Standard Method for Sampling and Accepting a Single Lot of Paper, Paperboard, Fiberboard or Related Product
ASTM D 642-90	Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads
ASTM D 645-92	Standard Test Method for Thickness of Paper and Paperboard
ASTM D 646-92	Standard Test Method for Grammage of Paper and Paperboard
ASTM D 689-92	Standard Test Method for Internal Tearing Resistance of Paper
ASTM D 828-87	Standard Test Method for Tensile Breaking Strength of Paper and Paperboard
ASTM D 996-92	Standard Terminology of Packaging and Distribution Environments

To conduct these tests, the Southern Container Corporation in Camilus, New York agreed to provide the needed samples. The reason Southern Container was chosen is that they have recently opened a state-of-the-art recycling mill producing 100% recycled LB. The liners that were examined were 35 pound basis weight high-performance (claimed as a ring-crush equivalent to 42 pound basis weight LB), 42 pound basis weight recycled, and 42 pound basis weight virgin kraft. These three grades were chosen because 42 pound basis weight is the most commonly used LB (Bakker, p. 66). The samples were received in three forms: LB, CB and regular slotted containers (RSCs). With a sufficient number of tests (minimum of 30) and following ASTM guidelines, a statistically valid comparison can be drawn between the new recycled board and the standard virgin kraft. The high-performance board was analyzed simply as a reference against virgin kraft and recycled liner since it is only expected to be comparable to the other two papers in stacking strength.

The testing facilities used in this analysis was the Packaging Science Laboratories at the Rochester Institute of Technology, Rochester, New York. The statistical analysis for this research used Minitab (Release 8) software. A significance level of .05 was chosen.

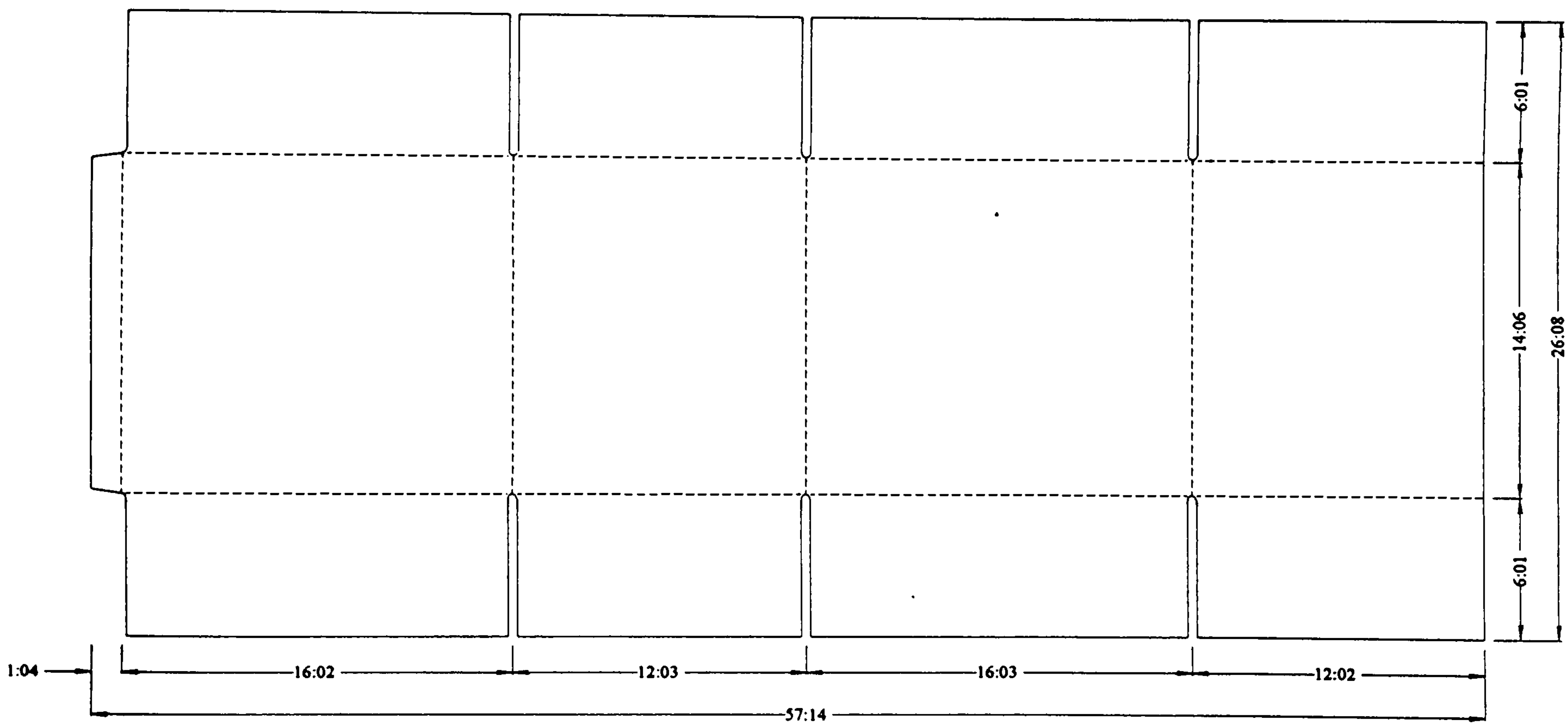
The next drawing is the specification of the corrugated carton that was fabricated (Figure 1.0).

Southern Container Corporation

STYLE RSC		BOARD 200C-	LINERS 42 - 26SC - 42 - -		
CUSTOMER QUOTE	CUST. NO. 2	DESIGN NO. 940628	REV. NO.	I.D. SIZE 16:00 x 12:00 x 14:00	JOINT GLUE INSIDE
IDENT. THESIS CARTON	SALESPERSON HOUSE	BLANK SIZE 26:08 CORR. x 57:14		DATE 10/21/94	DRAWN BY KAUFFMAN

1.DESIGN NOTES: THESIS CARTON FOR JEFF VILENSKI

2.DESIGN NOTES:



Statistical Analysis

Basis Weight and Caliper

The basis weight and caliper tests showed that the given samples were acceptable and statistically similar for evaluation purposes.

Although not enough data was collected to perform an ANOVA test on the basis weights of the three different papers (combined and as linerboard), the data clearly shows that the analyzed samples were acceptable:

Combined Board Samples	Mean Basis Wt of Both Liners (Lbs/1000ft^2)
High-Performance	35.2
Kraft	41.6
Recycled	42.2

Linerboard Samples	Basis Weight (Lbs/1000ft^2)
High-Performance	34.7
Kraft	42.5
Recycled	43.1

Figure 2.0

Compression Strength

The compression values for the combined board show a dramatic difference among the three corrugated grades.

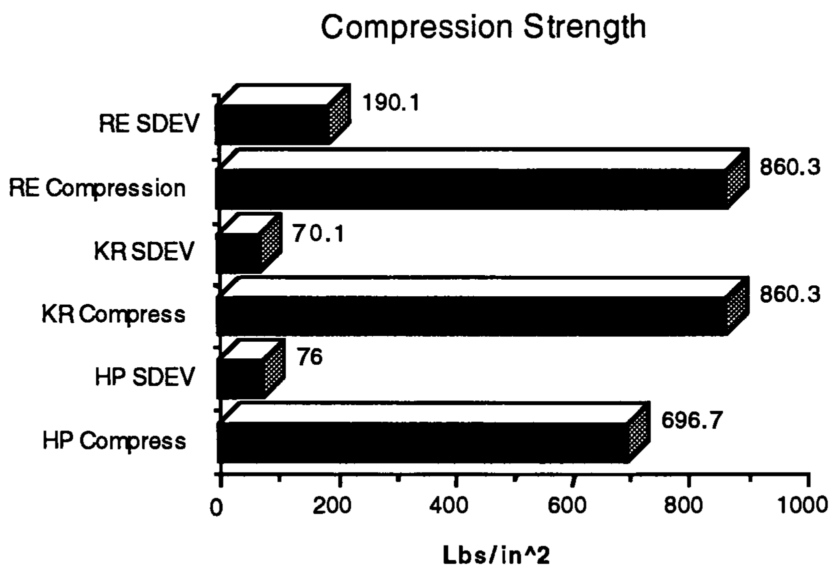


Figure 3.0

As was expected, kraft LB exceeded the compression strength of the other LBs. It also had the tightest tolerance. The second highest ranking corrugated was the recycled CB. This scored surprisingly well when comparing the mean and median values. However, the standard deviation for the recycled CB was not as favorable. The standard deviation equaled 190.1 which is slightly more than 114 pounds greater than the high-performance grade and 120 pounds greater than that of the kraft corrugated. The increased standard deviation means that, according to Chebyshev's theorem, the user can be 95% confident that the range for the compression strength of recycled corrugated falls below that of the high-performance board. The wide variance of recycled board is indicative of the problems with source consistency in recycling operations. The high-performance board had approximately the same tight tolerance as the kraft, but it displayed a far weaker compression strength. The median compression value for the high-performance board was 200 pounds less than that of the kraft corrugated.

Internal Tear Strength

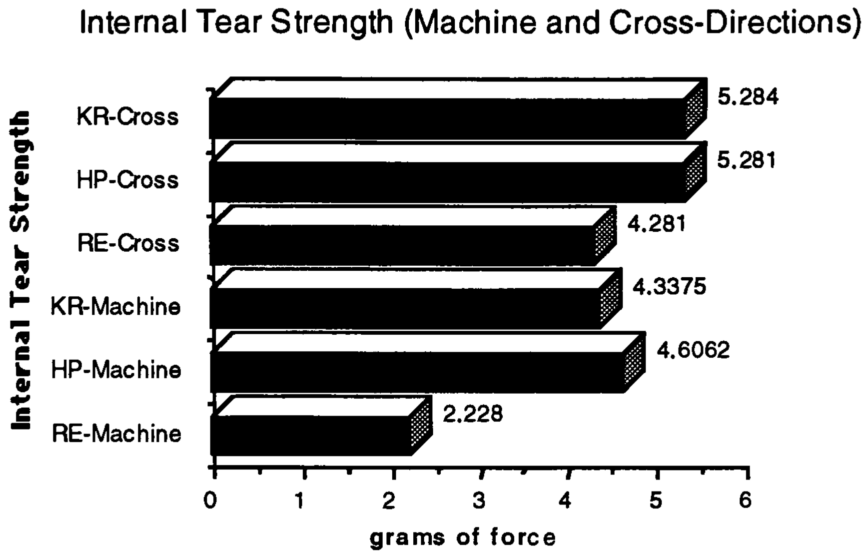


Figure 4.0

As expected, in each of the three samples of LB the cross-direction was stronger than the machine-direction. Following the analysis of the compression strength, it makes sense that the kraft LB also has the strongest internal tear values (see Figure 25.0). In fact, the machine-direction values for kraft exceeded the cross-direction strength values for the recycled LB. The tolerances for the kraft remained far tighter than the recycled and moderately closer than the high-performance LB. Although the mean and median values for the high-performance paper placed this group in second place, the high standard-deviation for internal tear may explain the trailing results of the compression strength analysis. As the strength from high-performance LB comes in part from greater attention to fiber orientation, it is important to note that the difference of machine-direction and cross-direction strength is smallest for the high-performance LB.

Tensile Strength

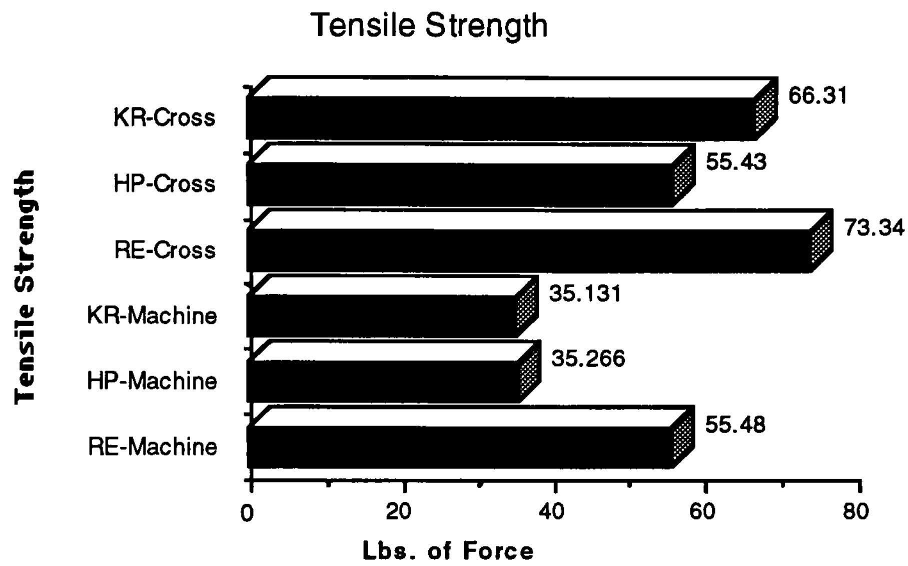


Figure 5.0

The recycled LB rated highest in both the machine-direction and cross-direction. However, it did possess a high variance in the machine-direction compared to kraft and high-performance LB. This high variance mirrors the results of the other tests. The high-performance LB rated well, with small standard deviations. The kraft LB rated lowest in the machine-direction with 35.131 mean pounds of force. In the cross-direction, which is most important for compression strength, the paper demonstrated a 66.31 mean tensile strength.

Sources of Error

While this research was focused on both accuracy and consistency in the data collection, it contains numerous opportunities to include error. However, it should be noted that the error factors contained in this thesis are comparable to the uncertainty which exists in both the corrugated environment as well as its subsequent distribution system. Little within the corrugated world is controlled. For example, humidity control is seldom employed, and LB is frequently converted without prior testing to determine its quality.

Moisture Content

The first source of error is humidity. Although ample time was allowed for the LB and the resulting CB to assimilate to the same environmental conditions, the exact moisture properties were not determined. It is possible that one or more of the LBs or CBs contained more moisture than the others.

Material Variability

Second, the CB was not made from the same LB as was tested. In the corrugated environment, it is too difficult to collect samples of LB just prior to CB being formed due to the high speed of the process. This brings into question whether or not the LB is representative of the LB used in the CB. With the reasonably variable tolerances which the corrugated industry considers acceptable, these small variances should be considered negligible.

Sample Variability

Finally, the samples were hand-made. Although this increased the consistency versus machine-fabricated cartons, it should be noted that the compression strength of corresponding machine-run cartons would be less, because of increased processing and handling.

Summary

Overall, the data shows that virgin kraft fibers are currently still the strongest and afford the corrugated user the greatest physical strength. Further, the quality virgin source material contributed to the tightest tolerances of the three materials. Recycled LB demonstrated favorable results, although the high variability must be taken into consideration when specifying corrugated strength needs. The high-performance paper also performed well, considering the basis weight difference.

The solution for effective corrugated selection is to know what physical properties are needed from a carton and what can be provided by the available CB. When CB strength is not a paramount concern, recycled and high-performance CB are attractive cost-saving options. In addition, if compression strength is important but the strength from kraft will far exceed the stress placed on the shipping container in the distribution environment, the other CB grades may offer an adequate solution.

The important point to understand is that recycled and high-performance CB is not acceptable as an interchangeable board grade with kraft CB as conventional wisdom within the corrugated industry suggests. With a substitution using recycled CB for example, the user must allow for the wider variations that exist in performance.

This idea mirrors the same decision process involving the selection between

Mullen-tested and ECT-tested CB. There is no exact correlation between Mullen and ECT for the same reasons that one does not exist for kraft versus high-performance versus recycled CB. Using a blanket rule for conversion is like comparing "apples and oranges." All of the LB and CB materials researched in this study provide the same function: they all protect products. However, each LB and CB grade is manufactured differently to enhance specific physical characteristics and as such, they cannot be looked at as equal. The packaging performance requirements of the distribution system must be analyzed and examined independently for each shipping container before a substitution should be recommended.

Of course, as paper mills and corrugated facilities refine their source quality and enhance their manufacturing processes, the performance gaps should diminish.

Recommendations

There are several avenues available for continued investigation in this field.

This experiment could be repeated while controlling and/or manipulating variables which were not examined within the scope of this thesis. These variables include moisture content, humidity, time, and sample variability.

Another variation of this research involves the examination of machine-run and/or die-cut cartons versus hand-made samples. This additional data collection would determine if the added handling effects the compression strength differently according to material type. Differences would suggest that distinct liners react uniquely to heat, moisture, handling etc..

Appendix I—Data

Caliper Evaluation

Equipment: Dead Weight Micrometer Model 553E, Testing Machines Inc., Amityville, NY

HPCaliper	KRCaliper	RECaliper
0.1612	0.1616	0.1610
0.1614	0.1628	0.1608
0.1615	0.1632	0.1649
0.1622	0.1617	0.1624
0.1623	0.1617	0.1616
0.1613	0.1620	0.1610
0.1624	0.1628	0.1602
0.1622	0.1617	0.1614
0.1617	0.1616	0.1616
0.1614	0.1615	0.1608
0.1613	0.1619	0.1616
0.1618	0.1609	0.1612
0.1615	0.1617	0.1616
0.1614	0.1584	0.1608
0.1612	0.1601	0.1616

0.1614	0.1616	0.1615
0.1625	0.1625	0.1602
0.1615	0.1620	0.1600
0.1614	0.1627	0.1614
0.1614	0.1598	0.1594
0.1614	0.1609	0.1608
0.1613	0.1619	0.1616
0.1614	0.1614	0.1616
0.1612	0.1617	0.1616
0.1615	0.1619	0.1624
0.1615	0.1610	0.1614
0.1612	0.1613	0.1616
0.1615	0.1620	0.1602
0.1612	0.1615	0.1616
0.1615	0.1623	0.1615
0.1615	0.1632	0.1610
0.1616	0.1609	0.1616

*all units in inches

Compression Testing

Equipment: Container Compression Tester, Lansmont Corporation, Program Version 1.4, Model Number 122-15K, Serial Number 56330

HPComprs	KRComprs	REComprs
795	882	770.3
766	954	909.3
700	861	981.7
696	888	1018.6
655	972	1074.7
791	927	360.2
741	891	395.7
462	970	862.4
714	857	890.8
578	946	845.2
739	740	1121.0
693	791	1218.3
744	799	500.0
671	814	750.5
772	777	890.5
616	994	710.5
657	861	780.2
633	974	1172.7
640	896	862.6

708	879	936.0
689	960	1022.9
708	959	921.7
693	902	914.1
715	918	867.3
791	955	949.2
668	938	710.0
644	811	936.6
815	900	878.5
781	818	750.0
694	830	805.0
763	1007	842.5
562	965	880.4

*all units in pounds/in^2

Internal Tear Testing

Equipment: Elmendorf Tear Tester, Thwing Albert Instument Co., Serial Number 5429

REIT Mac	REIT Crs	HPIT Mac	HPIT Crs	KRIT Mac	KRIT Crs
2.0	2.5	5.0	6.0	4.5	5.0
2.0	3.5	3.6	6.0	5.1	6.0
2.2	3.2	4.0	5.0	3.8	5.5
3.2	4.3	4.7	3.5	3.5	3.8
2.1	3.2	4.0	3.9	4.0	5.1
1.9	4.0	4.7	5.1	3.0	5.2
1.9	3.6	5.2	6.1	3.8	5.0
1.5	4.2	5.0	6.0	5.0	5.0
2.0	4.8	5.0	5.0	3.9	5.5
3.2	3.9	4.0	7.0	4.0	5.2
2.1	5.1	5.0	5.3	4.6	6.0
4.0	4.7	4.3	4.8	4.7	5.5
2.1	5.0	4.4	4.0	4.8	5.0
2.0	6.0	5.0	6.5	4.0	4.8
2.0	4.0	5.0	5.6	4.7	4.8
3.0	4.0	5.0	5.5	4.9	5.0
3.0	4.8	5.0	5.0	4.2	6.2
2.5	3.6	5.0	5.6	5.3	5.4
1.3	4.7	4.0	6.0	4.0	7.0

1.2	4.0	5.1	4.0	4.0	5.7
2.5	5.1	4.9	5.0	4.8	5.0
2.8	4.1	5.0	7.0	4.7	6.0
2.6	3.9	5.3	6.0	4.0	4.8
1.5	4.1	5.4	6.3	4.5	5.0
2.7	5.0	5.0	5.3	4.0	6.0
2.5	5.0	4.0	5.0	4.0	5.2
1.4	4.0	5.0	4.0	4.8	5.3
1.5	3.6	4.1	4.6	5.0	5.0
1.9	5.3	3.7	4.9	3.8	5.5
2.3	3.8	4.3	4.8	4.7	4.0
2.4	4.8	4.0	4.0	4.4	5.4
2.0	5.2	3.7	6.2	4.3	5.2

*all units in grams of force

Tensile Tear Evaluation

Equipment: Instron Model 1122, Serial Number 4494

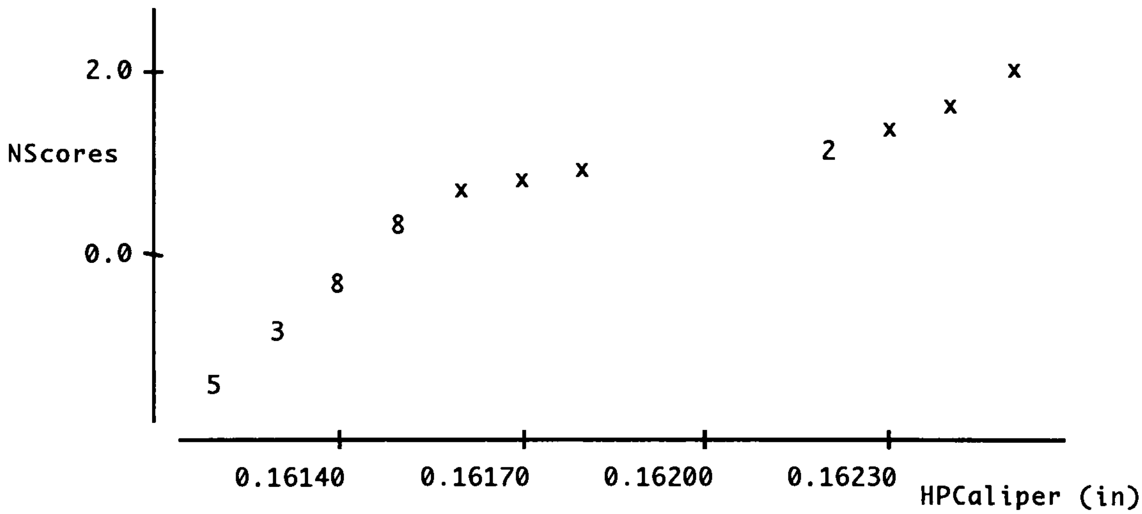
HPTenCrs	HPTenMac	KRTenCrs	KRTenMac	RETenCrs	RETenMac
51.8	34.1	81.1	38.2	74.0	58.0
59.7	31.0	61.4	38.0	63.2	52.1
58.2	37.0	64.6	32.4	78.0	67.0
42.6	35.5	66.2	36.0	71.5	68.9
51.2	35.2	66.1	33.0	82.0	53.5
57.5	38.0	66.9	34.8	82.0	53.0
38.5	32.0	73.0	36.0	70.6	66.0
72.1	36.5	59.3	30.2	77.0	63.0
66.0	40.2	68.0	35.9	75.5	44.5
60.4	31.9	56.0	36.4	72.0	50.0
54.2	34.5	45.1	34.0	77.0	48.0
65.1	35.0	54.4	32.1	64.0	53.7
65.5	38.5	60.3	36.0	76.2	59.2
43.6	32.0	61.8	38.7	80.0	56.0
48.0	33.5	42.5	35.2	76.0	62.0
49.8	38.0	44.6	35.1	83.0	59.2
66.0	40.3	56.6	35.5	74.0	68.0
64.5	35.0	78.1	35.0	67.5	68.0
57.0	37.2	78.0	33.0	78.0	53.0

55.0	37.0	68.0	37.0	72.5	51.7
49.0	27.6	68.0	37.4	70.5	54.6
53.5	34.0	68.5	36.5	64.3	56.3
40.2	35.0	72.8	35.0	69.5	40.0
44.0	39.5	73.1	33.8	68.0	52.1
55.5	34.0	75.8	38.2	69.0	64.2
61.0	38.0	74.5	34.5	72.7	52.0
55.3	38.5	68.3	37.0	76.5	63.7
54.5	31.5	88.9	37.0	73.4	45.8
60.1	34.2	80.7	32.0	83.0	75.2
56.1	35.5	70.4	31.2	72.4	45.5
54.8	34.1	62.3	37.2	73.5	49.7
63.0	34.2	66.7	31.9	70.2	37.3

*all units in pounds of force

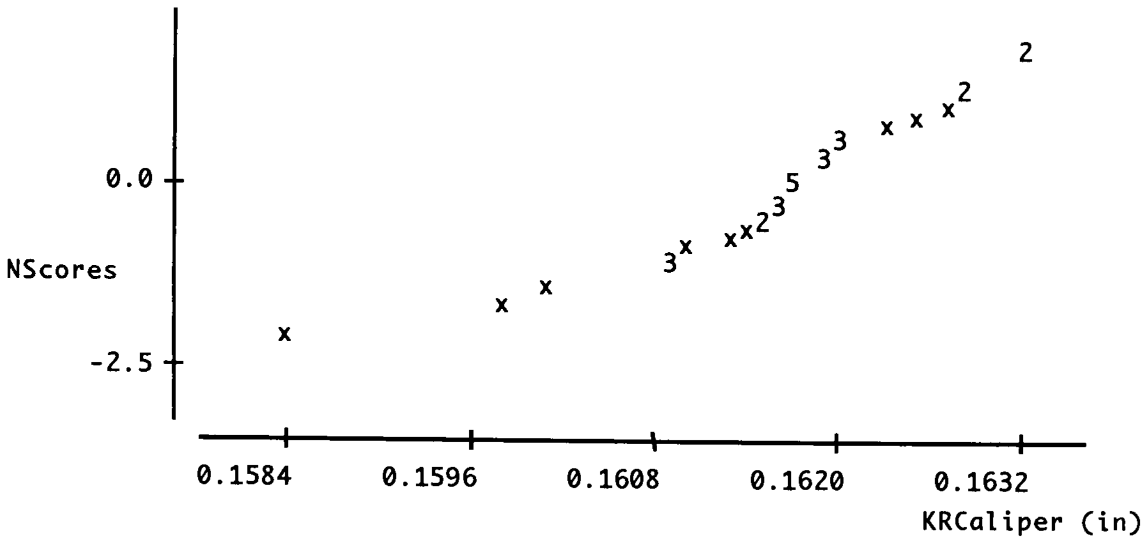
Appendix II—Normalcy of Data

The following graphs are normal probability plots (NPP) for the collected data. Since all of the graphs are approximately straight lines, it is reasonable to conclude that the samples came from a population which is approximately normal.



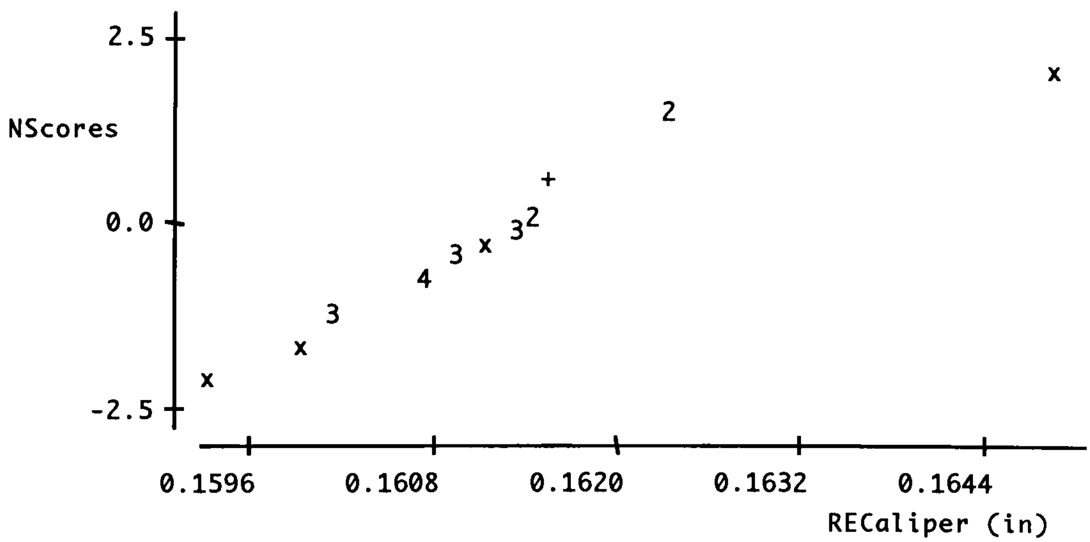
NPP of High-Performance Board Caliper vs. the Normal Score

Figure 6.0



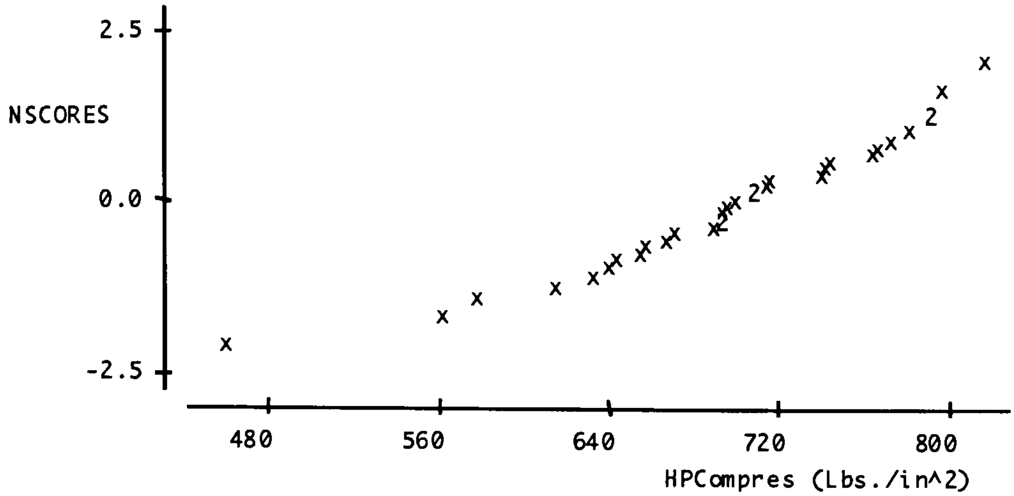
NPP of Kraft Board Caliper vs. the Normal Score

Figure 7.0



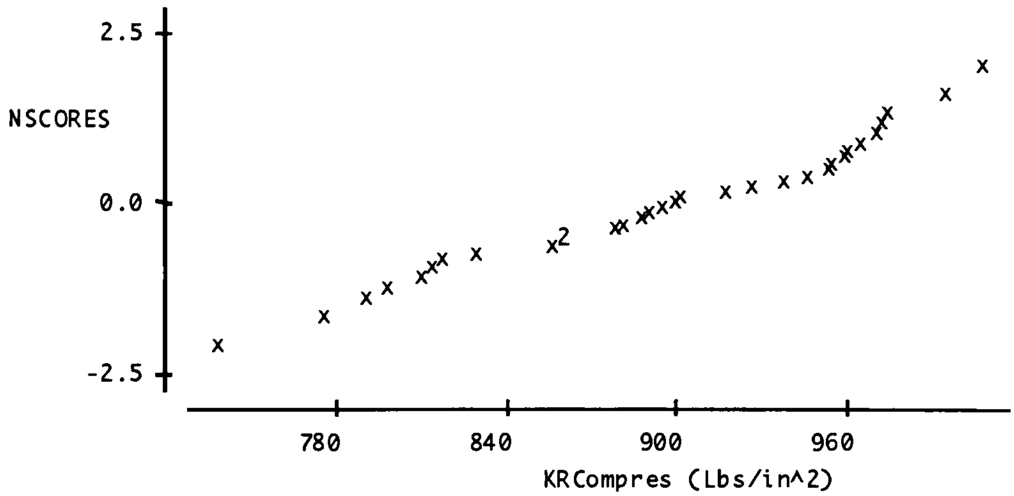
NPP of Recycled Board Caliper vs. the Normal Score

Figure 8.0



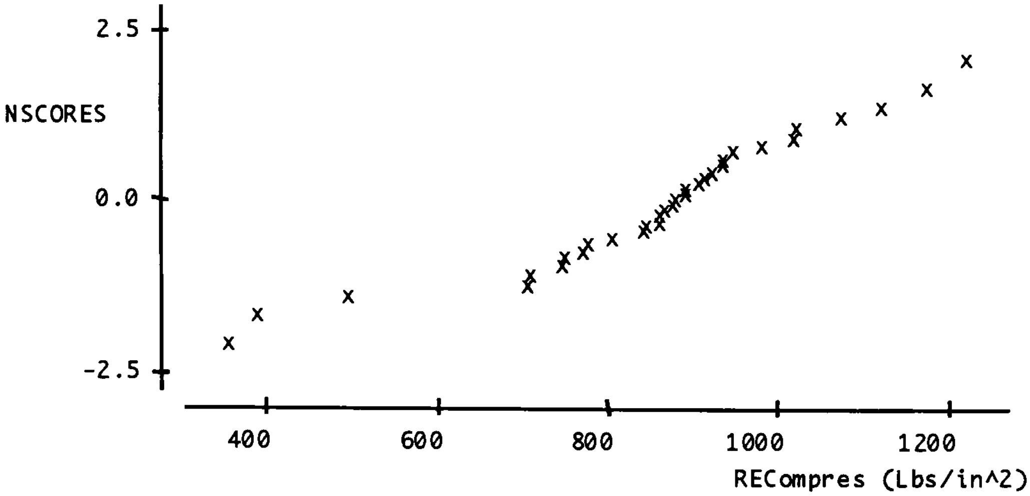
NPP of High-Performance Compression Strength vs. the Normal Score

Figure 9.0



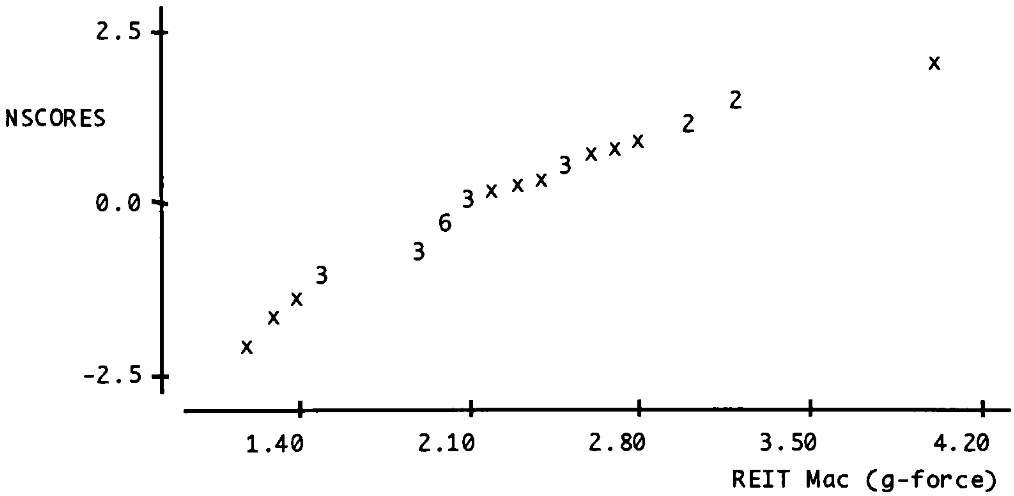
NPP of Kraft Compression Strength vs. the Normal Score

Figure 10.0



NPP of Recycled Compression Strength vs. the Normal Score

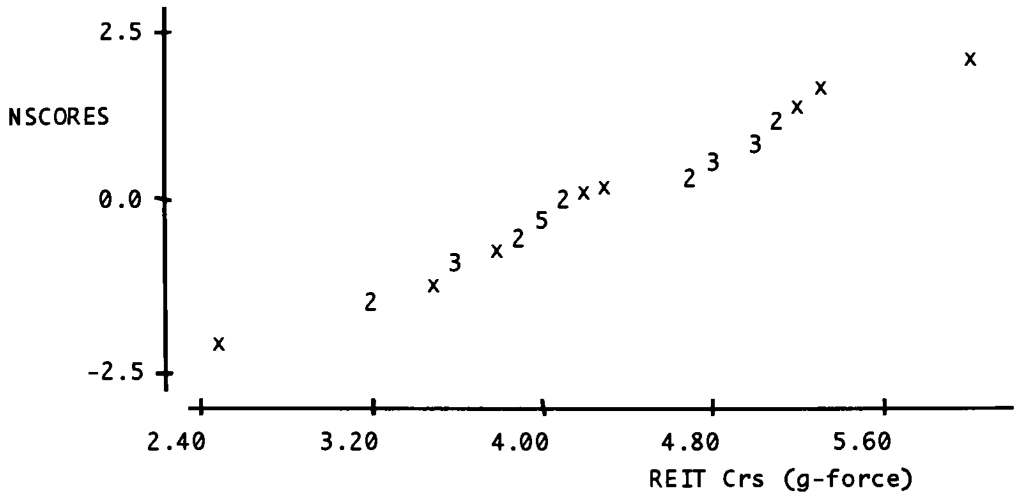
Figure 11.0



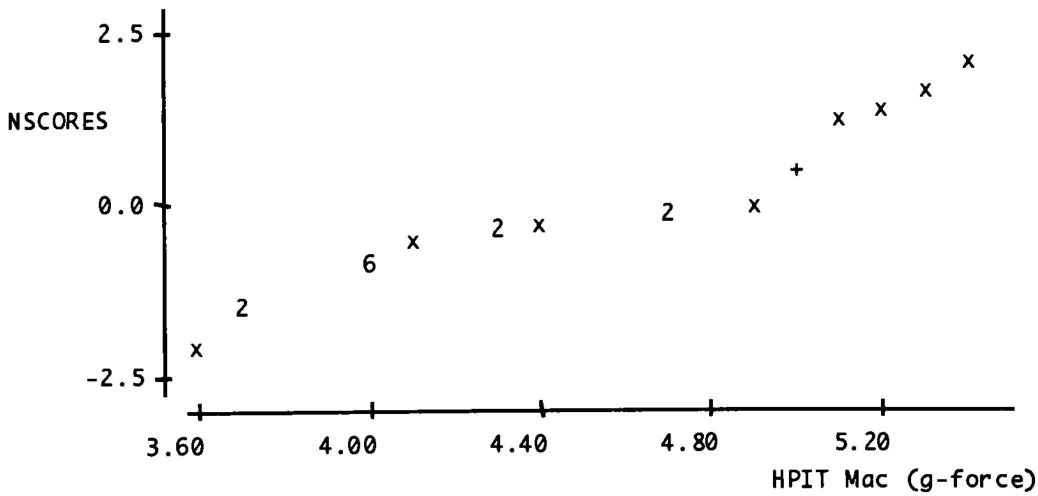
NPP of the Internal Tear Strength for Recycled Board

in the Machine-Direction vs. the Normal Score

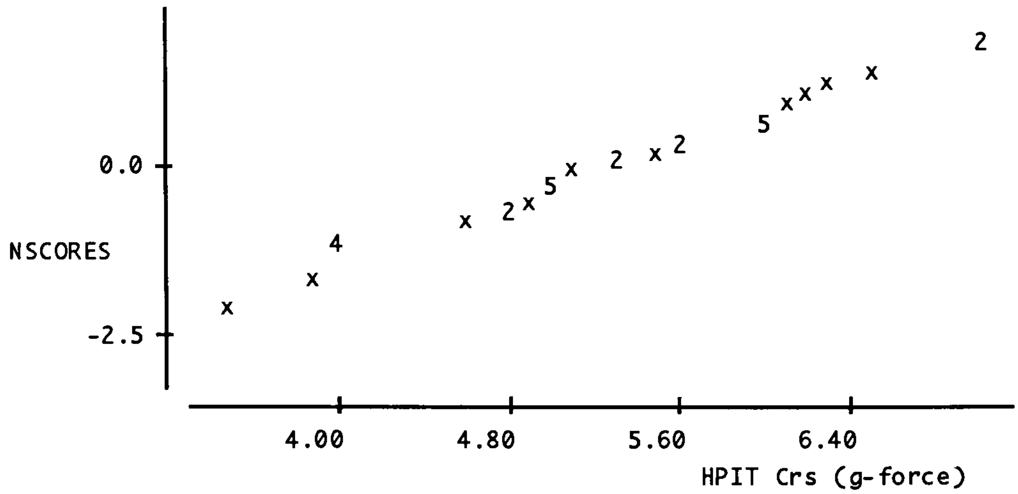
Figure 12.0



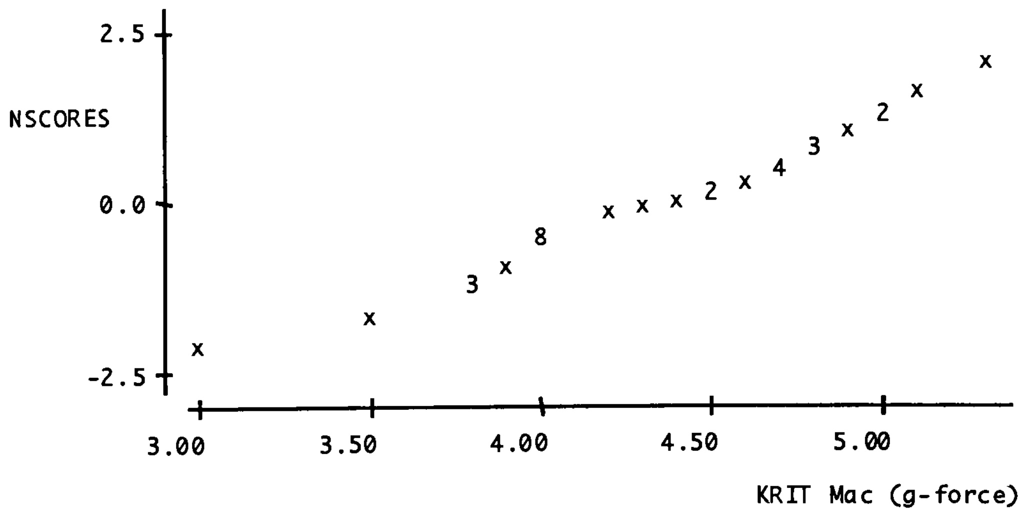
NPP of the Internal Tear Strength for Recycled Board
in the Cross-Direction vs. the Normal Score
Figure 13.0



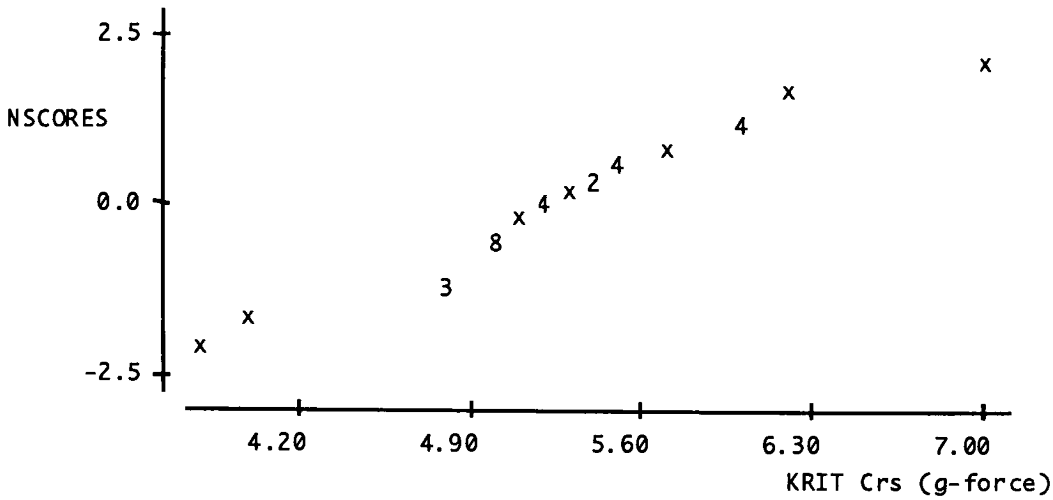
NPP of the Internal Tear Strength for High-Performance Board
in the Machine-Direction vs. the Normal Score
Figure 14.0



NPP of the Internal Tear Strength for High-Performance Board
in the Cross-Direction vs. the Normal Score
Figure 15.0



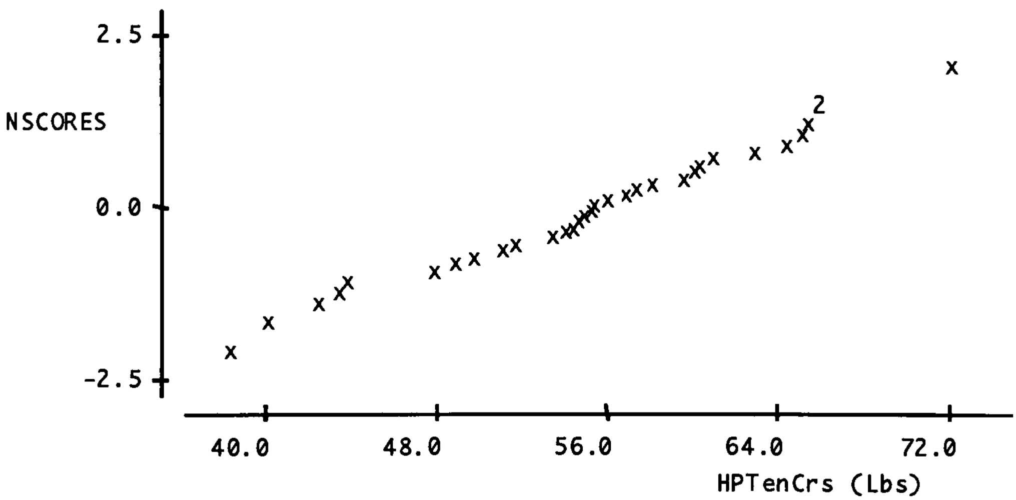
NPP of the Internal Tear Strength for Kraft Board
in the Machine-Direction vs. the Normal Score
Figure 16.0



NPP of the Internal Tear Strength for Kraft Board

in the Cross-Direction vs. the Normal Score

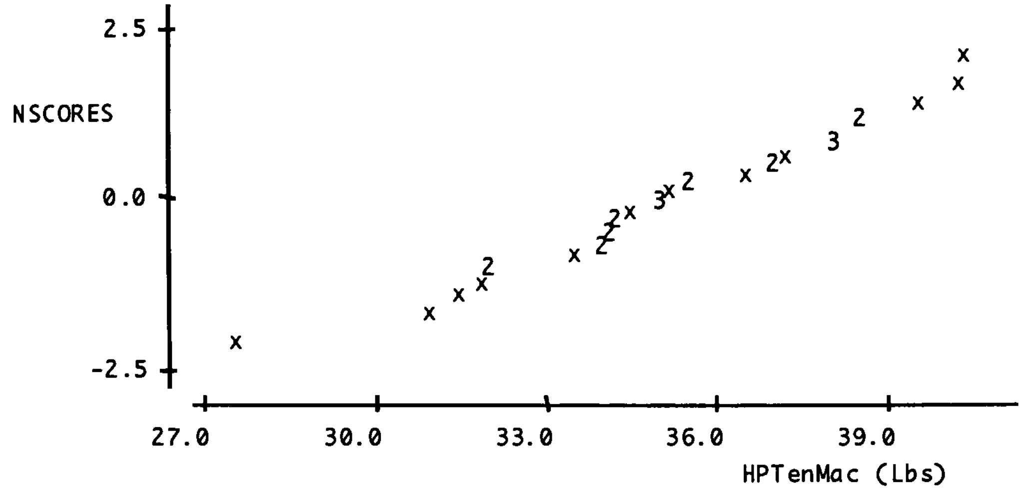
Figure 17.0



NPP of Tensile Strength for High-Performance Board

in the Cross-Direction vs. the Normal Score

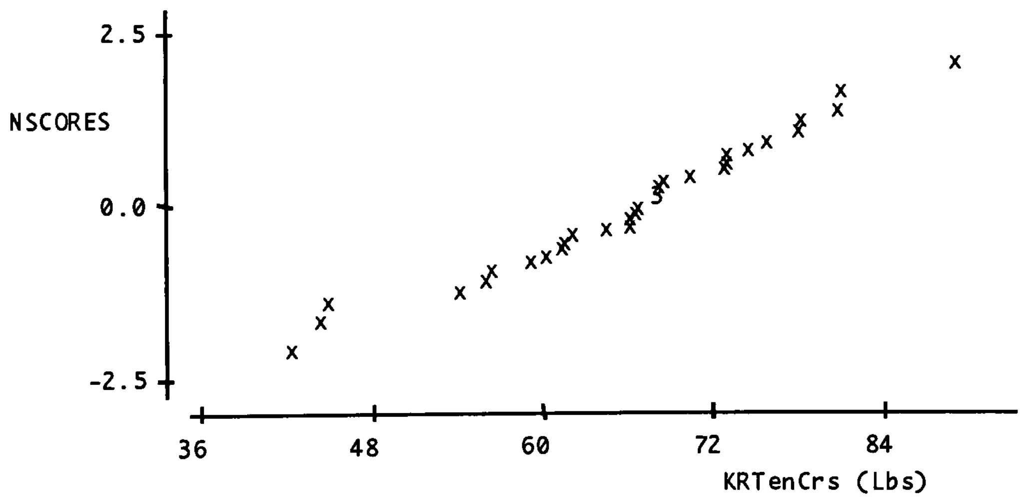
Figure 18.0



NPP of Tensile Strength for High-Performance Board

in the Machine-Direction vs. the Normal Score

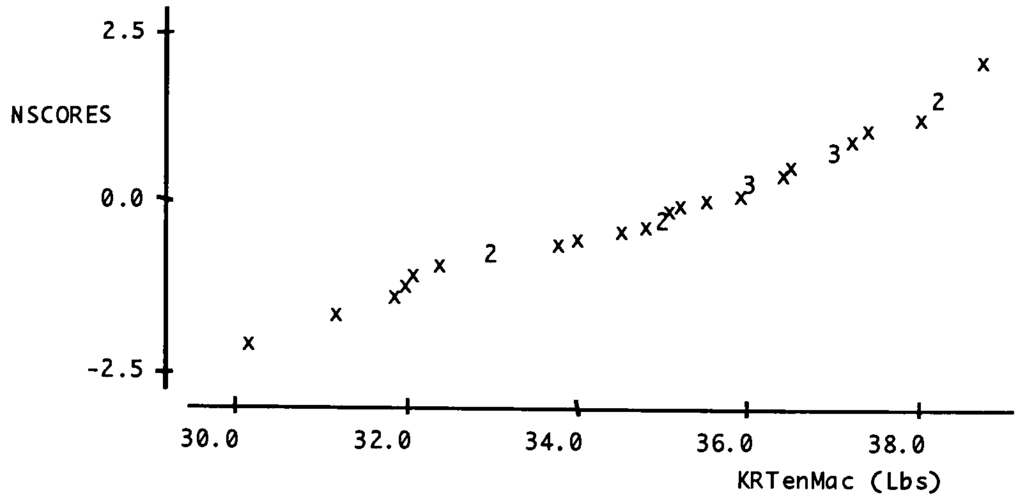
Figure 19.0



NPP of Tensile Strength for Kraft Paper

in the Cross-Direction vs. the Normal Score

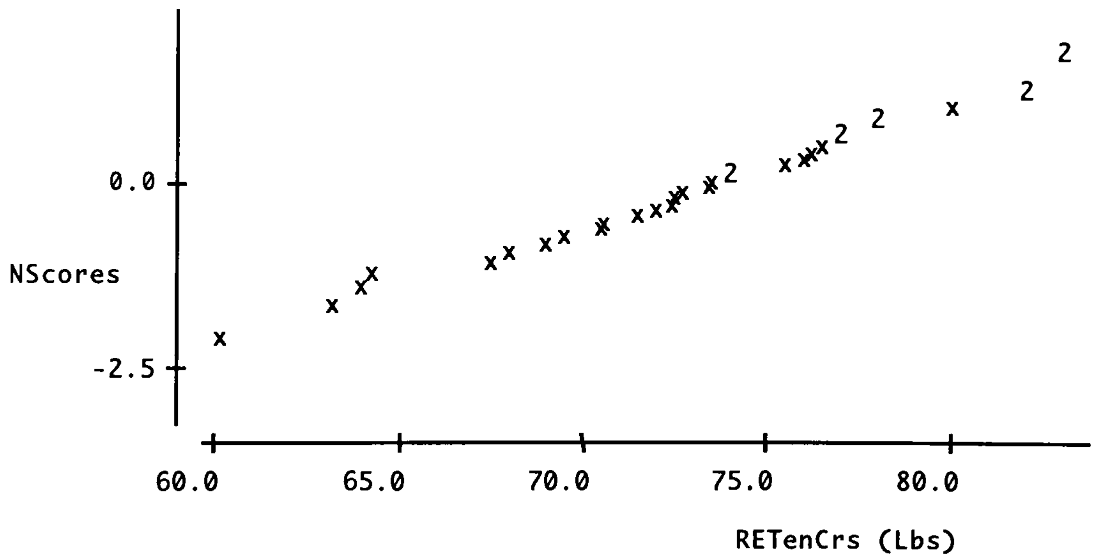
Figure 20.0



NPP of Tensile Strength for Kraft Paper

in the Machine-Direction vs. the Normal Score

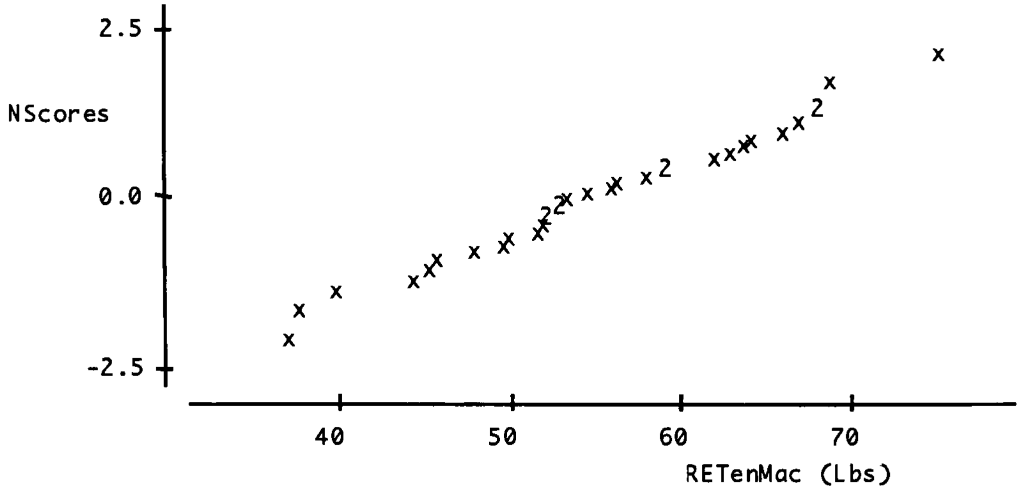
Figure 21.0



NPP of Tensile Strength for Recycled Paper

in the Cross-Direction vs. the Normal Score

Figure 22.0



NPP of Tensile Strength for Recycled Paper

in the Machine-Direction vs. the Normal Score

Figure 23.0

Appendix III—Statistical Analysis

Board Caliper

Following are the descriptive statistics corresponding to the analysis of board caliper:

	N	MEAN	MEDIAN	STDEV	SEMEAN
HPCalipr	32	0.16156	0.16145	0.00036	0.00006
KRCalipr	32	0.16163	0.16170	0.00097	0.00017
RECalipr	32	0.16126	0.16140	0.00093	0.00016

	MIN	MAX	Q1	Q3
HPCalipr	0.16120	0.16250	0.16133	0.16157
KRCalipr	0.15840	0.16320	0.16133	0.16200
RECalipr	0.15935	0.16485	0.16075	0.16155

Figure 24.0

Shown below, the P-value associated with caliper thickness is 0.152 which is greater than the chosen 0.05 significance level. As a result, the null hypothesis (H_O) cannot be rejected which means that there is no significant evidence of difference among the caliper values for the three samples.

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	p
FACTOR	2	0.0000025	0.0000012	1.93	0.152
ERROR	93	0.0000598	0.0000006		
TOTAL	95	0.0000623			

INDIVIDUAL 95 PCT CI'S FOR MEAN BASED ON POOLED STDEV

LEVEL	N	MEAN	STDEV
HPCalipr	32	0.161556	0.000365
KRCalipr	32	0.161631	0.000967
RECalipr	32	0.161259	0.000928

```
-----+---------+---------+---------+-
          (--------*---------)
             (---------*--------)
(--------*---------)
-----+---------+---------+---------+-
0.1611  0.1614  0.1617  0.1620
```

POOLED STDEV = 0.000802

Figure 25.0

Compression Strength

Following are the descriptive statistics for the vertical compression analysis of the cartons:

	N	MEAN	MEDIAN	STDEV	SEMEAN
HPCompres	32	696.7	698.0	76.0	13.4
KRCompres	32	894.9	898.0	70.1	12.4
RECompres	32	860.3	879.5	190.1	33.6

	MIN	MAX	Q1	Q3
HPCompres	462.0	815.0	655.5	758.3
KRCompres	740.0	1007.0	836.8	958.0
RECompres	360.2	1218.3	772.8	946.0

Figure 26.0

Shown below, the P-value associated with compression strength is 0.00 which is less than the chosen 0.05 significance level. As a result, H_O is rejected which means that there is significant evidence of difference among the compression values for the three samples.

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	p
FACTOR	2	717239	358619	22.97	0.000
ERROR	93	1451821	15611		
TOTAL	95	2169060			

INDIVIDUAL 95 PCT CI'S FOR MEAN BASED ON POOLED STDEV

```
LEVEL      N    MEAN    STDEV   ---------+---------+---------+-------
HPComprs  32   696.7     76.0    (----*-----)
KRComprs  32   894.9     70.1                            (-----*----)
REComprs  32   860.3    190.1                        (-----*----)
                                ---------+---------+---------+-------
POOLED STDEV =  124.9                  720       800       880
```

Figure 27.0

Internal Tear Strength

Following are the descriptive statistics for the analysis of internal tear in both the cross and machine-directions:

	N	MEAN	MEDIAN	STDEV	SEMEAN
REIT Mac	32	2.228	2.100	0.623	0.110
REIT Crs	32	4.281	4.100	0.749	0.132
HPIT Mac	32	4.6062	4.9500	0.5394	0.0953
HPIT Crs	32	5.281	5.200	0.915	0.162
KRIT Mac	32	4.3375	4.3500	0.5229	0.0924
KRIT Crs	32	5.284	5.200	0.609	0.108

	MIN	MAX	Q1	Q3
REIT Mac	1.200	4.000	1.900	2.575
REIT Crs	2.500	6.000	3.825	4.950
HPIT Mac	3.6000	5.4000	4.0000	5.0000
HPIT Crs	3.500	7.000	4.800	6.000
KRIT Mac	3.0000	5.3000	4.0000	4.7750
KRIT Crs	3.800	7.000	5.000	5.500

Figure 28.0

Shown below, the P-value associated with internal tear strength in the machine-direction is 0.00 which is less than the chosen 0.05 significance level. As a result, H_O is rejected which means that there is significant evidence of difference among the tear values for the three samples.

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	p
FACTOR	2	108.556	54.278	170.89	0.000
ERROR	93	29.538	0.318		
TOTAL	95	138.095			

INDIVIDUAL 95 PCT CI'S FOR MEAN BASED ON POOLED STDEV

```
LEVEL       N    MEAN      STDEV     -----+---------+---------+---------+-
REIT Mac    32   2.2281    0.6233    (--*-)
HPIT Mac    32   4.6062    0.5394                                 (--*-)
KRIT Mac    32   4.3375    0.5229                              (-*--)
                                     -----+---------+---------+---------+-
POOLED STDEV = 0.5636                   2.40      3.20      4.00      4.80
```

Figure 29.0

Shown below, the P-value associated with internal tear strength in the cross-direction is 0.00 which is less than the chosen 0.05 significance level. As a result, H_O is rejected which means that there is significant evidence of difference among the tear values for the three samples.

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	p
FACTOR	2	21.400	10.700	18.16	0.000
ERROR	93	54.800	0.589		
TOTAL	95	76.200			

INDIVIDUAL 95 PCT CI'S FOR MEAN BASED ON POOLED STDEV

```
LEVEL       N    MEAN      STDEV     ----------+---------+---------+------
REIT Crs    32   4.2812    0.7490    (-----*----)
HPIT Crs    32   5.2812    0.9146                        (-----*----)
KRIT Crs    32   5.2844    0.6086                        (-----*----)
                                     ----------+---------+---------+------
POOLED STDEV = 0.7676                        4.50      5.00      5.50
```

Figure 30.0

Tensile Strength

Following are the descriptive statistics for the tensile strength for the machine and cross-direction paper samples of the kraft, high-performance, and the recycled papers:

	N	MEAN	MEDIAN	STDEV	SEMEAN
HPTenCrs	32	55.43	55.40	8.16	1.44
HPTenMac	32	35.266	35.000	2.886	0.510
KRTenCrs	32	66.31	67.45	10.65	1.88
KRTenMac	32	35.131	35.350	2.240	0.396
RETenCrs	32	73.34	73.45	5.81	1.03
RETenMac	32	55.48	54.05	9.48	1.68

	MIN	MAX	Q1	Q3
HPTenCrs	38.50	72.10	50.15	60.85
HPTenMac	27.600	40.300	34.000	37.800
KRTenCrs	42.50	88.90	60.58	73.07
KRTenMac	30.200	38.700	33.200	37.000
RETenCrs	60.20	83.00	69.75	77.00
RETenMac	37.30	75.20	49.77	63.52

Figure 31.0

Shown below, the P-value associated with tensile strength in the cross-direction is 0.00 which is less than the chosen 0.05 significance level. As a result, H_O is rejected. This means that there is significant evidence of difference among the tensile values for the three samples.

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	p
FACTOR	2	5214.7	2607.3	36.59	0.000
ERROR	93	6627.4	71.3		
TOTAL	95	11842.1			

INDIVIDUAL 95 PCT CI'S FOR MEAN BASED ON POOLED STDEV

```
LEVEL       N    MEAN      STDEV    ------+---------+---------+---------+
HPTenCrs   32    55.428    8.164     (---*---)
KRTenCrs   32    66.312   10.649               (----*---)
RETenCrs   32    73.344    5.807                         (---*---)
                                    ------+---------+---------+---------+
POOLED STDEV =  8.442                   56.0      63.0      70.0      77.0
```

Figure 32.0

Shown below, the P-value associated with tensile strength in the machine-direction is 0.00 which is less than the chosen 0.05 significance level. As a result, H_O is rejected which means that there is significant evidence of difference among the tensile values in the machine-direction for the three samples.

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F	p
FACTOR	2	8774.0	4387.0	127.52	0.000
ERROR	93	3199.5	34.4		
TOTAL	95	11973.5			

INDIVIDUAL 95 PCT CI'S FOR MEAN BASED ON POOLED STDEV

LEVEL	N	MEAN	STDEV
HPTenMac	32	35.266	2.886
KRTenMac	32	35.131	2.240
RETenMac	32	55.478	9.480

```
---+---------+---------+---------+---
 (--*--)
(--*--)
                              (--*--)
---+---------+---------+---------+---
 35.0      42.0      49.0      56.0
```

POOLED STDEV = 5.865

Figure 33.0

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