THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

INVESTIGATION OF AN IMPROVED DEVICE FOR EVALUATING THE CRACKING POTENTIAL OF LINERBOARD

Project 1108-29

Report Two

A Preliminary Report

to

TECHNICAL COMMITTEE
FOURDRINIER KRAFT BOARD INSTITUTE INC.

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SUMMARY

A recurrent problem in the manufacture and use of corrugated boxes is rupture or cracking of the double-face liner along the score when the board is folded. Cracking is usually most severe for vertical scorelines when the score is oriented at 90° to the machine direction of the liner—because the strains set up during folding coincide with the direction of least stretch. With such considerations in mind, the Institute was requested to undertake an investigation to evaluate methods for determining the cracking potential of linerboard.

The initial results obtained in this study were described in Report One dated June 18, 1963. In this particular report attention was focused on a "foldability" tester designed at the Institute for determining the cracking potential of linerboard. This tester was used for an initial study of the relationship of various physical characteristics of the liner to its cracking performance in the form of combined board. The initial results indicated that the new tester exhibited some promise, however, additional refinements appeared desirable to permit better evaluations within individual grades of linerboard.

The results in the present study were obtained using the modified tester. The principal change made was to redesign the anvil heads over which the specimen is bent to prevent cutting of the underside of the specimen. The anvil heads were machined to have 0.010 inch radii for this study. Other changes in the tester are described in the text.

To test the efficiency of the device for predicting combined board cracking, the 90-lb. liner samples used in the previous study were used as double-face liners and laminated to single-faced board having a 90-lb. liner. The range of cracking was increased by subjecting the linerboards before fabrication to heat or humidity to change their characteristics. After scoring and folding, the degree of cracking of the combined boards and the liner cracking angle were determined at 10, 20, 30, 40, and 50% R.H.

In general, the results of this study indicated that.

1. The linerboard cracking device appears to be a practical means for evaluating the cracking potential of linerboard because it appears to be significantly related to combined board cracking. Recommendations with regard to possible additional improvements are mentioned in the text.

2. The relationship between combined board cracking and relative humidity was such that a probability-type equation appeared to fit the data reasonably well.

3. Exponential or probability-type equations appeared to best fit the liner cracking vs. combined board cracking data although the latter may be preferred at this time.

INTRODUCTION

Preliminary Report One dated June 18, 1963 described initial results obtained in an investigation of methods for determining the cracking potential of linerboard. For this purpose, a study of the relationship of various physical characteristics of the liner to its cracking performance in the form of combined board was initiated. Particular attention was focused on the foldability tester designed at the Institute.

In general, the results indicated that the new tester might have promise, however, further improvements in design appeared necessary to improve its correlation with combined board cracking. Specifically, it was observed that the device tended to cut the under side of the liner – thus possibly relieving the tensile stresses causing cracking to some degree. To prevent cutting, the anvil heads were redesigned so as to have a small radius – 0.010 inch with 0.032 inch spacing between anvils for the trials reported herein. The specimen holder was also redesigned to permit substitution of anvils having other tip radii in the event that cutting still occurred with the 0.010 inch radii anvils. A change in clamping was also made to give more even clamping pressures and faster clamping action. It was thought that toggle-action clamps would be suitable; however, slippage occurred. Because of time limitations, the original clamps were then crudely modified to a centrally applied screw closure system.

In the previous work, samples of 42, 69, and 90-lb. liner samples were employed; however, only a limited number of samples were available in each grade. This, coupled with the variability involved in the combined board and linerboard evaluations, made it difficult to assess the degree of relationship between combined board cracking and linerboard evaluations within grades. For this reason, it was thought desirable to concentrate attention on the 90-lb. grade and to artificially increase the number of samples in this grade by (a) subjecting portions of six samples to high humidity (90% R.H.) for at least 12 hours to relax a portion of the stresses built in during manufacture, and (b) to degrade portions of five samples by subjecting them to a temperature of 125°C. for 36 hours. After reconditioning, the humidity relaxation technique would have the tendency to reduce cracking failure under given conditions as compared to untreated samples, since the relaxed samples should have a higher stretch. The samples treated by heating, on the other hand, would be expected to crack more readily than the untreated controls. In addition, to increasing the severity of cracking, the combined board samples were all fabricated using a standard single-faced sample having a 90-lb. single-face liner rather than the 42-lb. liner sample used in the previous trials.

The results obtained are summarized herein.

LINERBOARD FOLDABILITY TESTER

As illustrated in Fig. 1, the linerboard foldability apparatus involves folding a strip of linerboard about a solid angle. The strip is clamped at the ends; therefore, the outer surface of the liner is subjected to tensile strains arising from the elongation of the neutral axis and to tensile strains arising from the flexure of the strip. The first type of strain will be proportional to the tensile stiffness of the board; the second type of strain will be proportional to the bending and shear stiffness of the board.

From a more simplified standpoint, the strains occurring in the linerboard are schematically illustrated in Fig. 2. As shown in the figure, the change in length (ΔL) of the top surface of the specimen would be as follows:

$$\Delta L = \theta t \quad (1)$$

where θ = angle of rotation, radians and t = specimen thickness.

It will be assumed that the maximum strain (ϵ) in the outer surface is concentrated in a small zone near the center of the bent area and may be represented as follows:

$$\epsilon = k\theta t \quad (2)$$

where k = constant

Then, when the maximum stretch (ϵ_f) in the outer surface is exceeded, rupture will occur, i.e.

$$\epsilon_f = k\theta_f t \quad (3)$$

where θ_f = angle of rotation when rupture occurs.

$$\text{or } \theta_f = \epsilon_f/kt = k_1\epsilon_f/t \quad (4)$$

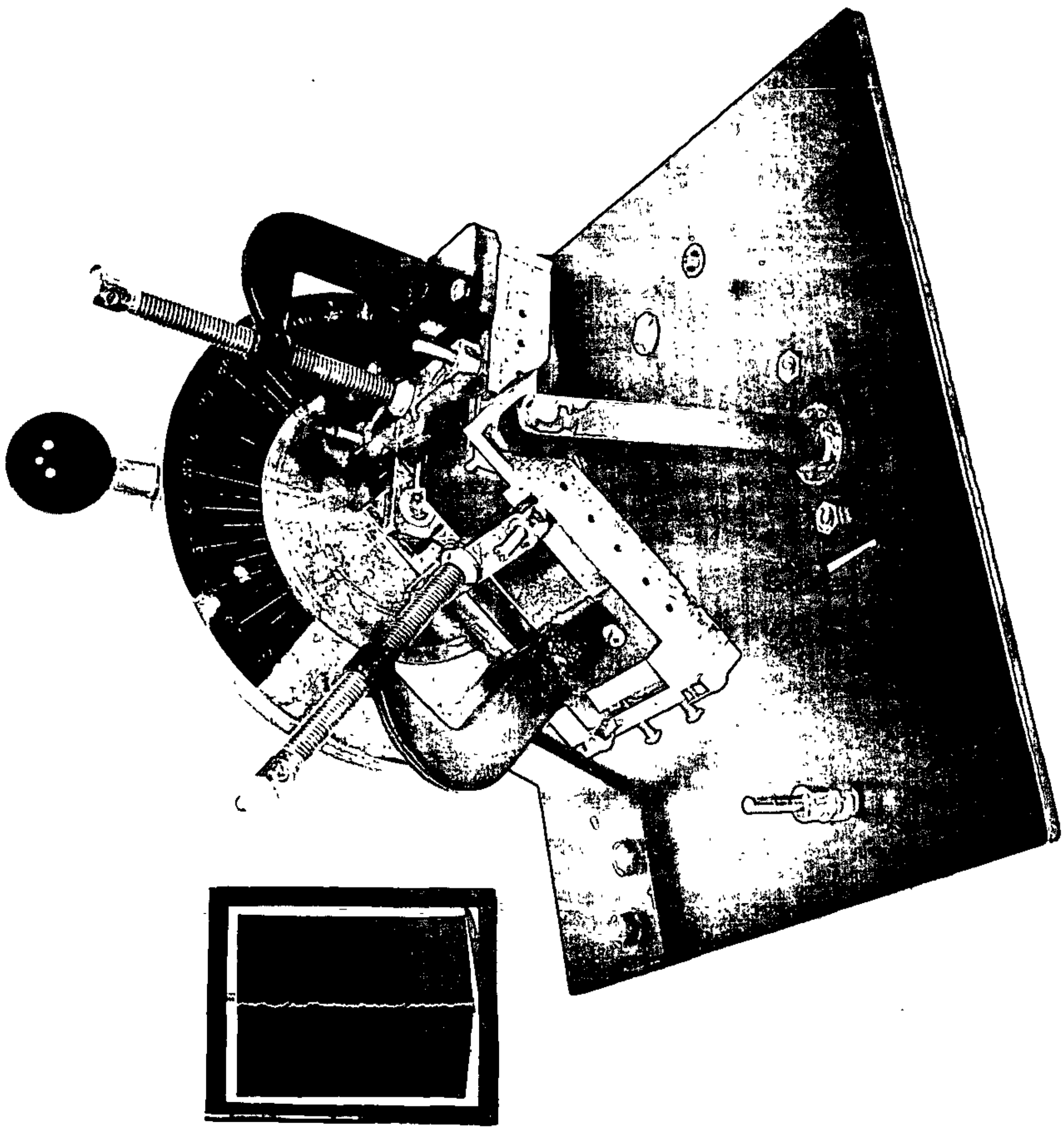

Figure 1. Modified Linerboard Foldability Tester

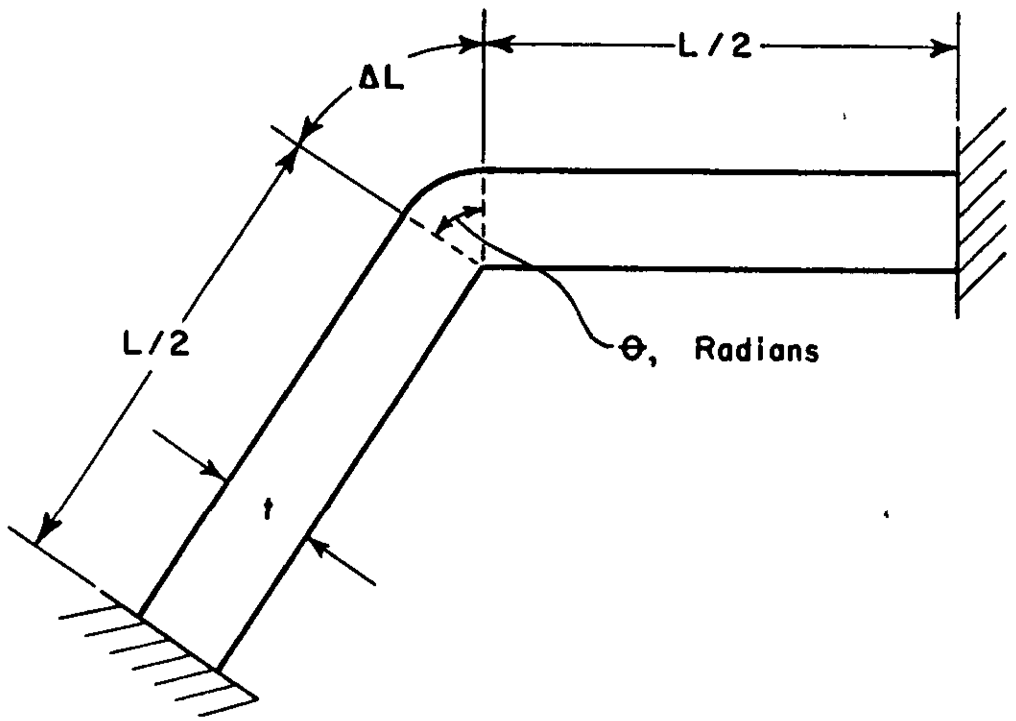

Figure 2. Idealized Representation of Strain Induced in Linerboard Foldability Test

Equation (4) is in agreement with the general observations that other things being equal (1) the thicker the sheet, the smaller should be the angle of fold required to produce fracture, and (2) the smaller the potential stretch in the outside surface layers, the smaller should be the angle of fold required to produce fracture.

The combined board evaluation differed from that used for the liner-board in that the combined board is folded 180 degrees and the extent of the cracking is observed. This would be analogous to bending the liner in the liner-board test to a given angle and observing the extent of the cracking. Thus, the percentage cracking figures are equivalent to working with cumulative probability distributions.

In general, failure will occur when the rupture stretch ($\epsilon_{\underline{f}}$) in the outer layers of the double-face liner is exceeded. Assuming that the rupture stretch in the outside layers is normally distributed about some average value $\bar{\epsilon}_{\underline{f}}$ with standard deviation σ_{ϵ}, then (1)

$$P = \int_{-\infty}^{\epsilon} (1/\sqrt{2\pi}) \exp[-(\epsilon - \bar{\epsilon}_{\underline{f}})^2/2\sigma_{\epsilon}^2]\, d\epsilon \qquad (5)$$

where $\underline{P}$ = failure probability

ϵ = strain applied in combined board fold at outer surface of double-face liner

$\bar{\epsilon}_{\underline{f}}$ = average rupture strain in outer surface of double-face liner

σ_{ϵ} = standard deviation of rupture strain.

Making the appropriate substitutions from Equations (2) and (3) into Equation (5) and making the further assumption that the variance in thickness is small in comparison with that of $\theta_{\underline{f}}$, Equation (5) may be written as follows:

$$P = kt\int_{-\infty}^{\theta}(1/\sqrt{2\pi})\exp[-(\theta - \bar{\theta}_f)^2/2\sigma_\theta^2]\,d\theta \qquad (6)$$

Thus, this approach suggests that for a given sample, the degree of combined board cracking will be nonlinearly dependent on the rupture angle observed in the linerboard test. A decrease in humidity, e.g., which has the effect of decreasing the rupture stretch and angle θ_f would have a marked effect on the probability or degree of combined board cracking.

Equation (6) cannot be explicitly integrated, however, tables of areas under the normal distribution curve are readily available (1). The form of Equation (6) indicates that one analytical approach which might be useful in relating combined board cracking and liner cracking angle would be the response or probit curve technique described in Reference (2). In using this approach, the percentage cracking values would be transformed to values of the normal deviate for correlation purposes.

MATERIALS

The physical characteristics of the 90-lb. liner samples used are tabulated in Table I.

TABLE I

PHYSICAL CHARACTERISTICS OF 90-LB. LINER SAMPLES

Sample No.	Basis Weight, lb./M sq. ft.	Caliper, pt.	Tensile, lb./in. In	Tensile, lb./in. Cross	Stretch, % In	Stretch, % Cross
2414	88.4	25.4	131.2	71.4	1.3	2.6
2420	93.5	25.4	145.4	74.1	1.4	3.6
2427	92.2	23.5	136.8	74.5	1.8	3.0
2451	87.9	26.1	105.4	62.6	1.3	2.8
2464[a]	84.0	24.6	167.4	78.0	2.0	5.1
2465	93.6	27.6	149.4	68.6	1.5	3.0
2466[b]	90.1	26.7	131.2	87.8	2.0	4.1
2486[b]	93.8	26.2	146.3	87.2	2.0	4.0
2491	91.6	25.6	127.6	65.3	1.6	3.0

[a] Laminated (2-42 lb. plies).

[b] Laminated (fourdrinier board laminated to extensible sheet).

All the above samples were fabricated into double-faced board and evaluated for cracking at 10, 20, 30, 40, and 50% R.H. In addition, portions of the following samples were treated as noted below prior to the double-facing operation.

1. At least 72 hours exposure to 90% R.H. and 73°F. followed by preconditioning at less than 35% R.H. and conditioning at 50% and 73°F. prior to fabrication or evaluation—Sample numbers 2414, 2420, 2427, 2464, 2465, and 2491.

2. At least 36 hours exposure at 125°C. followed by preconditioning and conditioning as noted in (1) above—Sample numbers 2427, 2451, 2466, 2486, and 2491.

DOUBLE-FACING AND SCORING

Double-faced board was made by hand gluing sheets of the linerboard to a single-faced board corrugated on the Institute's experimental corrugator. With the exception that a 90-lb. liner was used as the single-face liner, the same conditions were used as specified in Report One.

FOLDING

As in the previous work, five sheets of board with 3-11 inch long panel scores per sheet were evaluated for cracking for each sample in each atmosphere. Thus, each percentage cracking value is based on an examination of 165 inches of scoreline. The folded board was taped together to standardize the viewing and handling conditions and the cumulative length of severe cracks was measured—a minimum length of 0.10 inch was used corresponding to a minimum percentage cracking of about 0.1%.

To increase crack visibility, a spray coating of flat black paint was used as described in the previous study. The length and occurrence of severe cracks was judged in comparison with a reference scoreline.

LINERBOARD FOLDABILITY TEST

Ten specimens of each linerboard sample were evaluated at each humidity level with the fold line at right angles to the machine direction. As in the case of the combined board samples, a spray coating of flat black paint was used to increase crack visibility. The rupture angle associated with the first appearances of a crack in the liner surface was measured. Efforts were also made to measure the angle associated with a more severe degree of cracking, however, these readings would have been in excess of the maximum angle permitted by the tester in the higher humidities. Therefore, the severe cracking criterion was discontinued; however, it may be tried in future work in an effort to improve and simplify the routine evaluation of linerboard.

DISCUSSION OF RESULTS

A tabulation of the combined board cracking results together with the linerboard cracking evaluations at each humidity level are summarized in Table II. As may be noted, no severe cracking was recorded for Samples 2466 and 2486 at any humidity level for the material given no special prefabrication treatment. Only slight amounts of cracking were recorded at 10 and 20% R.H. for the portions of these samples heated at 125°C. prior to fabrication. In the linerboard evaluation of these samples, no cracking was observed at the highest angle permitted by the tester. Thus, the linerboard tests were in qualitative agreement with the combined board cracking results. However, the results were not suitable for quantitative analyses and were not used in the following analyses.

Inspection of the table indicates that, in general, both the combined board and linerboard tests exhibit the expected trends with folding humidity and fabrication treatment. For example, with increasing folding humidity, the degree of combined board cracking decreases and the linerboard cracking angle increases. Similarly, the samples heated at 125°C. prior to fabrication into combined board tended to exhibit increased combined board cracking and smaller linerboard cracking angles relative to the untreated samples.

EFFECT OF HUMIDITY ON COMBINED BOARD CRACKING

To illustrate the effect of humidity at time of folding, Fig. 3 through 8 were prepared. Fig. 3 and 4 show results plotted in linear and semilogarithmic co-ordinates, respectively; Fig. 5 through 8 show the results plotted on arithmetic probability paper. (Note: The curves were drawn in by "eye" in all figures.) Inspection of the figures indicates that:

TABLE II

COMBINED BOARD AND LINERBOARD CRACKING RESULTS

(Black coated)

Sample No.	Combined Board Cracking, %					Linerboard Cracking Angle, °				
	10% R.H.	20% R.H.	30% R.H.	40% R.H.	50% R.H.	10	20	30	40	50
2414	99.7	96.1	76.7	37.5	30.9	41.6	44.2	47.3	56.1	56.7
2420	77.4	53.5	21.2	1.7	1.0	45.4	51.6	57.6	71.2	67.2
2427	69.5	33.4	6.2	0.1	30.2	51.7	58.2	64.6	76.9	78.5
2451	31.1	17.1	1.4	0.1	10.0	51.6	59.3	71.7	76.8	76.2
2464	99.9	99.6	81.5	39.1	19.9	45.4	54.3	60.0	68.5	73.1
2465	84.4	69.7	26.1	2.7	2.2	42.9	50.2	59.2	62.6	65.2
2466	0.0	0.0	0.0	0.0	0.0	--[a]	--[a]	--[a]	--[a]	--[a]
2486	0.0	0.0	0.0	0.0	0.0	--[a]	--[a]	--[a]	--[a]	--[a]
2491	53.0	25.6	4.8	0.1	0.3	51.1	61.5	72.2	73.7	80.5
After High Humidity Relaxation Treatment										
2414	99.9	97.3	65.3	38.1	21.8	40.8	47.8	57.2	57.5	58.9
2420	78.3	42.8	11.0	1.6	1.5	48.4	55.3	64.1	64.5	65.8
2427	49.3	28.2	3.1	0.2	0.1	54.6	59.6	72.1	68.0	75.0
2464	99.9	100.0[b]	81.0	32.2	6.4	44.2	53.7	66.7	63.6	73.8
2465	81.6	69.4	21.9	1.6	0.5	43.6	51.8	63.5	57.7	68.2
2491	47.1	35.5	5.4	0.4	0.2	52.2	58.1	72.9	74.1	75.7
After Drying at 125°C. for 36 Hours										
2427	94.3	88.9	51.4	34.2	16.3	45.1	48.7	58.0	61.6	62.5
2451	96.0	92.9	51.9	39.1	10.0	41.1	49.2	57.9	57.1	59.0
2466	1.0	0.5	0.0	0.0	0.0	--[a]	--[a]	--[a]	--[a]	--[a]
2486	10.0	0.2	0.0	0.0	0.0	--[a]	--[a]	--[a]	--[a]	--[a]
2491	96.4	90.8	44.3	17.6	5.0	44.3	50.7	57.0	59.5	63.0

[a] In excess of Maximum angle (100°) permitted by tester.

[b] Arbitrarily considered as 99.9 for transformation to the normal deviate.

Note: Linerboard cracking angle corresponding to initial observed crack.

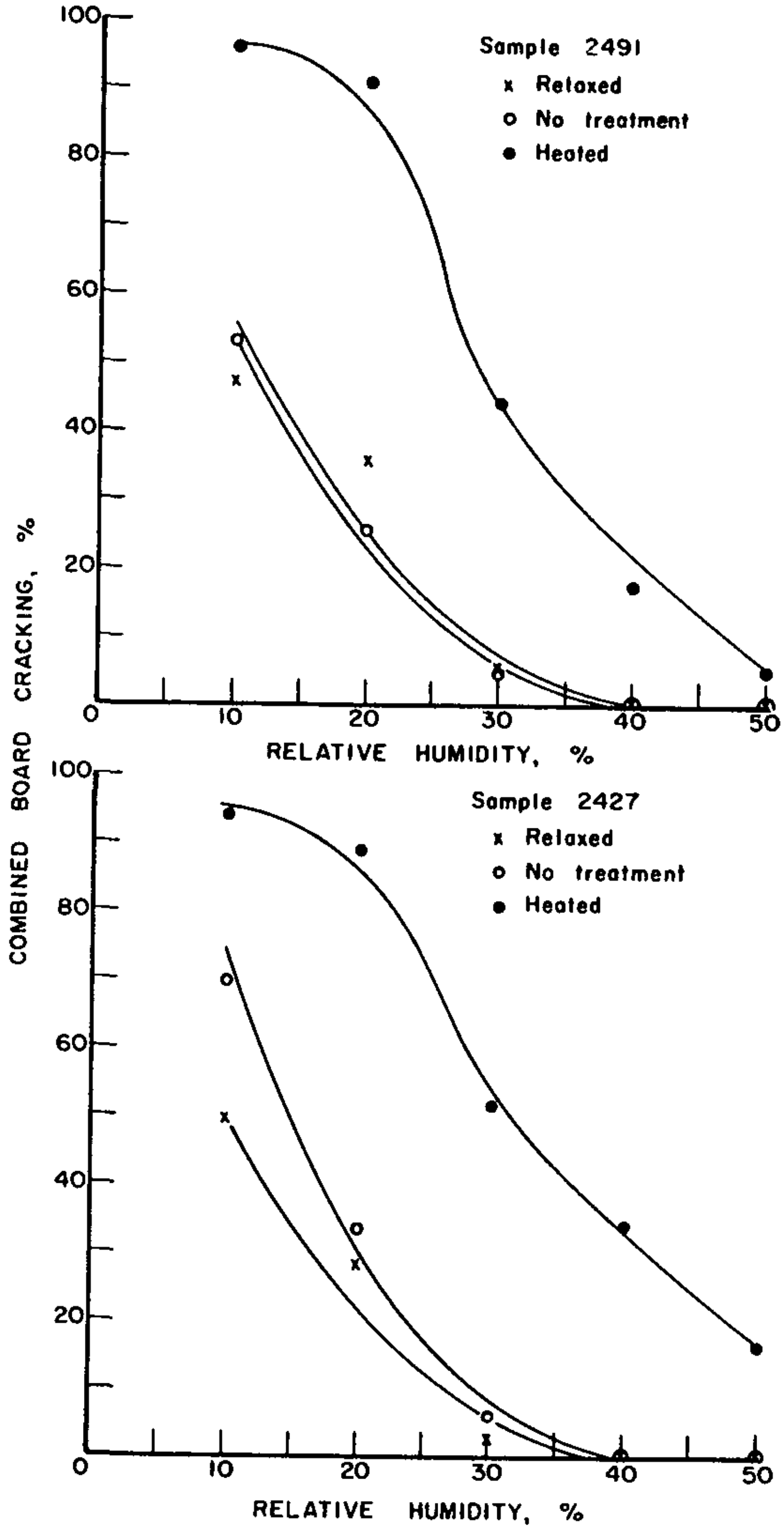

Figure 3. Effect of R.H. on Combined Board Cracking For Samples 2427 and 2491 (Linear Co-ordinates)

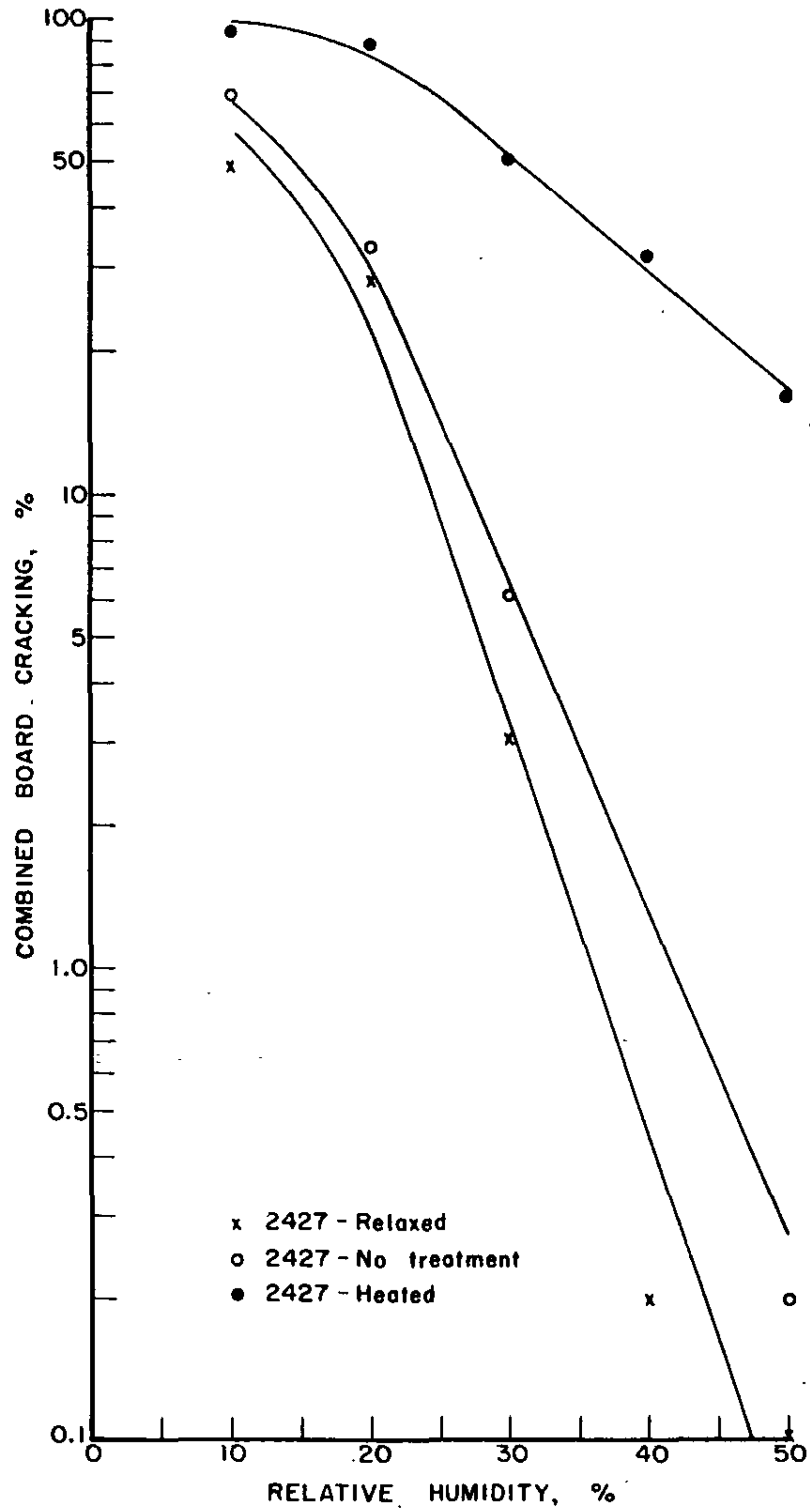

Figure 4. Effect of R.H. on Combined Board Cracking For Sample 2427 (Semilogarithmic Co-ordinates)

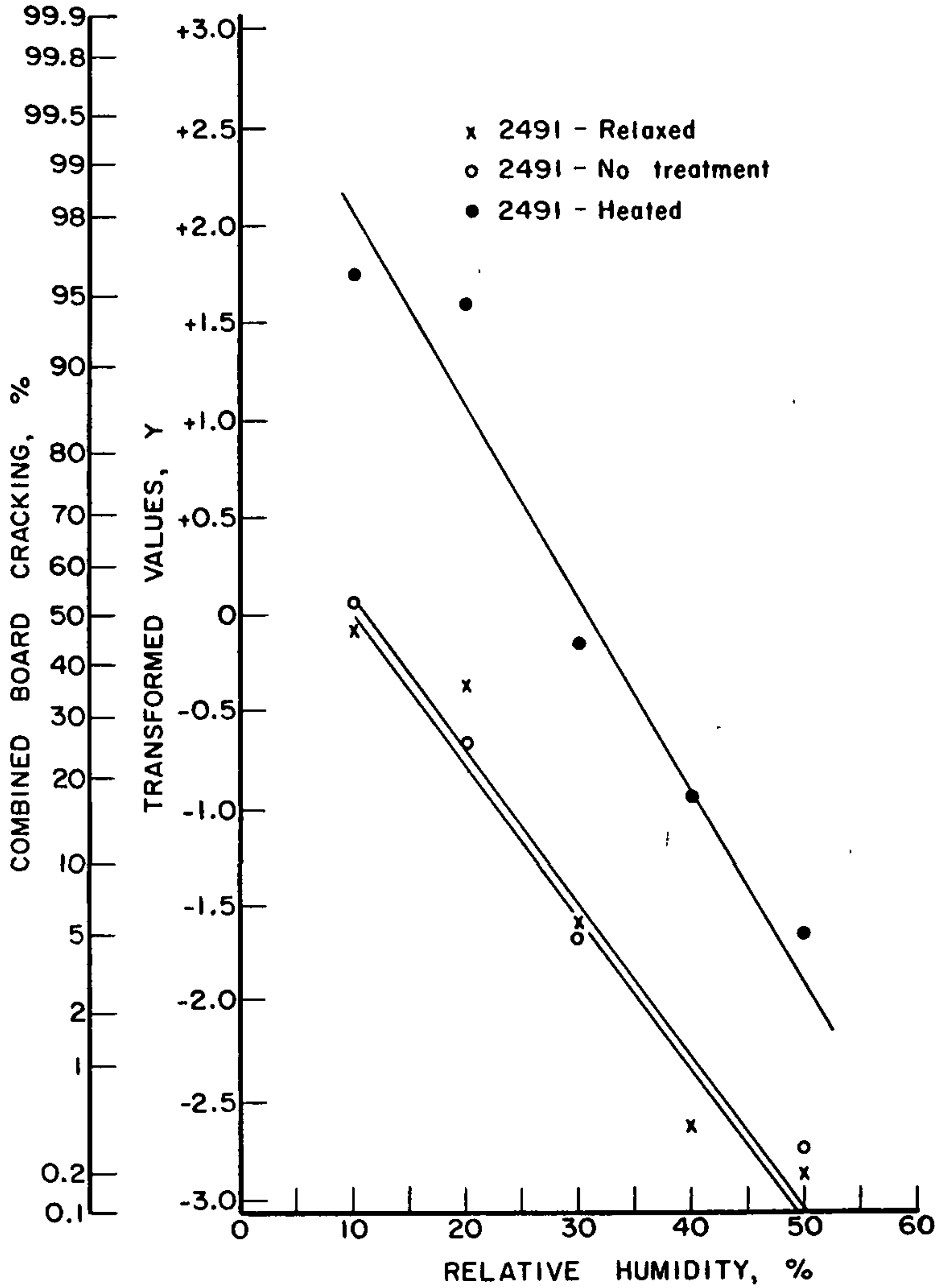

Figure 5. Effect of R.H. on Combined Board Cracking For Sample 2491
(Arithmetic Probability Co-ordinates)

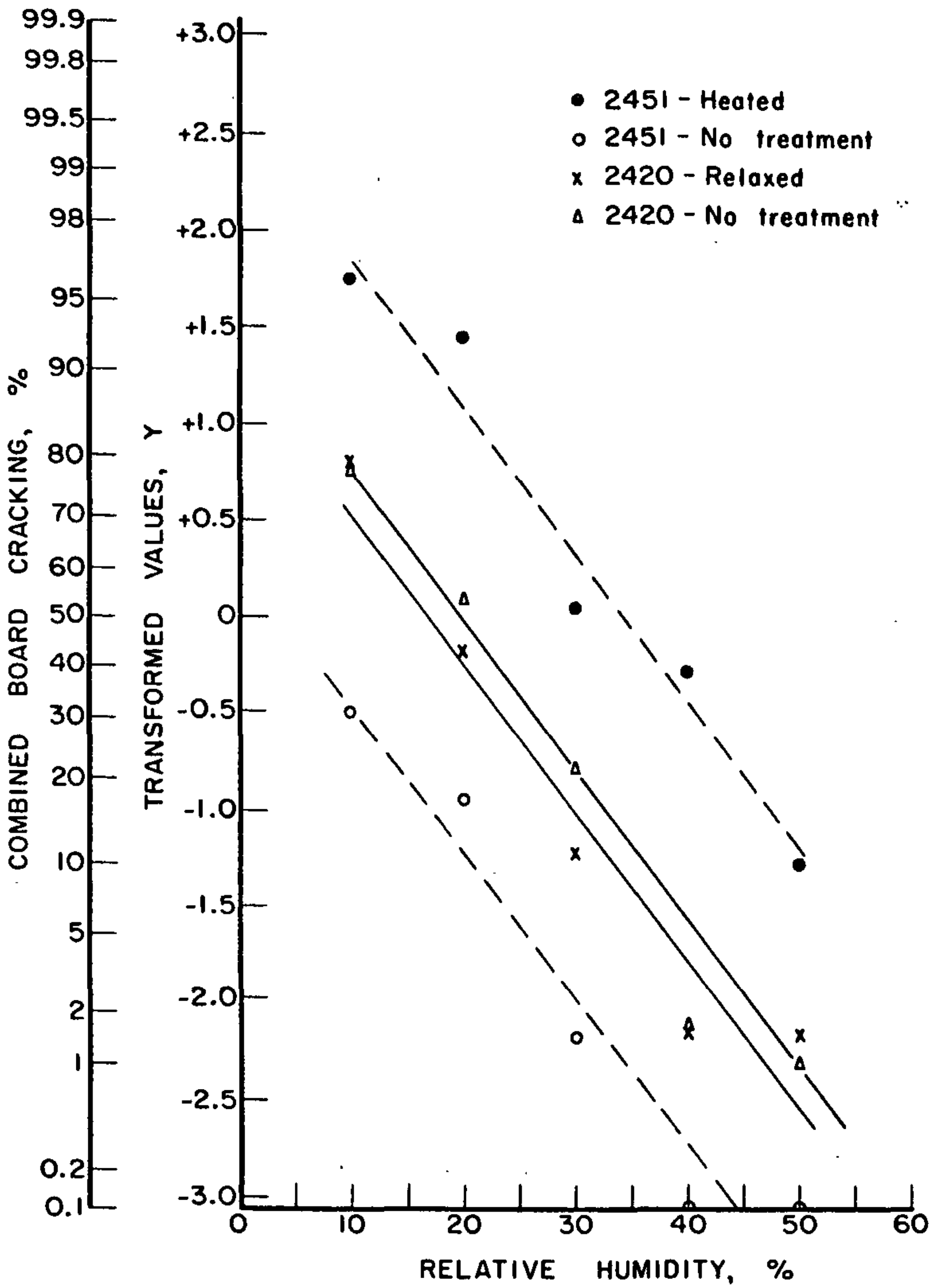

Figure 6. Effect of R.H. on Combined Board Cracking For Samples 2420 and 2457 (Arithmetic Probability Co-ordinates)

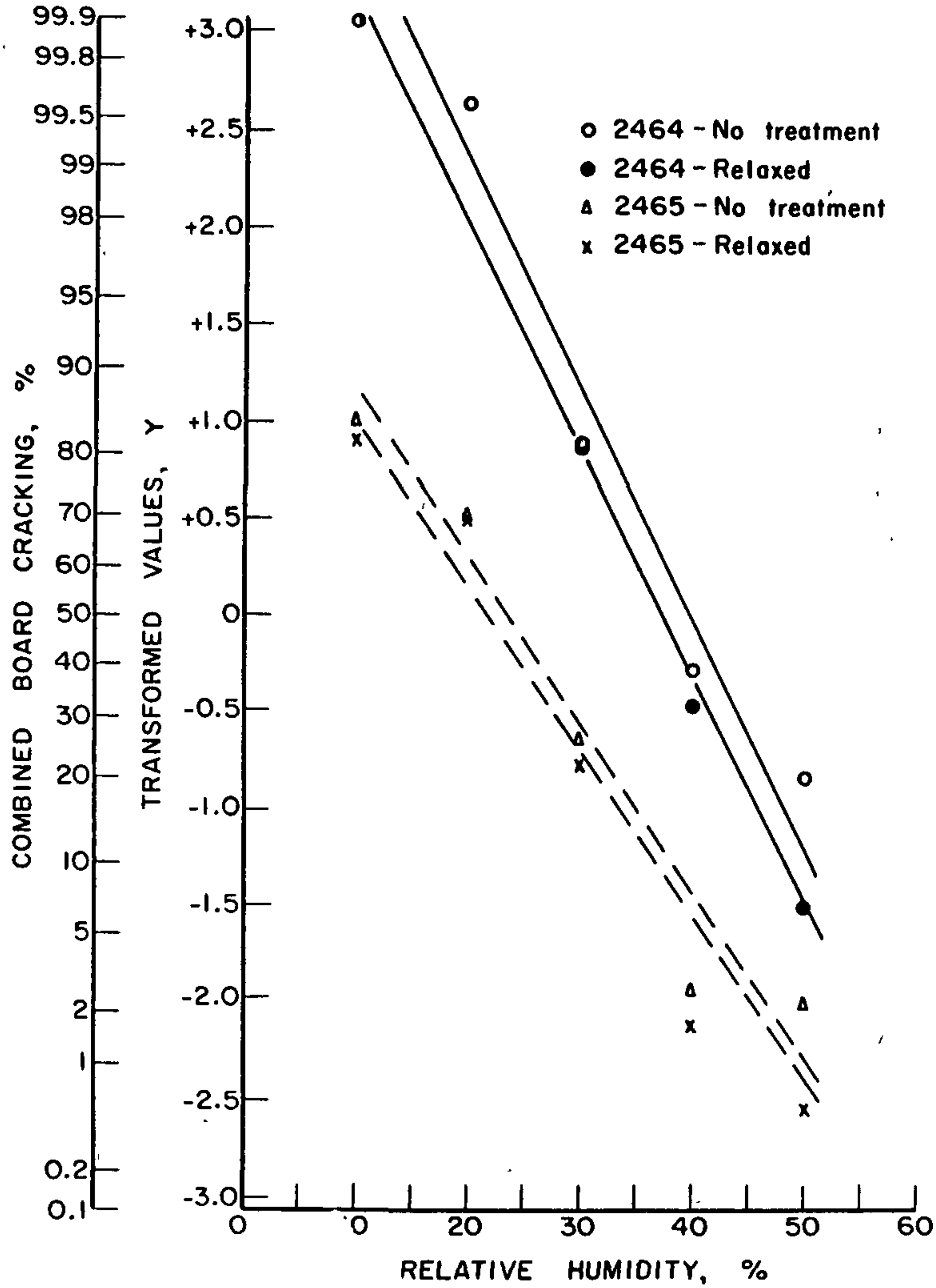

Figure 7. Effect of R.H. on Combined Board Cracking For Samples 2464 and 2465 (Arithmetic Probability Co-ordinates)

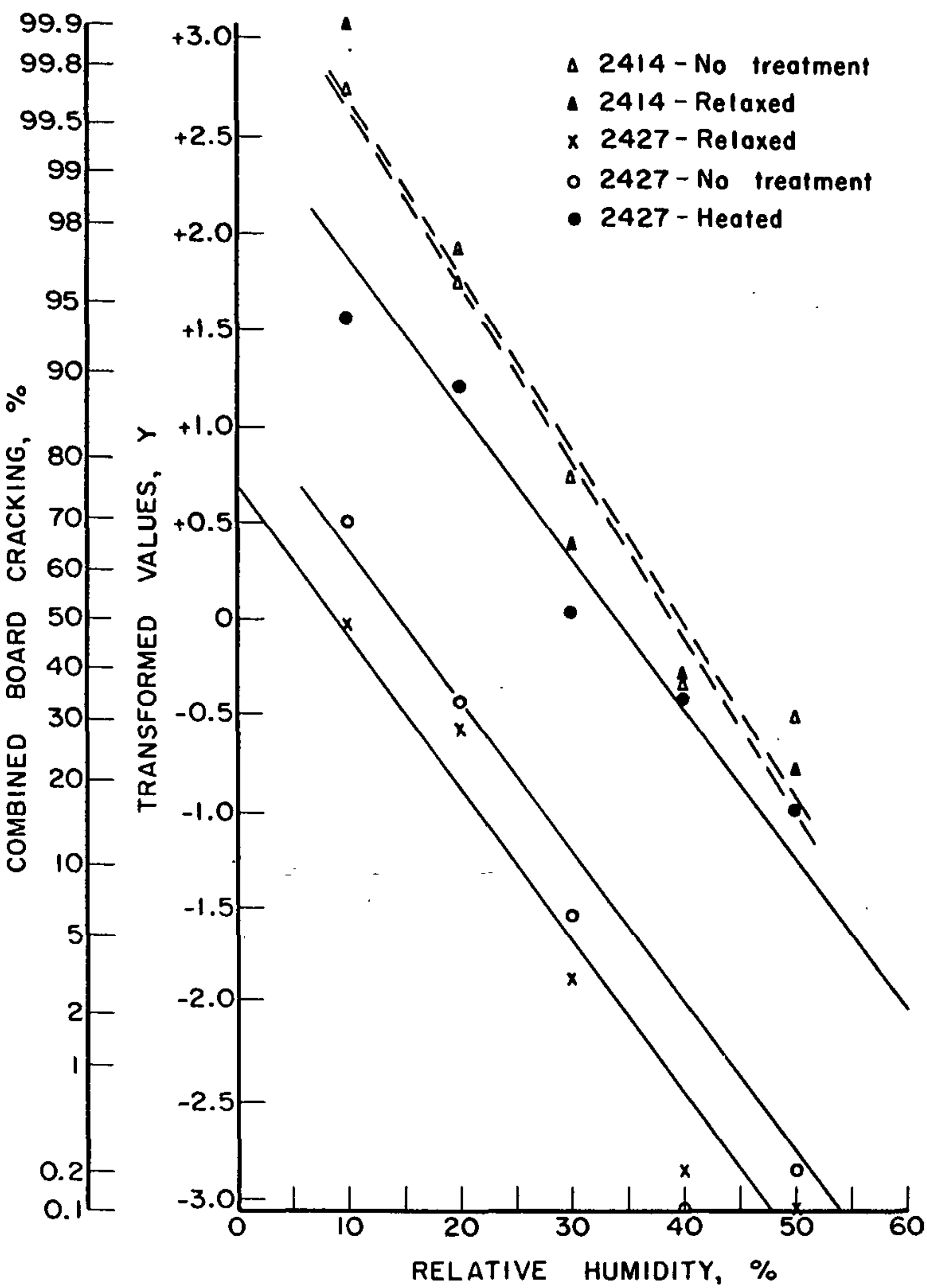

Figure 8. Effect of R.H. on Combined Board Cracking For Samples 2414 and 2427 (Arithmetic Probability Co-ordinates)

1. In linear co-ordinates the relationship of combined board cracking and relative humidity was markedly nonlinear.

2. In semilogarithmic and arithmetic probability co-ordinates more nearly linear relationships between combined board cracking and humidity were obtained.

On this basis, a statistical analysis was carried out for each sample using two types of regression function. They were (a) exponential: $p = a\,(10)^{bx}$ or $\log p = \log a + bx$ and (b) probability: $Y = c + dx$ where p = combined board cracking, %.

Y = combined board cracking, % transformed to standard deviation units (Note: The transformed values may be found in Appendix I.)

x = linerboard cracking angle, °

a, b, c, d = constants

In carrying out the transformation to normal deviate values, any table tabulating areas under the normal curve may be used. Such tables may be found in most statistical texts. Table A in Appendix III of Reference (3) was convenient and was used in this study.

Referring to Table III, it may be noted that either type of function appeared to give good fits to the data in terms of correlation coefficient. In general, however, the better correlation coefficients were obtained with the probability function. In this connection, it is particularly interesting to note that the slopes of the regression lines for the probability function were nearly equal for all samples except 2464—a laminated board sample, whose tensile

TABLE III

RELATIONSHIPS BETWEEN COMBINED BOARD CRACKING AND RELATIVE HUMIDITY

Sample	Data Subdivision	Probability[a] Intercept	Probability[a] Slope	Probability[a] Correlation Coefficient	Exponential[b] Intercept	Exponential[b] Slope	Exponential[b] Correlation Coefficient
2414	Untreated	3.458	−0.0858	−0.98	2.21387	−0.0143	−0.95
	Relaxed	3.857	−0.0997	−0.98	2.26322	−0.0173	−0.97
	Combined	3.658	−0.0928	−0.98	2.23854	−0.0158	−0.95
2420	Untreated	1.629	−0.0837	−0.98	2.61738	−0.0528	−0.96
	Relaxed	1.370	−0.0786	−0.97	2.44817	−0.0486	−0.97
	Combined	1.500	−0.0812	−0.98	2.53278	−0.0507	−0.96
2427	Untreated	1.346	−0.0944	−0.96	2.77353	−0.0761	−0.93
	Relaxed	0.844	−0.0844	−0.98	2.64752	−0.0753	−0.98
	After heating	2.315	−0.0675	−0.99	2.25797	−0.0194	−0.97
	Combined	1.502	−0.0821	−0.78	2.55967	−0.0569	−0.73
2451	Untreated	0.238	−0.0734	−0.96	2.33996	−0.0722	−0.96
	After heating	2.685	−0.0781	−0.98	2.35398	−0.0234	−0.92
	Combined	1.462	−0.0758	−0.67	2.34697	−0.0478	−0.62
2464	Untreated	4.345	−0.1081	−0.98	2.30229	−0.0181	−0.93
	Relaxed	4.847	−0.1277	−0.97	2.50811	−0.0288	−0.89
	Combined	4.596	−0.1179	−0.97	2.40520	−0.0234	−0.87
2465	Untreated	1.953	−0.0857	−0.98	2.56586	−0.0458	−0.95
	Relaxed	2.065	−0.0857	−0.98	2.57733	−0.0486	−0.93
	Combined	2.009	−0.0909	−0.98	2.57160	−0.0472	−0.94
2491	Untreated	0.766	−0.0800	−0.95	2.52894	−0.0690	−0.92
	Relaxed	0.854	−0.0790	−0.98	2.57937	−0.0669	−0.97
	After heating	2.826	−0.0914	−0.99	2.49146	−0.0328	−0.96
	Combined	1.482	−0.0835	−0.82	2.53326	−0.0563	−0.80
Composite		2.266	−0.0884	−0.72	2.46681	−0.0443	−0.63

[a] Combined board cracking transformed to normal deviate.

[b] Exponential function: Log p = Log a + bx.

and shear characteristics would be expected to be markedly different from unlaminated boards. The fact that the slopes of the regression lines for the other samples are nearly equal suggests that, for many purposes, a regression line of average slope could be used to represent the change in combined board cracking with relative humidity for all but laminated 90-lb. boards. For this situation, boards of varying characteristics would be represented by lines of equal slope but different intercepts. For example, in Fig. 9 the average regression line is shown together with lines drawn parallel through it to give per cent cracking levels at 30% R.H. of 0.1, 0.5, 1, 2, 5, 10, and 20% cracking. Thus, for example, if it were known that a given sample of board exhibited about 10% cracking at 30% R.H. (or equivalent in moisture content) then the expected degree of cracking at other humidity levels may be read from the graph or computed using the appropriate regression equation and "area" table.

To briefly sum up, an analysis of the relationship between combined board cracking and relative humidity indicated that.

1. Exponential or probability type functions appeared to fit the data well with somewhat higher correlation coefficients being attained with the probability functions.

2. The slopes of the regression lines for the probability-type functions were approximately equal for all samples except the laminated material. This suggests that estimates of cracking for any humidity level (within the range tested) may be made if the degree of cracking at any one humidity level is known.

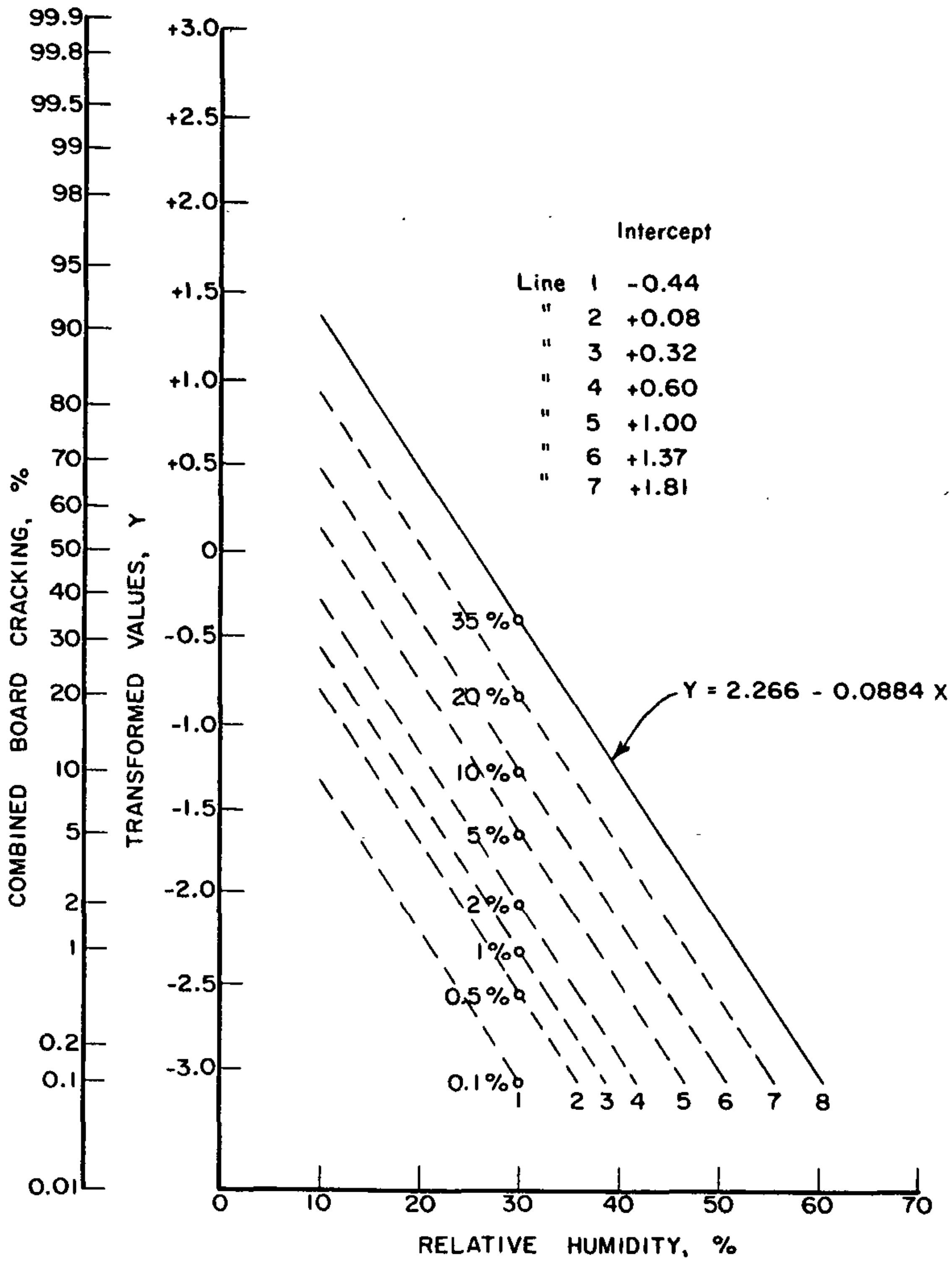

Figure 9. Relationship Between Combined Board Cracking and R.H. For Various Degrees of Cracking at 30% R.H.

RELATIONSHIP BETWEEN COMBINED BOARD AND LINERBOARD CRACKING

The relationships between the linerboard cracking test and combined board cracking were explored using several different types of function. These results are tabulated in Table IV and graphically illustrated in Fig. 10 through 12. In Fig. 10, the results are plotted in linear co-ordinates, in Fig. 11 semilogarithmic co-ordinates were used, and in Fig. 12 arithmetic probability co-ordinates were used. Inspection of the figures suggests that either the exponential or probability co-ordinates give more nearly linear relationships over the entire range of data.

It may be noted in the figures that the data points for the laminated Sample CS2464 tend to be considerably displaced from the remaining data. This possibly occurs because the shear and tensile characteristics of the laminated board could be expected to differ significantly from the other board samples. Because the linerboard cracking test does not exactly simulate the strains induced during combined board folding, it appears that a separate relationship is required for laminated board samples. For this reason, the results for this sample were treated separately in the analysis.

Referring to Table IV, it may be noted that.

1. The inclusion of nonlinear terms in regressions of the form $\underline{p} = \underline{a} + \underline{bx} + \underline{cx}^2$ ... appeared to significantly improve the correlation (See regressions 1, 2, and 3). These regression equations were regarded, however, as somewhat awkward for predictive purposes.

2. The use of liner cracking angle values to the square or cubic powers in the simple exponential equations also appeared to improve the correlations for the entire data. The use of the angle value squared appeared to

TABLE IV

CORRELATION OF COMBINED BOARD CRACKING AND THE LINERBOARD CRACKING TEST

Regression No.	Data Subdivision	N	Regression Equation	Correlation Coefficient		Type of Function
1	All except laminated[a]	70	$p = 178.6 - 2.42$	0.85	3	Linear
2			$p = 125.9 - 0.247 X - 0.0209 x$	0.87		Two factor
3			$p = 57.8 + 10.4 x - 0.316 x + 0.0022 x^2$	0.95		Three factor
4			$\text{Log } p = 4.8054 - 0.0640 x$	0.81	4	Exponential
5			$\text{Log } p = 3.4029 - 0.000656 x^2$	0.89	1	Exponential
6			$\text{Log } p = 2.7228 - 0.00000742 x^3$	0.91		Exponential
7			$Y = 5.93 - 0.112 x$	0.87	2	Probability
8	10% R.H.[a]	14	$p = 119.7 - 1.00 x$	0.55	2	Linear
9			$\text{Log } p = 2.1367 - 0.00636 x$	0.51	3	Exponential
10			$\text{Log } p = 2.1461 - 0.000139 x^2$	0.66	1	Exponential
11			$Y = 2.87 - 0.0417 x$	0.49	4	Probability
12	20% R.H.[a]	14	$p = 341.7 - 5.28 x$	0.95	1	Linear
13			$\text{Log } p = 4.0834 - 0.0444 x$	0.94	3	Exponential
14			$\text{Log } p = 2.9134 - 0.000417 x^2$	0.94	3	Exponential
15			$Y = 9.71 - 0.175 x$	0.94	3	Probability
16	30% R.H.[a]	14	$p = 212.8 - 2.96 x$	0.89	4	Linear
17			$\text{Log } p = 5.3063 - 0.0657 x$	0.90	3	Exponential
18			$\text{Log } p = 3.3042 - 0.000532 x^2$	0.92	1.5	Exponential
19			$Y = 6.14 - 0.111 x$	0.92	1.5	Probability
20	40% R.H.[a]	14	$p = 115.9 - 1.58 x$	0.73	4	Linear
21			$\text{Log } p = 8.0447 - 0.1179 x$	0.88	1.5	Exponential
22			$\text{Log } p = 4.1628 - 0.000883 x^2$	0.88	1.5	Exponential
23			$Y = 6.37 - 0.125 x$	0.86	3	Probability
24	50% R.H.[a]	14	$p = 70.55 - 0.943 x$	0.76	4	Linear
25			$\text{Log } p = 7.2780 - 0.105 x$	0.93	1	Exponential
26			$\text{Log } p = 3.6708 - 0.000752 x^2$	0.92	2	Exponential
27			$Y = 4.99 - 0.104 x$	0.91	3	Probability

TABLE IV (Continued)

CORRELATION OF COMBINED BOARD CRACKING AND THE LINERBOARD CRACKING TEST

Regression	Data Subdivision	N	Regression Equation	Correlation Coefficient		Type of Function
28	Laminated (2464)	10	$p = 248.95 - 3.03\,x$	0.87	2	Linear
29			$\log p = 3.4959 - 0.0297\,x$	0.79	4	Exponential
30			$\log p = 2.6766 - 0.000260\,x^2$	0.82	3	Exponential
31			$Y = 10.60 - 0.158\,x$	0.93	1	Probability

Note. p = Combined board cracking, %, Y = Combined board cracking, % transformed to standard deviation units.
x = Liner cracking angle, °

[a]Results for laminated sample 2464 not included.

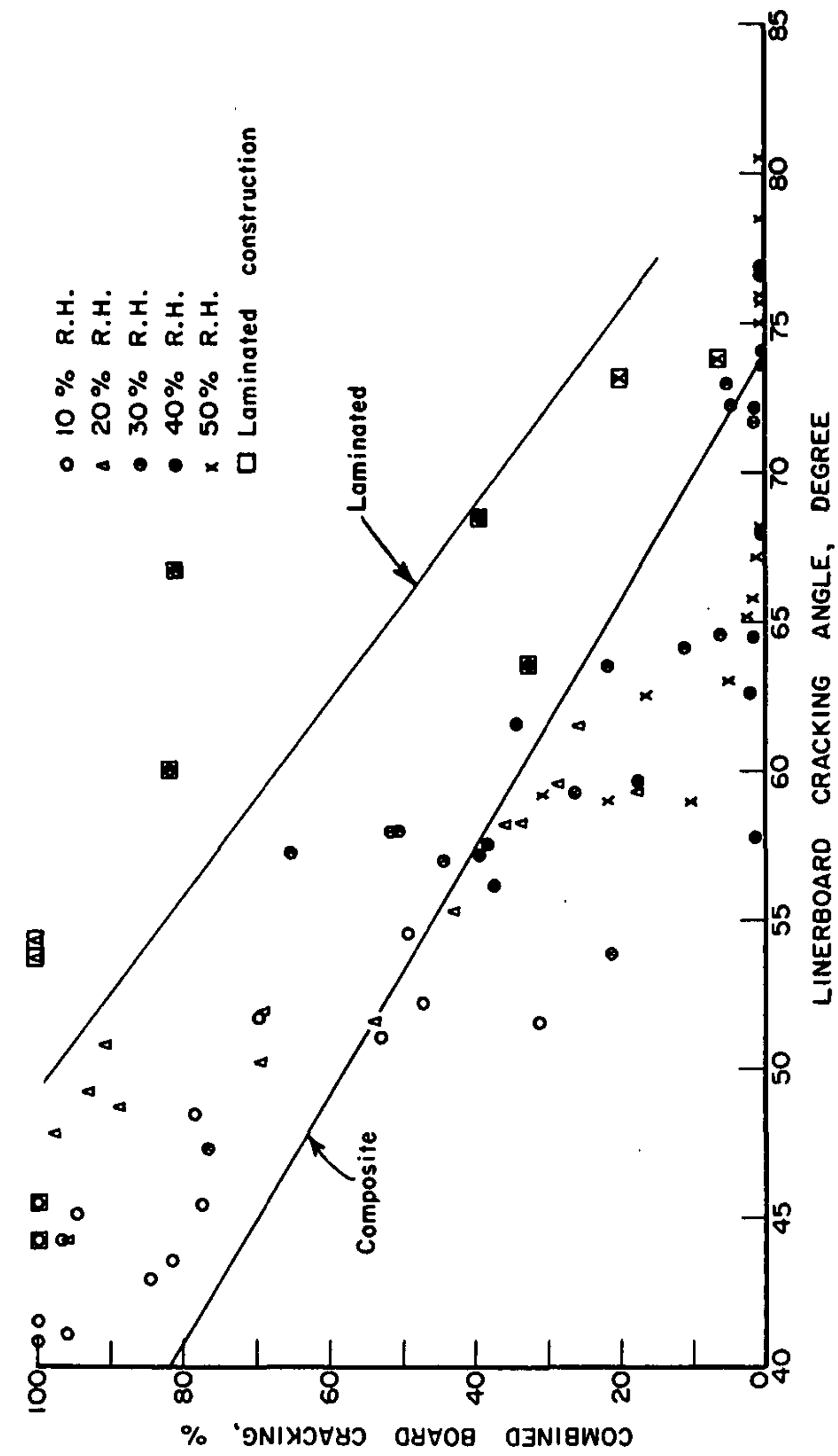

Figure 10. Relationship Between Combined Board Cracking and the Liner Cracking Angle (Linear Co-ordinates)

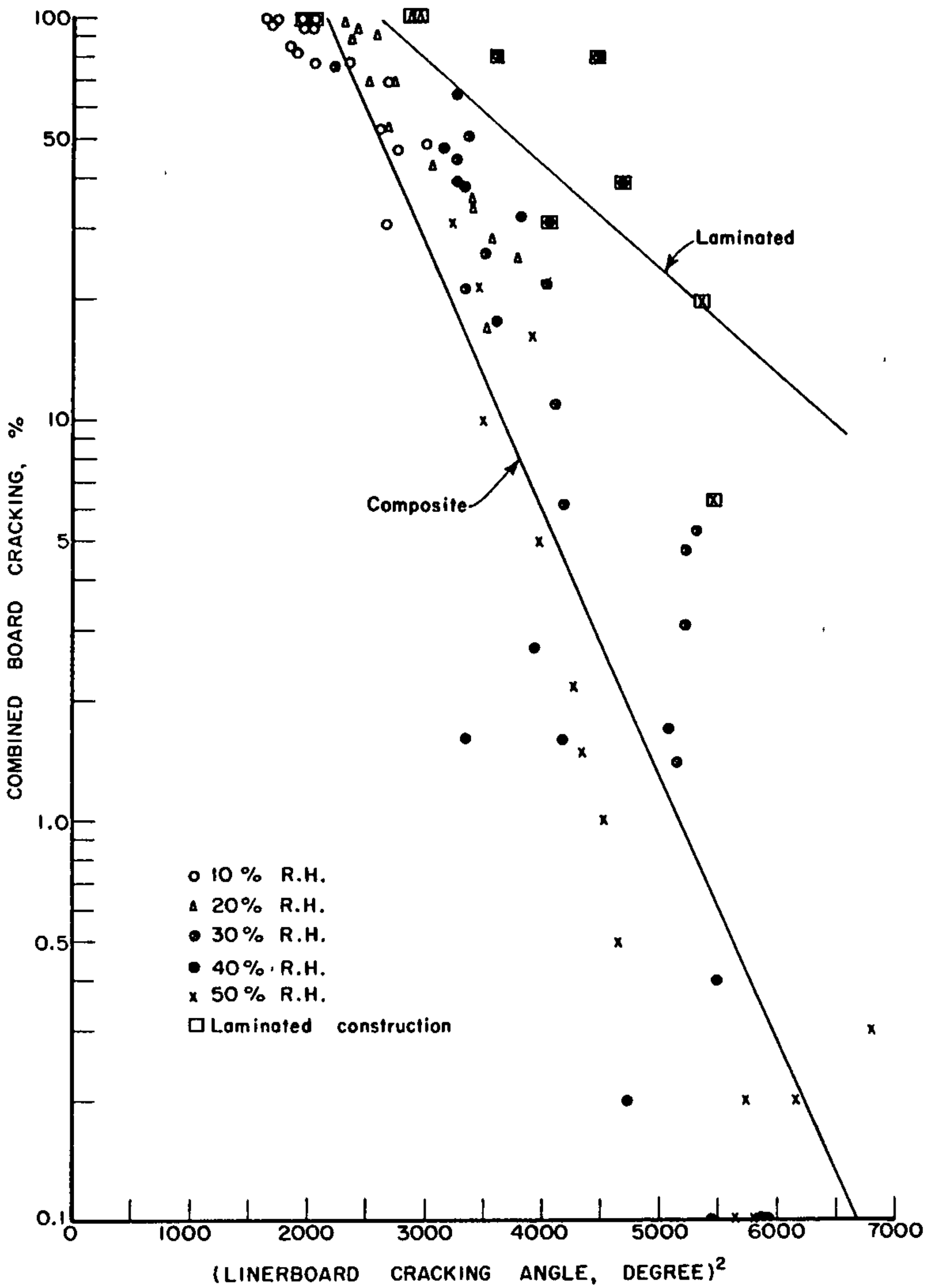

Figure 11. Relationship Between Combined Board Cracking and the Square of the Liner Cracking Angle (Semilogarithmic Co-ordinates)

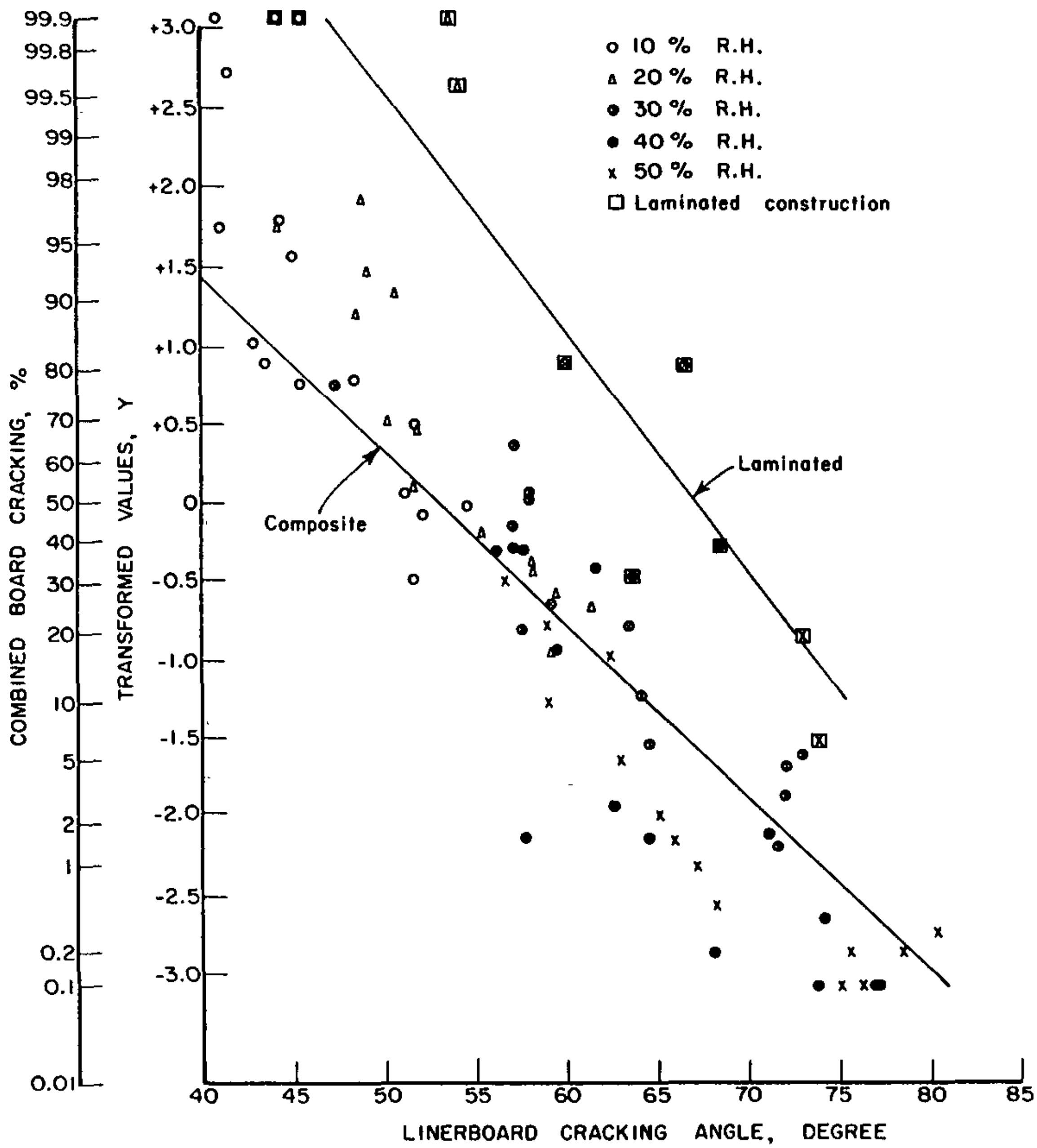

Figure 12. Relationship Between Combined Board Cracking and the Liner Cracking Angle (Arithmetic Probability Co-ordinates)

give the major improvement in correlation. (See regressions 4,5, and 6). For the individual humidity levels the differences were often quite slight, however, (see regressions 9, 10, 13, 14, 17, 18, 21, 22, 25 and 26).

3. In terms of correlation coefficient, none of the functions were markedly inferior. Which to use, therefore, is partly a matter of taste, however, it is thought that the probability function may have the most general application.

Using the graph or regression lines in Table IV for the combined data, estimates were made of the minimum average liner cracking angle required to give combined board having 0.1, 0.5, 1, 2, 5, and 10% cracking. These estimates are shown below.

Minimum Cracking Angle, °

Cracking, %	Linear (Regression 1)	Exponential (Regression 5)	Probability (Regression 7)
0	74	--	--
0.1	74	82	81
0.5	74	75	76
1.0	73	72	74
2.0	73	69	71.5
5.0	72	64	68
10.0	70	61	65

As may be noted, the minimum cracking angle required by the three equations at the various levels of combined board cracking is quite different.

Regression 1 implies that a liner cracking angle of about 74° would be sufficient to give no combined board cracking; however, minor amounts of severe cracking were encountered in this study at angles as great as 80°. From this standpoint, regressions 5 and 7 are probably more realistic. At the other extreme of 10% cracking, the linear equation gives a minimum angle of 70°; however, the graphs indicate no samples exhibiting 10% cracking with liner angles near 70°. In this case, regression 7 appeared to yield the more realistic estimate. On this basis, regressions 5 and 7 may be favored.

Too much attention cannot be given the specific figures mentioned in these examples because of the subjective nature of both the combined board and linerboard evaluation. If other individuals evaluated these or similar samples, it may be anticipated that the results would differ in magnitude from those cited herein; however, it is believed that the trends exhibited by such data would be similar to those reported herein. In addition, it may be desirable to investigate several additional variables in the linerboard tester. They are:

1. Anvil diameter
2. Location of center of rotation
3. Spacing between anvils

Finally, a few tests have suggested that torque vs. angle of rotation measurements may show a peak when the specimen cracks. If so, this would permit converting the test from a subjective to objective evaluation and would have merit when many personnel may be required to perform the evaluations.

As mentioned above, Regression 7 suggests that linerboard having a minimum average rupture angle of 74° may be fabricated into combined board and exhibit no more than about 1% cracking when folded in the same atmosphere in which the liner test was conducted. The degree of combined board cracking in other atmospheres may be estimated using the combined board cracking vs. R.H. relationships previously developed. For example, if the liner cracking test (74° average) was conducted at 30% R.H., then line 3 in Fig. 9 would indicate that the cracking at 20% R.H. would be near 7 or 8%. For the same test average but at 47% R.H., line 7 in Fig. 9 indicates the cracking at 20% R.H. would be near 51-52%. Thus, the two analyses complement each other.

To briefly summarize, the data of this study appeared to indicate that:

1. The linerboard cracking test devised at the Institute may be a practical means for evaluating the cracking potential of linerboard because it appears to be significantly related to combined board cracking. Recommendations with regard to possible improvements are mentioned in the text.

2. The relationship between combined board cracking and relative humidity was such that a probability-type equation appeared to fit the data reasonably well.

3. Exponential or probability-type equations appeared to best fit the liner cracking vs. combined board cracking data. While either may be used, the probability form is preferred at this time.

4. Separate relationships between combined board cracking and the liner cracking angle appeared to be required for unlaminated and laminated 90-lb. boards. It is hypothesized that this is due to a probable difference in shear characteristics for the two types of board.

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APPENDIX I

COMBINED BOARD CRACKING PERCENTAGES TRANSFORMED TO NORMAL DEVIATE VALUES

Sample No.	Combined Board Cracking, Transformed[b]				
	10	20	30	40	50
2414	+2.75	+1.76	+0.73	-0.32	-0.50
2420	+0.75	+0.09	-0.80	-2.12	-2.33
2427	+0.51	-0.43	-1.54	-3.09	-2.88
2451	-0.49	-0.95	-2.20	-3.09	-3.09
2464	+3.09	+2.65	+0.90	-0.28	-0.85
2465	+1.01	+0.52	-0.64	-1.93	-2.05
2491	+0.08	-0.75	-1.66	-3.09	-2.75
After High Humidity Relaxation Treatment					
2414	+3.09	+1.93	+0.39	-0.30	-0.78
2420	+0.78	-0.18	-1.23	-2.14	-2.17
2427	-0.02	-0.58	-1.87	-2.88	-3.09
2464	+3.09	+3.09[a]	+0.88	-0.46	-1.52
2465	+0.90	+0.51	-0.78	-2.14	-2.58
2491	-0.07	-0.37	-1.61	-2.65	-2.88
After Drying At 125°C. for 36 Hours					
2427	+1.58	+1.22	+0.04	-0.41	-0.98
2451	+1.75	+1.47	+0.05	-0.28	-1.28
2491	+1.80	+1.33	-0.14	-0.93	-1.64

[a] Arbitrarily taken as equal to 99.9%.

[b] Transformed to normal deviate values using statistical table giving area under normal curve. (3).