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EVALUATION OF THE EFFECT OF PROCESSING
PARAMETERS ON THE ADHESIVE BONDING OF
GLASS-REINFORCED PLASTICS

D. W. LEVI
A. T. DEVINE
W. C. TANNER
R. F. WEGMAN
M. J. BODNAR
M. D. ANDERSON

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20. ABSTRACT (Continued)

for the EC-2214 and AF-126 systems. No appreciable difference between hand or machine sanding was discerned for the Epon 828/V-140 system. Only in the case of AF-126 were bond strengths significantly lower after aging 30 days at 120°F (49°C) and 95% RH. These results indicate that the effect of processing parameters on resultant bond strengths is highly dependent on the adhesive system used in bonding the glass-reinforced plastic.

Methods are described and curves are shown illustrating how smoothed distribution curves of bond strength can be used to observe data overlap and differences. Such methods can be helpful to the engineer in deciding on tradeoffs involving sacrificing a little in optimum properties in order to attain maximum fabrication ease and efficiency.

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INTRODUCTION

In an earlier report (ref. 1), the effects of several processing variables on the strength and durability of adhesive-bonded, glass-reinforced plastic were investigated. Three adhesives (Epon 828/V-140, EC-2214, AF-126) were used with a four-ply, bioriented, glass-reinforced epoxy laminate (3M XP-114). Variables studied included surface exposure time (SET) from 1-4 hours up to 30 days, hand sanding as compared to machine sanding in surface preparation, and conditioning for 7 days at 73°F (23°C) and 50% RH and for 30 days at 120°F (49°C) and 95% RH.

The work reported in reference 1 involved the generation of a significant volume of shear strength data after each of the various treatments. However, interpretation of the results was not always entirely straightforward because the differences in strength after the various treatments, while frequently appreciable, tended to be relatively small with a good deal of data overlap. The use of average strength values often raised a question as to whether the differences were really significant. In this report, we re-examine the data using simple statistical approaches. Thus, it is possible to determine the cases where the differences were statistically significant. These determinations make it easier to specify the occasions where explanations of differences are really required.

The shear strength data for the three adhesives bonded to the glass reinforced plastic are graphically summarized in figure 1. The distribution curve for each set of data was determined by using the two parameters calculated for the linear Weibull distribution function. Each distribution curve in the figure represents a statistically significant entity, as determined by the significance tests discussed later in this report. For example, comparing the curves for adhesive AF-126, shows that machine sanding leads to somewhat stronger bonds than hand sanding. Also, the 7 days aging of AF-126 results in stronger shear strengths than the harsh environment conditions. Details of the similarities and differences are also discussed later in this report. Figure 1 is used only to illustrate the overlap in data and the statistically significant differences; the curves are calculated from the linearized Weibull parameters and hence represent the primary data as smoothed curves. An estimate of the quality of fit is given by the correlation coefficients in table 1 for the linear Weibull plots.

The basic detailed data in reference 1 was recorded as breaking loads (pounds or newtons) and these units are used in the current report. The shear strength specimens were 2.54 cm (1 inch) wide with a 1.27 cm (0.5 inch) overlap.

RESULTS AND DISCUSSION

Note. The experimental procedures are given in detail in reference 1.

Epon 828/V-140

The raw data for this adhesive system is in table 2. For convenience, the values are arranged in the order of increasing breaking load; and, the surface exposure time (SET) is coded beside each value.

Examination of table 2 indicates that, although there is a considerable overlapping of data, the values after 30 days SET appear to be somewhat low. To test this observation, the Wilcoxon Sum of Ranks test was used (refs. 2-4). In order to illustrate this method, the data from column 1 of table 2 is reproduced in table 3 which shows that the test determines if the 30 hours SET data (code VI) is significantly lower than the other values. Note that the data is in two groups (A and B). Rank values are obtained by numbering and it should also be noted that numbering may be either from bottom to top or from top to bottom because a significant difference may exist on either the low or the high side. In the present case, the B values are near the top and the numbering from top to bottom is sufficient. In any case, the sum of the A rank or B rank column that gives the smallest number is the one used in the test. In table 3 this sum is $R = 19.5$ as shown.

In determining if the A and B ranks are significantly different, table 4 can be used with up to 20 measurements in each sample. With more than 20 measurements in one or both samples, the significance of the smaller rank total (R) is found by calculating Z from the formula

$$Z = \frac{n_R(n_A+n_B+1) - 2R}{\left(\frac{n_A n_B (n_A+n_B+1)}{3}\right)^{\frac{1}{2}}} \quad (1)$$

Where n_R is the number of measurements in whichever sample gives the smaller rank total. It may equal either n_A or n_B depending on the circumstances. Values of Z corresponding to important probability levels are as follows:

Z Table

P = 10%	P = 5%	P = 1%	P = 0.2%
Z = 1.64	Z = 1.96	Z = 2.58	Z = 3.09

Since in table 3 the A samples consist of 25 measurements ($n_A = 25$) and there are 5 values in the B samples ($n_B = 5$), we must use equation 1 and the above Z table. From table 3, $Z = 3.22$ in equation 1. From the Z table above P is less than 0.2%. This means that in less than one case in 500 these results would have been obtained by chance. Usually anything less than one chance in 20 (i.e., $P = 5\%$) is taken to mean that there is a significant difference. In this case, the 30 days SET strengths are interpreted as being significantly lower than the remaining data.

The Wilcoxon Sum of Ranks test was applied to each of the other 3 columns of table 2 in testing for differences between 30 days SET and the other SET values combined. The following results were obtained:

7 days aging - Hand sanding Compare: To 14 days with 30 days SET	Z = 3.22	P < 0.2%	Significant difference
7 days aging - Machine sanding Compare: To 14 days with 30 days SET	Z = 3.22	P > 5%	Probably no significant difference
30 days aging - Hand sanding Compare: To 14 days with 30 days SET	Z = 2.14	P < 5%	Probably a significant difference
30 days aging - Machine sanding Compare: To 14 days with 30 days SET	Z = 2.67	P < 1%	Significant difference

Thus, in 3 out of 4 cases the 30 days SET test results appear to be significantly low. For the 7 days, 73°F (23°C), 50% RH with machine sanding, P is slightly more than 5%, so that 30 days SET does not appear to be significantly low in this case. By tentatively assuming that the data in table 2 may be combined, and using the Wilcoxon

rank test to compare all 30 days SET with all SET up to 14 days, the following results were obtained:

All data

Compare: To 14 days with 30 days SET $Z = 4.64$ $P < 0.2\%$ Very significant difference

The foregoing results clearly indicate that using 30 days SET will probably degrade the bond strength to some extent. Therefore, this condition (30 days SET) was eliminated for the Epon 828/V-140 system and is not included in the subsequent discussion.

The next questions that were addressed for the SET data up to 14 days involved any differences between hand and machine sanding as well as possible difference between 7 days, 73°F (23°C), 50% RH and 30 days, 120°F (49°C), 95% RH. Eliminating 30 days SET data and tentatively assuming that all the remaining data in table 2 does not differ significantly, the Wilcoxon Sum of Ranks test was used to test for possible differences arising from hand or machine sanding and between the two conditioning treatments. For the comparison of the conditioning treatments the results are:

To 14 days SET - Hand sanding
Compare: 7 days with 30 days aging $Z = 1.06$ $P > 10\%$ No significant difference

To 14 days SET - Machine sanding
Compare: 7 days with 30 days aging $Z = 0.38$ $P > 10\%$ No significant difference

And for the comparison of hand and machine sanding:

To 14 days SET - 7 days and 30 days aging
Compare: Hand with machine sanding $Z = 1.46$ $P > 10\%$ No significant difference

With the elimination of 30 days SET, it appears that there are no discernible differences in bond strengths after either hand or machine sanding, or after either of the aging conditions.

The above discussion is based on the tentative assumption that there are no significant differences in SET times from 1-4 hours to 14 days. This assumption proved to be not completely true upon testing. The 1-4 hours SET appears to show a small but probably

significant difference on the high side. The comparison, using the same procedure as before, gave the following results:

All data

Compare: 1-4 hr SET with 1-14 days SET	Z = 2.75	P < 1%	Probably significant difference
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Since the data (based on the above) must be divided into two groups, namely 1-4 hours SET and 1-14 days SET, the equivalence of hand and machine sanding and of the 7 days and 30 days aging were checked for each group. For the 1-4 hour SET the results are:

Compare: Hand with machine	Table 5	P > 5%	No significant difference
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1-4 hr SET

Compare: 7 days with 30 days aging	Table 5	P > 10%	No significant difference
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For the 1-14 days SET the test gave the following:

1-14 days SET

Compare: Hand with machine sanding	Z = 0.66	P > 10%	No significant difference
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1-14 days SET

Compare: 7 days with 30 days aging	Z = 0.57	P > 10%	No significant difference
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For bonding glass-reinforced plastic with Epon 828/V-140, one may conclude that hand and machine sanding are equivalent. Aging for 30 days at 120°F (49°C) and 95% RH has no appreciable effect on shear strength. There is a small decrease in strength for SET times of 1-14 days are compared to SET = 1-4 hours, although there is a considerable overlap in the data. Figures 1 and 2 show the general magnitude of this loss of strength at the longer SET times.

For each set of data, i.e., SET = 1-4 hours and SET = 1-14 days, the Weibull distribution was found to describe the data reasonably well. The Weibull distribution function was used in the form (refs. 5,6):

$$\log \log \left[\frac{1}{1-F(X)} \right] = - \log \alpha + \beta (X-\gamma) \quad (2)$$

Where $F(X)$ is the distribution function, i.e., the fraction of samples failing at a breaking load (lbs or N) of X or less, X corresponds to the breaking load values and α , β , and γ are the parameters of the distribution. A plot of the left-hand side of equation 2 versus $\log(X-\gamma)$ should give a straight line. γ may be selected on an iterative basis by making trial plots: α and β are evaluated from the slope and intercept.

In application to the data, all data points (20 or more) are tabulated in order of increasing breaking load. $F(X)$ is calculated on a point-by-point basis (i.e., the fraction failing at X or below) and $\log \log \left[\frac{1}{1-F(X)} \right]$ is plotted against $\log X$. A computer was used to calculate linear correlation coefficients. For our purposes, taking $\gamma = 0$ (using a two-parameter Weibull distribution) appears to be satisfactory.

The linear Weibull plots for the Epon 828/V-140 adhesive system are shown in figure 3. The correlation coefficient is 0.956 for 1-4 hours SET and 0.977 for 1-14 days SET (table 1). These plots reinforce the previous finding that the 1-4 hour SET gives bonds that are a little stronger, although there is much overlap of data.

Although figure 3 may be used to indicate the overlap and difference in breaking strength for 1-4 hour and 1-14 days SET, it is probably easier to make these comparisons using the appropriate differential distribution plots (fig. 1). The curves in figure 1 were calculated by (ref. 6):

$$f(X) = \frac{b}{a} \left[\frac{X}{a} \right]^{b-1} e^{-\left(\frac{X}{a}\right)^b} \quad (3)$$

In equation 2, $\alpha = b \log a - 0.36$ and $\beta = b$, so that:

$$\log \log \left[\frac{1}{1-F(X)} \right] = -b \log a - 0.36 + b \log X \quad (4)$$

Having determined α and β in equation 2 from the intercept and slope of the straight line (fig. 3), we can now estimate a and b in equations 3 and 4. For example, for the 1-4 hour SET in figure 3, the equation of the straight line is:

$$\log \log \left[\frac{1}{1-F(X)} \right] = -35.4 + 12.0 \log X$$

$$\beta = b = 12.0$$

$$\alpha = - b \log a - 0.36 = 12.0 \log a - 0.36 = - 35.4$$

$$\log a = \frac{35.04}{12.0}$$

$$a = 830$$

These values of a and b are then used in equation 3. For selected values of X over the range of interest, the frequency (f(X)) is then calculated by equation 3 and plotted as in figure 1. Figure 2 shows both the overlap of data and the differences between 1-4 hour SET and 1-14 days SET for the Epon 828/V-140 system. The user of the adhesive will have to decide if the small degradation in strength which occurs from using a convenient SET time of more than a few hours is acceptable.

EC-2214

The raw data for this adhesive system are shown in table 5. For convenience, the values have been arranged in order of increasing breaking load and the surface exposure time (SET) has been coded beside each value.

The general method used to examine Epon 828/V-140 data was also used to examine the EC-2214 adhesive. For the EC-2214, the 30 days SET loads were very noticeably low. A summary of the Wilcoxon Sum of Ranks test applied to each column of table 5 is given below. These tests compare 30 days SET with all SET times through 14 days.

7 days aging - Hand sanding				Significant
Compare: To 14 days with 30 days SET	Z = 2.92	P<1%		difference
30 days aging - Hand sanding				Significant
Compare: To 14 days with 30 days SET	Z = 2.61	P<0.2%		difference
30 days aging - Hand sanding				Significant
Compare: To 14 days with 30 days SET	Z = 3.08	P≅0.2%		difference
30 days aging - Machine sanding				Significant
Compare: To 14 days with 30 days SET	Z = 3.31	P<0.2%		difference

Since, in every case, the 30 days SET breaking loads were significantly lower than the others, the 30 days values were eliminated from further consideration.

For each of the four sets of data identified above (hand sanding, 1-4 hours SET; hand sanding, 1-14 days SET; machine sanding, 1-4 hours SET; machine sanding, 1-14 days SET), the two-parameter linear Weibull line was plotted according to equation 2. The plots are shown in figure 4. The least square lines are drawn and the correlation coefficients are given in table 6. It should be noted that for the 1-4 hours SET data, since there were less than 20 points, a table of plotting positions was used to make an adjustment for the smallness of the sample size (refs. 5,6).

The differential distribution curves for the EC-2214 data shown in figure 5 were calculated by equation 3 using the parameters from the linear Weibull plots and the procedure described in the prior discussion of Epon 828/V-140. For this system, it is evident that machine sanding in surface preparation leads to somewhat improved bonds when compared to hand sanding. Aging for 30 days at 120°F (49°C) and 95% RH has no appreciable effect on bond strength. 1-4 hours SET gives somewhat better bonds than the longer SET times. The data overlap and general magnitude of this effect are shown in figure 5.

AF-126

The raw data for the AF-126 system is in table 6. As in tables 2 and 5, the values are in the order of increasing breaking load and the surface exposure time (SET) is coded.

Use of the Wilcoxon Sum of Ranks test indicated that SET was immaterial for this system, i.e., that essentially the same breaking loads were observed at SET from a few hours up to 30 days. However, the test comparing hand and machine sanding indicated that the differences are probably significant, as indicated below:

All SET - 7 days aging			
Compare: Hand with machine sanding	Z = 2.28	P < 5%	Probably significant difference

All SET - 30 days aging			
Compare: Hand with machine sanding	Z = 3.24	P < 0.2%	Significant difference

Despite a good deal of data overlap, it appears that the machine sanding produced stronger bonds.

A comparison of the 7 days and 30 days aging also indicated that 30 days at 120°F (49°C) and 95% RH degraded the bonds significantly. The test results are given below:

All SET - Machine sanding
 Compare: 7 days with 30 days aging Z = 2.81 P<1% Significant difference

S11 SET - Hand sanding
 Compare: 7 days with 30 days aging Z = 3.21 P<0.2% Significant difference

The significant differences described above using the simple rank tests were verified by a more effective t-test which was performed because the data indicated a large overlap. (The rank tests tend to give slightly higher probability levels than their more complicated alternatives (ref. 2)).

The t-test for testing two independent random samples generally fits experiments for comparing the effects of two treatments (ref. 7). This is the situation that obtains in the present case. The necessary data for accomplishing this test are shown in summary table 7. In this table "hand" and "machine" refer to the type of sanding, 7 days represents 7 days at 73°F (23°C) and 50% RH and 30 days corresponds to 30 days at 120°F (49°C) and 95% RH. n is the number of data points, DF = n-1 is degrees of freedom, \bar{Y} is the mean, and Y_1 represents the value of an individual data point. The sum of squares is obtained by determining individual differences between the data value and the mean, squaring, and then summing the squares.

The t-test may now be illustrated with a sample calculation. For this purpose we will compare hand and machine sanding where the samples were tested after 7 days at 73°F (23°C) and 50% RH. The pooled estimate of variance is

$$s^2 = \frac{\Sigma(Y_1 - \bar{Y}_1)^2 + \Sigma(Y_2 - \bar{Y}_2)^2}{n_1 + n_2 - 2}$$

And from table 7

$$s^2 = \frac{457,400 + 375,800}{58} = 14,400$$

The variance of the difference between the means is:

$$s_d^2 = s^2 \left(\frac{1}{n} + \frac{1}{n} \right) = 14,400 \left(\frac{2}{30} \right)$$

$$s_d^2 = 960$$

and the standard deviation of d is:

$$s_d = \sqrt{960} = 31$$

and;

$$t = \frac{\bar{Y}_1 - \bar{Y}_2}{s_d} = \frac{1150 - 1080}{31} = 2.26$$

In order to test for significant differences, we use the t-test table (table 8). Entering this table at DF = 58, we can interpolate between 40 and 60. Actually the difference is so small we can approximate with DF = 60. We immediately see that for t = 2.26, P is below 5% and the difference is probably statistically significant.

Using this procedure, the results shown below were obtained for the AF-126 system:

<u>Comparison</u>			
Hand sanding - 7 days aging with Machine sanding - 7 days aging	t = 2.26	P < 5%	Probably significant difference
Hand sanding - 30 days aging with Machine sanding - 30 days aging	t = 4.07	P < 0.2%	Very significant difference
Hand sanding - 7 days aging with Hand sanding - 30 days aging	t = 3.87	P < 0.2%	Very significant difference
Machine sanding - 7 days aging with Machine sanding - 30 days aging	t = 2.96	P < 1%	Significant difference

These results agree in all cases with our findings using the Wilcoxon Sum of Ranks test and lend added confidence to the validity of our conclusions.

Linear Weibull distribution plots were made for this system following the procedures described earlier in this report. These lines are shown in figure 6 and the corresponding correlation coefficients are recorded in table 1.

The appropriate differential distribution curves for the AF-126 data are shown in figure 7. The curves were calculated by equation 3 using the parameters from the linear Weibull plots and the procedure that was described in the discussion of Epon 828/V-140. For this system it is evident that preparing the surface by machine sanding produces stronger bonds than hand sanding. Aging for 30 days at 120°F (49°C) and 95% RH results in some degradation of the bond. SET up to 30 days is immaterial for this system. The data overlap and the magnitude of the differences are shown in figure 7.

Comparison of Adhesives

Examination of figure 1 indicates that the AF-126 adhesive forms the strongest bonds, followed by EC-2214, with Epon 828/V-140 showing the lowest breaking loads. This breaking load order is illustrated in simplified form in figure 8 in which the curves for the optimum conditions of each adhesive are shown. For AF-126 the optimum conditions are machine sanding, 7 days aging, and SET immaterial. For EC-2214 the conditions are machine sanding, 1-4 hours SET, and aging condition immaterial. For Epon 828/V-140 optimum conditions correspond to 1-4 hours SET with the type of sanding and the aging time making no difference.

CONCLUSIONS

1. The effect of the processing parameters on the shear strength in bonding glass-reinforced plastics is highly dependent on the adhesive system used.
2. Statistical methods are useful in evaluating the shear strength results.
3. Smoothed distribution curves, representing the bond strength data, can be helpful in deciding on trade-offs involving sacrificing a little in the optimum bonding properties in order to attain maximum fabrication ease and efficiency. The curves can also be useful in comparing adhesives.

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Table 1. Correlation coefficients for the linear Weibull distribution plots

	<u>Correlation coefficient</u>	
	<u>1-4 hours SET</u>	<u>1-14 days SET</u>
Epon 828/V-140	0.956	0.977
	<u>Correlation coefficient</u>	
	<u>Hand sanding 1-4 hrs SET</u>	<u>Machine sanding 1-4 hrs SET</u>
EC-2214	0.835	0.973
	<u>Correlation coefficient</u>	
	<u>Hand - 30 days</u>	<u>Machine - 7 days</u>
AF-126	0.980	0.976
	<u>Correlation coefficient</u>	
	<u>Hand - 7 days</u>	<u>Machine - 30 days</u>
	0.980	0.979

Table 2. Breaking loads for the system glass-reinforced plastic bonded with Epon 828/V-140

<u>Hand sanding</u>		<u>Machine sanding</u>		<u>Hand sanding</u>		<u>Machine sanding</u>	
7 dsys at 73°F + 50% RH		7 days at 73°F + 50% RH		30 days at 120°F + 95% RH		30 dsys at 120°F + 95% RH	
<u>N</u>	<u>LBS</u>	<u>N</u>	<u>LBS</u>	<u>N</u>	<u>LBS</u>	<u>N</u>	<u>LBS</u>
2370	532 (VI)	2560	575 (VI)	2650	595 (VI)	2890	650 (VI)
2630	590 (VI)	2740	615 (V)	2890	650 (II)	2980	670 (VI)
2710	608 (VI)	2760	620 (II)	2910	655 (VI)	3030	680 (VI)
2830	635 (I)	2780	625 (VI)	3000	675 (IV)	3050	685 (II)
2890	650 (V)	2830	635 (II)	3000	675 (V)	3120	700 (IV)
3000	674 (VI)	2850	640 (V)	3070	690 (IV)	3140	705 (III)
3090	695 (VI)	2870	645 (IV)	3120	700 (IV)	3160	710 (VI)
3090	695 (II)	2910	655 (V)	3120	700 (VI)	3200	720 (II)
3120	700 (V)	2980	670 (IV)	3140	705 (V)	3200	720 (IV)
3140	705 (II)	3140	705 (II)	3140	705 (V)	3230	725 (II)
3230	725 (IV)	3180	715 (VI)	3200	720 (VI)	3250	730 (II)
3230	725 (V)	3320	745 (III)	3200	720 (III)	3340	750 (II)
3290	740 (III)	3400	765 (VI)	3230	725 (I)	3350	752 (V)
3320	745 (V)	3450	775 (III)	3230	725 (III)	3360	755 (I)
3360	755 (IV)	3470	780 (V)	3230	725 (IV)	3380	760 (III)
3380	760 (I)	3520	790 (I)	3270	735 (VI)	3400	765 (IV)
3380	760 (II)	3540	795 (VI)	3290	740 (V)	3400	765 (VI)
3380	760 (III)	3560	800 (III)	3290	740 (V)	3470	780 (I)
3470	780 (V)	3560	800 (IV)	3360	755 (II)	3470	780 (III)
3490	785 (I)	3650	820 (II)	3360	755 (II)	3490	785 (IV)
3490	785 (IV)	3720	835 (V)	3400	765 (II)	3580	804 (V)
3560	800 (I)	3740	840 (III)	3430	770 (I)	3590	806 (V)
3560	800 (I)	3760	845 (I)	3470	780 (IV)	3600	810 (I)
3560	800 (IV)	3830	860 (III)	3520	790 (III)	3680	826 (V)
3580	805 (II)	3940	885 (I)	3540	795 (I)	3690	830 (IV)
3670	825 (III)	4010	900 (II)	3600	810 (I)	3740	840 (I)
3760	845 (III)	4010	900 (IV)	3630	815 (II)	3780	850 (V)
3800	855 (IV)	4210	945 (I)	3720	835 (II)	3800	855 (I)
3890	875 (II)	4210	945 (IV)	3890	875 (III)	3890	875 (III)
3960	890 (III)	4450	1000 (I)	4050	910 (I)	3920	880 (III)

I = 1-4 hrs SET; II = 1 day SET; III = 2 days SET;
 IV = 7 days SET; V = 14 days SET; VI = 30 days SET

Table 3. Use of Wilcoxon Sum of Ranks test to determine if 30 days SET values differ significantly from the remaining data. Epon 828/V-140, hand sanding, 7 days at 73°F and 50% RH

<u>PSI</u>	<u>Data value</u>		<u>Tally</u>	<u>Rank value</u>	<u>B Ranks</u>
		<u>N</u>			
2320	532	B	B	1	1
2630	590	B	B	2	2
2710	608	B	B	3	3
2830	635	A	A	4	
2890	650	A	A	5	
3000	674	B	B	6	6
3090	695	AB	A B	7, 8	7, 5
3120	700	A	A	9	
3140	705	A	A	10	
3230	725	AA	AA	11, 12	
3290	740	A	A	13	
3320	745	A	A	14	
3360	755	A	A	15	
3380	760	AAA	AAA	16, 17, 18	
3470	780	A	A	19	
3490	785	AA	AA	20, 21	
3560	800	AAA	AAA	22, 23, 24	
3580	805	A	A	25	
3670	825	A	A	26	
3760	845	A	A	27	
3800	855	A	A	28	
3890	875	A	A	29	
3960	890	A	A	30	

R = 19.5

B = 30 days SET

A = All other SET values

$$Z = \frac{5(25+5+1) - 2(19.5)}{\left(\frac{(5)(25)(25+5+1)}{3}\right)^{\frac{1}{2}}} = 3.22$$

Table 4. R tables for the Wilcoxon Sum of Ranks test

n_A	n_B	P=10%	P=5%	P=1%	P=0.2%
2	2	4	3	—	—
2	3	4	3	—	—
2	4	4	3	—	—
2	5	4	3	—	—
2	6	4	3	—	—
2	7	4	3	—	—
2	8	4	3	—	—
2	9	4	3	—	—
2	10	4	3	—	—
2	11	4	3	—	—
2	12	3	4	—	—
2	13	3	4	—	—
2	14	6	4	—	—
2	15	6	4	—	—
2	16	6	4	—	—
2	17	6	5	—	—
2	18	7	5	—	—
2	19	7	5	3	—
2	20	7	5	3	—
3	3	7	6	—	—
3	4	7	6	—	—
3	5	8	7	—	—
3	6	8	7	—	—
3	7	8	7	—	—
3	8	9	8	—	—
3	9	10	8	6	—
3	10	10	9	6	—
3	11	11	9	6	—
3	12	11	10	7	—
3	13	12	10	7	—
3	14	13	11	7	—
3	15	13	11	8	—
3	16	14	12	8	—
3	17	15	12	8	6
3	18	13	13	8	6
3	19	16	13	9	6
3	20	17	14	9	6
4	4	11	10	—	—
4	5	12	11	—	—
4	6	13	12	10	—
4	7	14	13	10	—
4	8	15	14	11	—
4	9	16	14	11	—
4	10	17	13	12	10
4	11	18	16	12	10
4	12	19	17	13	10
4	13	20	18	15	11
4	14	21	19	14	11
4	15	22	20	13	11
4	16	24	21	13	12
4	17	23	21	16	12
4	18	26	22	16	13
4	19	27	23	17	13
4	20	28	24	18	13
5	5	19	17	15	—

n_A	n_B	P=10%	P=5%	P=1%	P=0.2%
8	8	20	18	16	—
8	7	21	20	16	—
8	6	23	21	17	15
8	5	24	22	18	16
8	4	26	23	19	16
8	3	27	24	20	17
8	2	28	26	21	17
8	1	30	27	22	18
8	0	31	28	22	18
8	-1	33	29	23	19
8	-2	34	30	24	20
8	-3	33	32	23	20
8	-4	37	33	26	21
8	-5	38	34	27	22
8	-6	40	33	28	22
8	-7	28	26	23	—
8	-8	29	27	24	21
8	-9	31	29	25	22
8	-10	33	31	26	23
8	-11	35	32	27	24
8	-12	37	34	28	25
8	-13	38	35	30	25
8	-14	40	37	31	26
8	-15	42	38	32	27
8	-16	44	40	33	28
8	-17	46	42	34	29
8	-18	47	43	36	30
8	-19	49	45	37	31
8	-20	51	46	38	32
8	-21	53	48	39	33
8	-22	39	36	32	29
8	-23	41	38	34	30
8	-24	43	40	35	31
8	-25	45	42	37	33
8	-26	47	44	38	34
8	-27	49	46	40	35
8	-28	52	48	41	36
8	-29	54	50	43	37
8	-30	56	52	44	38
8	-31	58	54	46	39
8	-32	61	56	47	41
8	-33	63	58	49	42
8	-34	65	60	50	43
8	-35	67	62	52	44
8	-36	71	66	56	48
8	-37	74	69	59	50
8	-38	77	72	62	54
8	-39	80	74	64	56
8	-40	83	77	66	57
8	-41	86	80	69	60
8	-42	89	83	72	63
8	-43	92	86	75	66
8	-44	95	89	78	69
8	-45	98	92	81	72
8	-46	101	95	84	75
8	-47	104	98	87	78
8	-48	107	101	90	81
8	-49	110	104	93	84
8	-50	113	107	96	87
8	-51	116	110	99	90
8	-52	119	113	102	93
8	-53	122	116	105	96
8	-54	125	119	108	99
8	-55	128	122	111	102
8	-56	131	125	114	105
8	-57	134	128	117	108
8	-58	137	131	120	111
8	-59	140	134	123	114
8	-60	143	137	126	117
8	-61	146	140	129	120
8	-62	149	143	132	123
8	-63	152	146	135	126
8	-64	155	149	138	129
8	-65	158	152	141	132
8	-66	161	155	144	135
8	-67	164	158	147	138
8	-68	167	161	150	141
8	-69	170	164	153	144
8	-70	173	167	156	147
8	-71	176	170	159	150
8	-72	179	173	162	153
8	-73	182	176	165	156
8	-74	185	179	168	159
8	-75	188	182	171	162
8	-76	191	185	174	165
8	-77	194	188	177	168
8	-78	197	191	180	171
8	-79	200	194	183	174
8	-80	203	197	186	177
8	-81	206	200	189	180
8	-82	209	203	192	183
8	-83	212	206	195	186
8	-84	215	209	198	189
8	-85	218	212	201	192
8	-86	221	215	204	195
8	-87	224	218	207	198
8	-88	227	221	210	201
8	-89	230	224	213	204
8	-90	233	227	216	207
8	-91	236	230	219	210
8	-92	239	233	222	213
8	-93	242	236	225	216
8	-94	245	239	228	219
8	-95	248	242	231	222
8	-96	251	245	234	225
8	-97	254	248	237	228
8	-98	257	251	240	231
8	-99	260	254	243	234
8	-100	263	257	246	237

n_A	n_B	P=10%	P=5%	P=1%	P=0.2%
12	13	123	119	109	101
12	14	129	123	112	103
12	15	133	127	115	106
12	16	138	131	119	109
12	17	142	135	122	112
12	18	146	139	125	115
12	19	150	143	129	118
12	20	155	147	132	120
12	21	160	151	136	123
12	22	165	155	140	126
12	23	170	160	144	129
12	24	175	165	148	132
12	25	180	170	152	135
12	26	185	175	156	138
12	27	190	180	160	141
12	28	195	185	164	144
12	29	200	190	168	147
12	30	205	195	172	150
12	31	210	200	176	153
12	32	215	205	180	156
12	33	220	210	184	159
12	34	225	215	188	162
12	35	230	220	192	165
12	36	235	225	196	168
12	37	240	230	200	171
12	38	245	235	204	174
12	39	250	240	208	177
12	40	255	245	212	180
12	41	260	250	216	183
12	42	265	255	220	186
12	43	270	260	224	189
12	44	275	265	228	192
12	45	280	270	232	195
12	46	285	275	236	198
12	47	290	280	240	201
12	48	295	285	244	204
12	49	300	290	248	207
12	50	305	295	252	210
12	51	310	300	256	213
12	52	315	305	260	216
12	53	320	310	264	219
12	54	325	315	268	222
12	55	330	320	272	225
12	56	335	325	276	228
12	57	340	330	280	231
12	58	345	335	284	234
12	59	350	340	288	237
12	60	355	345	292	240

Table 5. Breaking loads for the system glass-reinforced plastic bonded with EC-2214

<u>Hand sanding</u> 7 days at 73°F + 50% RH		<u>Machine sanding</u> 7 days at 73°F + 50% RH		<u>Hand sanding</u> 30 days at 120°F + 95% RH		<u>Machine sanding</u> 30 days at 120°F + 95% RH	
<u>N</u>	<u>LBS</u>	<u>N</u>	<u>LBS</u>	<u>N</u>	<u>LBS</u>	<u>N</u>	<u>LBS</u>
	417 (VI)	2910	655 (V)		610 (IV)		680 (VI)
	507 (VI)	2940	660 (VI)	2830	635 (VI)	3470	780 (VI)
	540 (IV)	3230	725 (V)	2870	645 (VI)	3560	800 (I)
	610 (IV)	3380	760 (V)	2890	650 (VI)	3600	810 (VI)
3070	690 (VI)	3390	761 (VI)	2910	655 (VI)	3600	810 (VI)
3160	710 (IV)	3400	765 (VI)	2960	665 (V)	3670	825 (VI)
	721 (VI)	3400	765 (II)	2980	670 (V)	3780	850 (V)
3230	725 (V)	3460	778 (VI)	3160	710 (VI)	3890	875 (III)
3250	730 (III)	3540	795 (VI)	3180	715 (III)	3920	880 (III)
	731 (VI)	3650	820 (III)	3200	720 (V)	3920	880 (V)
3380	760 (III)	3760	845 (III)	3290	740 (III)	3940	885 (III)
3520	790 (III)	3830	860 (IV)	3320	745 (III)	4010	900 (IV)
3560	800 (II)	3890	875 (II)	3320	745 (IV)	4050	910 (II)
3600	810 (IV)	3980	895 (III)	3470	780 (V)	4050	910 (II)
3650	820 (V)	4050	910 (V)	3540	795 (II)	4070	915 (IV)
3670	825 (III)	4140	930 (III)	3560	800 (III)	4090	920 (III)
3780	850 (I)	4210	945 (I)	3600	810 (II)	4090	920 (IV)
3780	850 (II)	4210	945 (IV)	3690	830 (III)	4270	960 (II)
3830	860 (I)	4290	965 (III)	3690	830 (IV)	4325	970 (IV)
3870	870 (I)	4340	975 (IV)	3740	840 (IV)	4340	975 (I)
3890	875 (V)	4380	985 (IV)	3760	845 (V)	4410	990 (II)
3890	875 (V)	4520	1015 (IV)	3850	865 (I)	4440	998 (V)
3940	885 (III)	4560	1025 (I)	3850	865 (IV)	4500	1012 (V)
4050	910 (V)	4560	1025 (V)	3890	875 (I)	4520	1015 (I)
4120	925 (IV)	4650	1045 (I)	3920	880 (I)	4520	1015 (III)
4230	950 (II)	4720	1060 (II)	4010	900 (I)	4560	1025 (I)
4290	965 (II)	4720	1060 (II)	4120	925 (II)	4650	1045 (IV)
4430	995 (II)	4810	1080 (I)	4320	970 (II)	4900	1100 (V)
4580	1030 (I)	4940	1110 (II)	4340	975 (I)	5070	1140 (I)
4610	1035 (I)	5300	1190 (I)	4340	975 (II)	5670	1275 (II)

I = 1-4 hrs SET; II = 1 day SET; III = 2 days SET;

IV = 7 days SET; V = 14 days SET; VI = 30 days SET

Table 6. Breaking loads for the system glass-reinforced plastic bonded with AF-126

Hand sanding Machine sanding Hand sanding Machine sanding
 7 days at 73°F + 50% RH 7 days at 73°F + 50% RH 30 days at 120°F + 95% RH 30 days at 120°F + 95% RH

<u>N</u>	<u>LBS</u>	<u>N</u>	<u>PSI</u>	<u>N</u>	<u>PSI</u>	<u>N</u>	<u>PSI</u>
3800	853 (VI)		917 (VI)	3430	770 (IV)	4010	900 (II)
4010	900 (II)	4320	970 (II)	3450	775 (II)	4120	925 (VI)
4110	924 (VI)	4340	975 (IV)	3450	775 (II)	4160	935 (I)
4120	925 (IV)		1027 (VI)	3580	805 (IV)	4230	950 (IV)
4290	963 (VI)	4650	1045 (IV)	3630	815 (III)	4270	960 (III)
4290	965 (III)	4670	1050 (III)	3690	830 (III)	4270	960 (V)
4340	975 (II)	4570	1065 (II)	3850	865 (IV)	4430	995 (II)
4380	985 (I)	4780	1075 (II)	3870	870 (II)	4450	1000 (I)
4410	990 (I)	4900	1100 (I)	3940	885 (I)	4450	1000 (II)
4520	1015 (I)	4900	1100 (II)	4030	905 (III)	4470	1005 (III)
4550	1023 (VI)	4940	1110 (III)	4070	915 (II)	4580	1030 (III)
4560	1025 (IV)	4980	1119 (VI)	4090	920 (IV)	4630	1040 (V)
4630	1040 (V)	4980	1120 (III)	4230	950 (VI)	4650	1045 (III)
4670	1050 (II)	5010	1125 (I)	4320	970 (I)	4720	1060 (IV)
4720	1060 (II)	5010	1125 (III)	4450	1000 (V)	4740	1065 (II)
4780	1075 (IV)	5090	1144 (VI)	4470	1005 (V)	4760	1070 (I)
4850	1090 (IV)	5230	1175 (III)	4470	1005 (V)	4810	1080 (VI)
4870	1094 (VI)	5250	1180 (I)	4490	1010 (V)	4830	1085 (VI)
4960	1115 (III)	5250	1180 (IV)	4490	1010 (VI)	4830	1085 (VI)
4980	1120 (III)	5250	1180 (IV)	4520	1015 (III)	4960	1115 (IV)
5010	1125 (V)	5410	1215 (IV)	4540	1020 (III)	5010	1125 (IV)
5070	1140 (I)	5450	1225 (V)	4540	1020 (VI)	5070	1140 (III)
5100	1145 (IV)	5470	1230 (VI)	4580	1030 (IV)	5100	1145 (VI)
5380	1210 (II)	5540	1245 (V)	4610	1035 (VI)	5120	1150 (V)
5430	1220 (V)	5540	1245 (V)	4670	1050 (VI)	5150	1158 (V)
5500	1235 (III)	5220	1285 (II)	4690	1055 (II)	5160	1160 (I)
5500	1235 (III)	5760	1295 (I)	5030	1130 (V)	5300	1190 (I)
5630	1265 (I)	5850	1315 (V)	5070	1140 (I)	5340	1200 (II)
5240	1290 (V)	6050	1360 (I)	5180	1165 (I)	5450	1225 (IV)
6070	1365 (V)	6140	1380 (V)	5230	1175 (I)	5460	1227 (V)

I = 1-4 hrs SET; II = 1 day SET; III = 2 days SET;

IV = 7 days SET; V = 14 days SET; VI = 30 days SET

Table 7. t test summary table

<u>Conditions</u>	<u>n</u>	<u>DF</u>	<u>Mean</u>	<u>Sum of squares</u> <u>$(Y_1 - \bar{Y})^2$</u>
Hand - 7 days	30	29	1080	457,400
Hand - 30 days	30	29	960	393,800
Machine - 7 days	30	29	1150	375,800
Machine - 30 days	30	29	1070	247,600

n = Number of samples tested
 DF = Degrees of freedom = n - 1
 \bar{Y} = Mean
 Y_1 = Value for individual data joint

Table 8. t test table

Degrees Of Freedom n	Probability of no significant difference between M and m			
	P = 10%	P = 5%	P = 1%	P = 0.2%
3	t = 2.92	4.30	9.92	22.33
4	2.35	3.18	5.84	10.21
5	2.13	2.78	4.60	7.17
6	2.02	2.57	4.03	5.89
7	1.94	2.45	3.71	5.21
8	1.89	2.36	3.50	4.79
9	1.86	2.31	3.36	4.50
10	1.83	2.26	3.25	4.30
11	1.81	2.23	3.17	4.14
12	1.80	2.20	3.11	4.02
13	1.78	2.18	3.05	3.93
14	1.77	2.16	3.01	3.85
15	1.76	2.14	2.98	3.79
16	1.75	2.13	2.95	3.73
17	1.75	2.12	2.92	3.69
18	1.74	2.11	2.90	3.65
19	1.73	2.10	2.88	3.61
20	1.73	2.09	2.86	3.58
21	1.72	2.09	2.85	3.55
22	1.72	2.08	2.83	3.53
23	1.72	2.07	2.82	3.50
24	1.71	2.07	2.81	3.48
25	1.71	2.06	2.80	3.47
26	1.71	2.06	2.79	3.45
27	1.71	2.06	2.78	3.44
28	1.70	2.05	2.77	3.42
29	1.70	2.05	2.76	3.41
30	1.70	2.05	2.76	3.40
40	1.68	2.02	2.70	3.31
60	1.67	2.00	2.66	3.23
120	1.66	1.98	2.62	3.16
∞	1.64	1.96	2.58	3.09

From ref. 2.

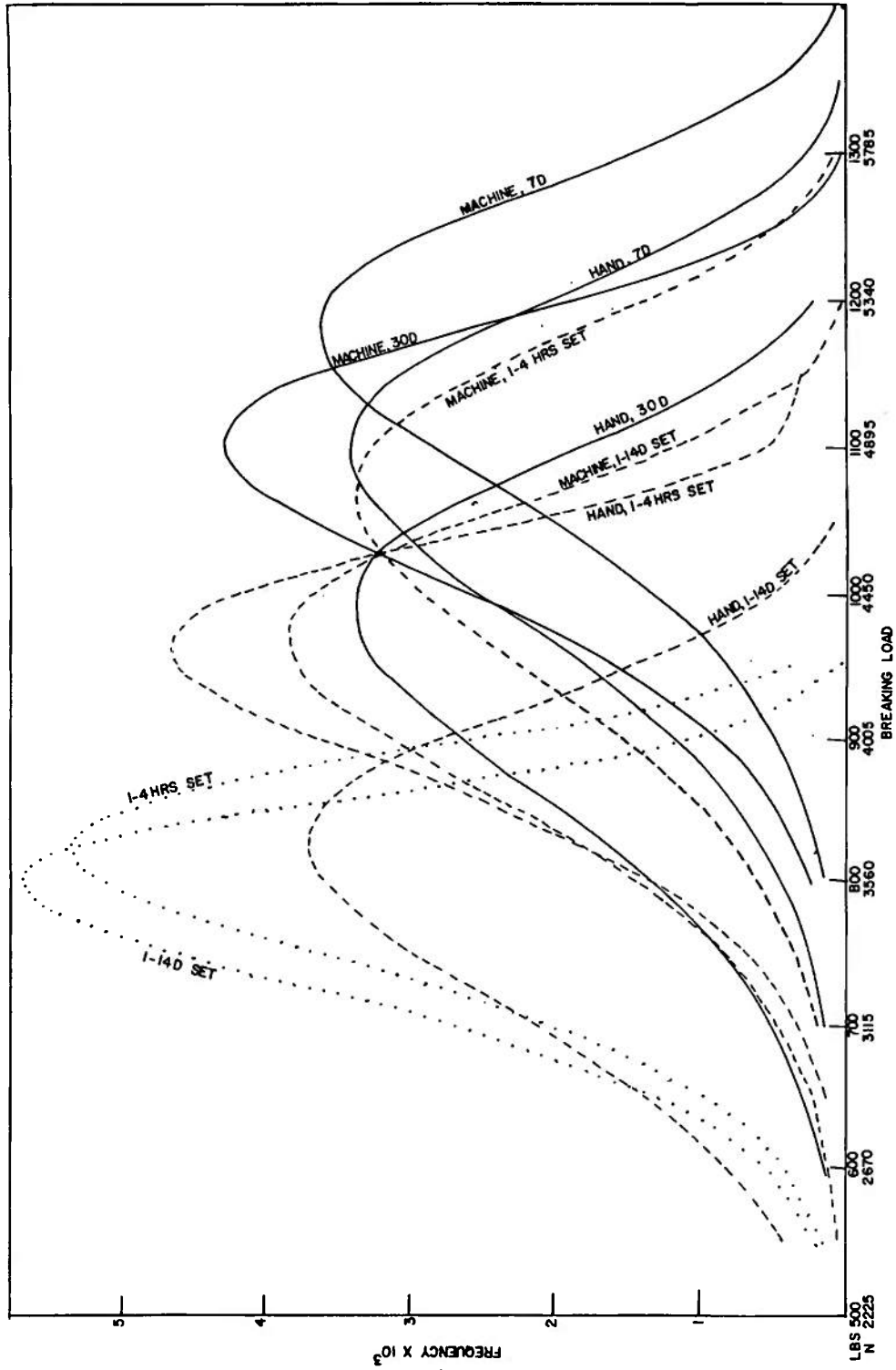


Figure 1. Differential Weibull distribution curves for lap shear data after various treatments. AF-126—; EC-2214-----; Epon 828/V-140.....

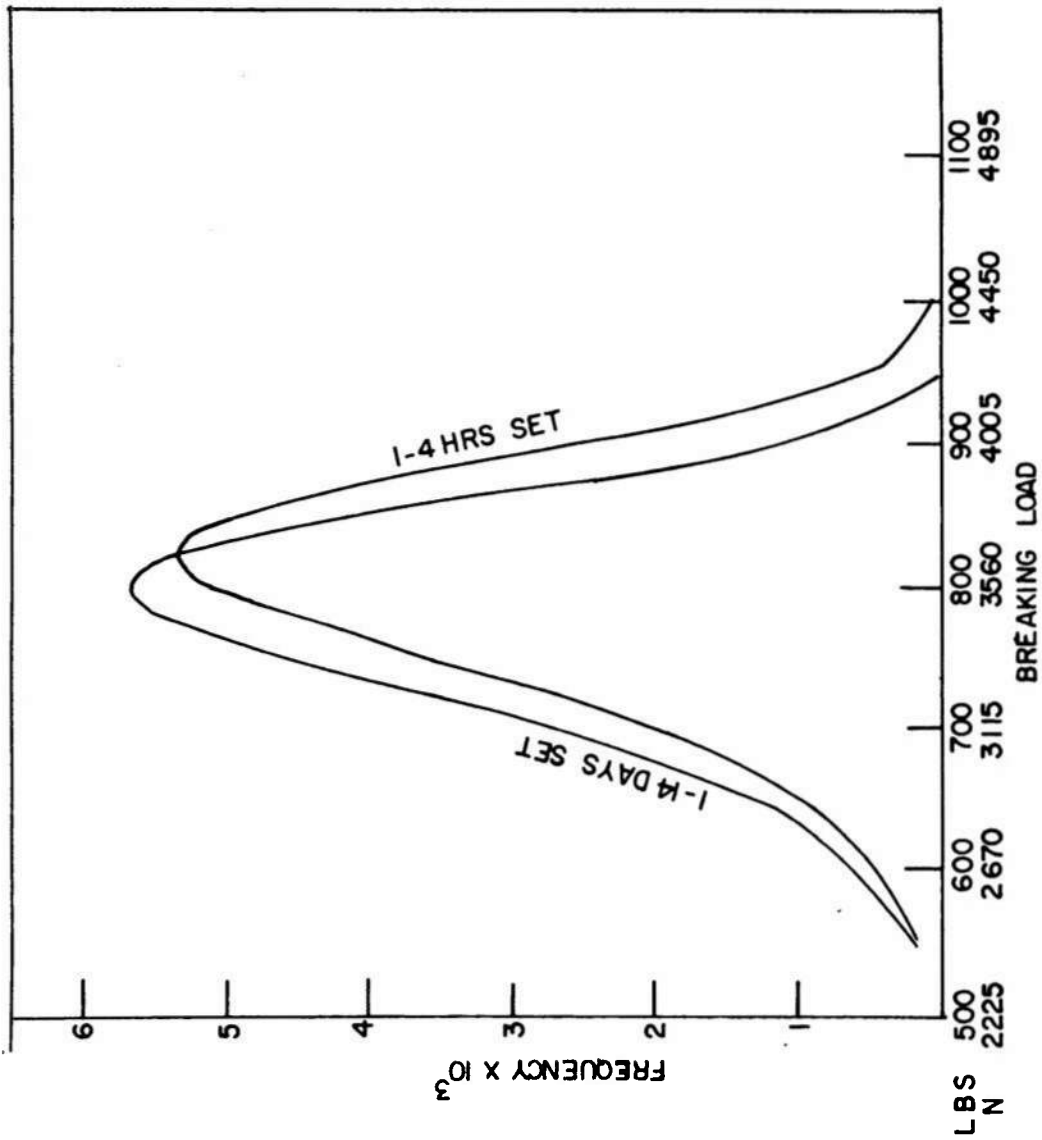


Figure 2. Differential Weibull distribution curves for Epon 828/V-140.

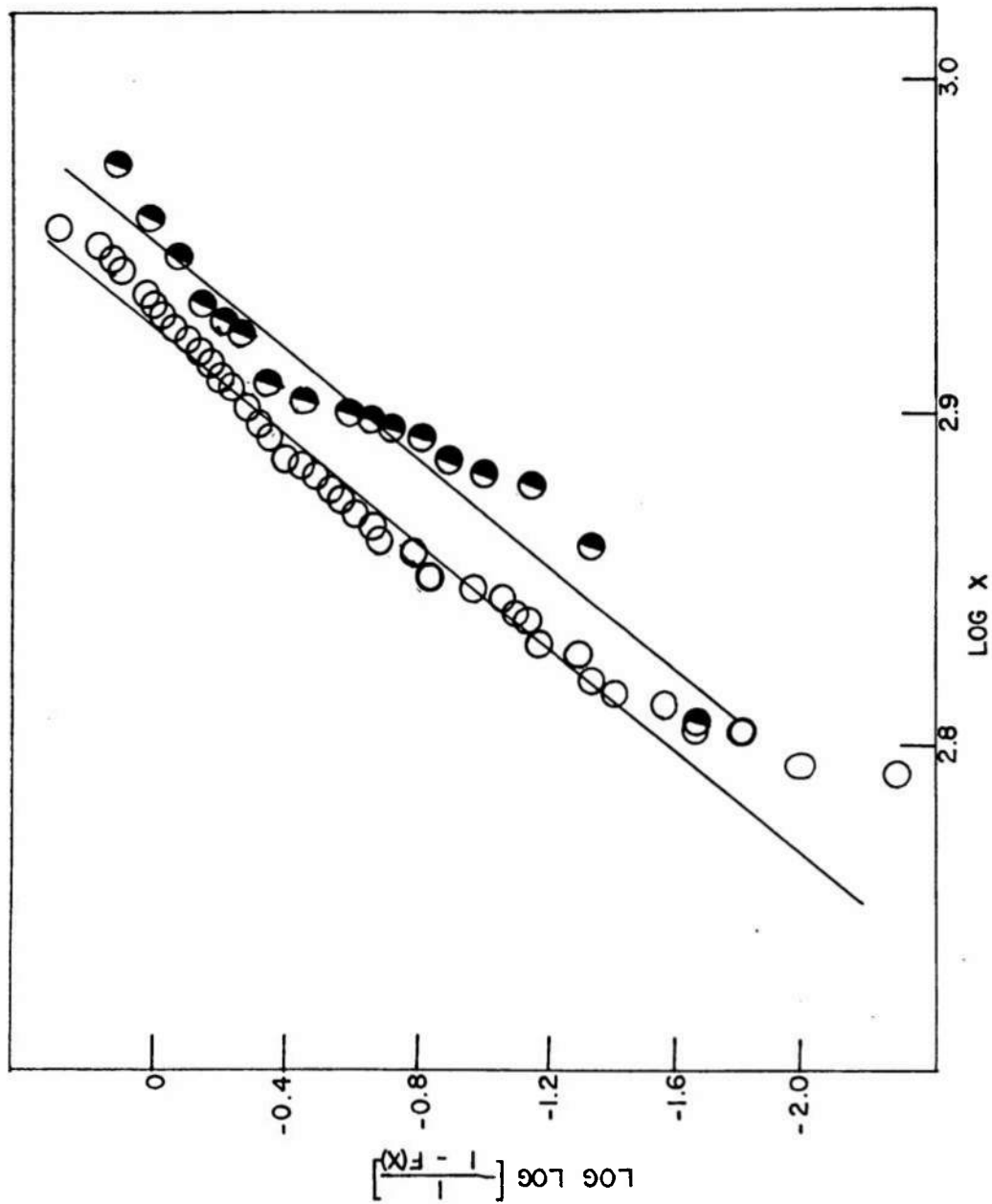


Figure 3. Linear Weibull distribution for Epon 828/V-140.
 O = 1-14 days SET; ● = 1-4 hrs SET.

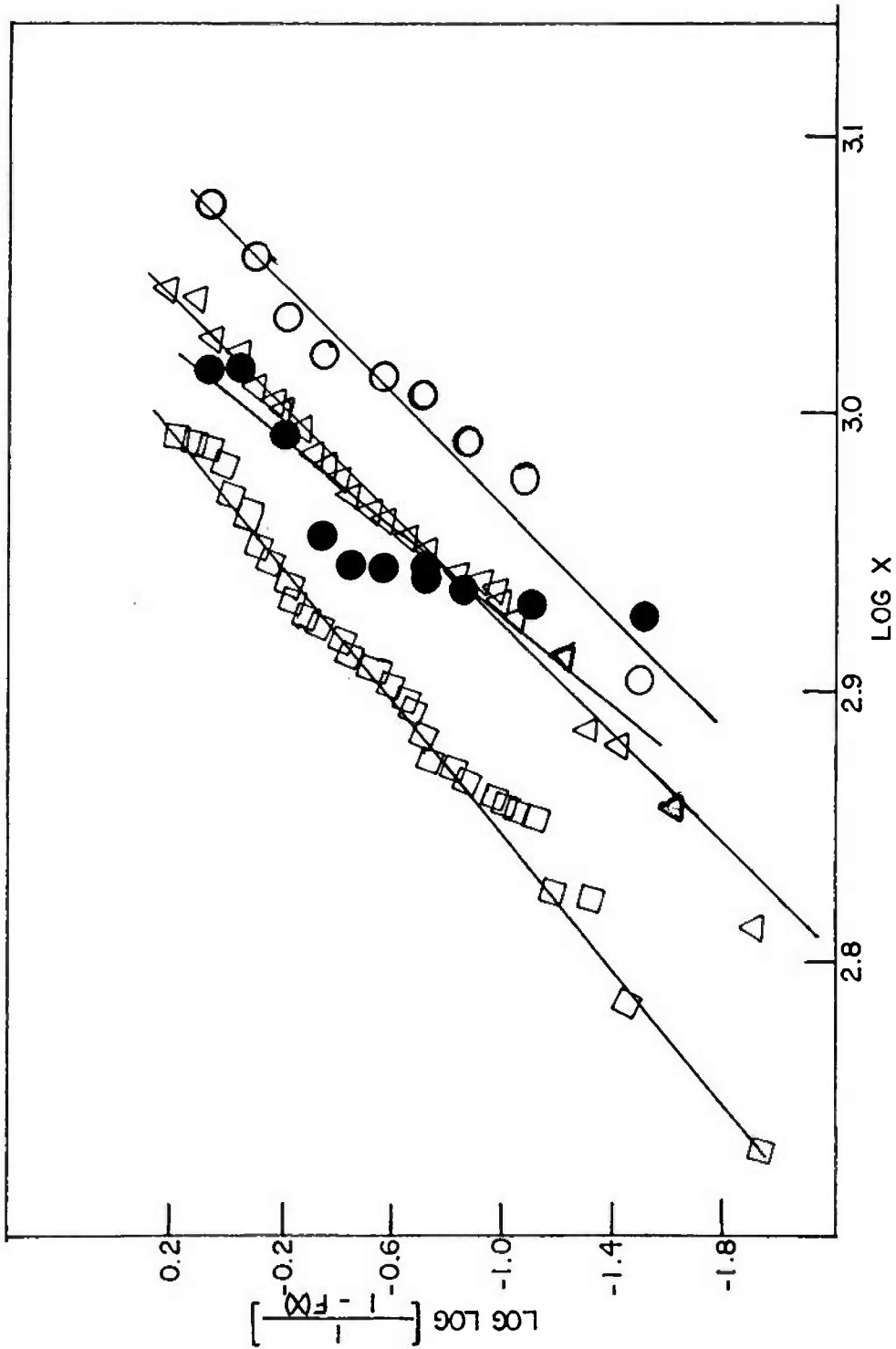


Figure 4. Linear Weibull distribution for EC-2214, ○ = Machine sanding, 1-4 hrs SET;
 △ = machine sanding, 1-14 days SET; ● = hand sanding, 1-4 hrs SET;
 □ = hand sanding, 1-14 days SET.

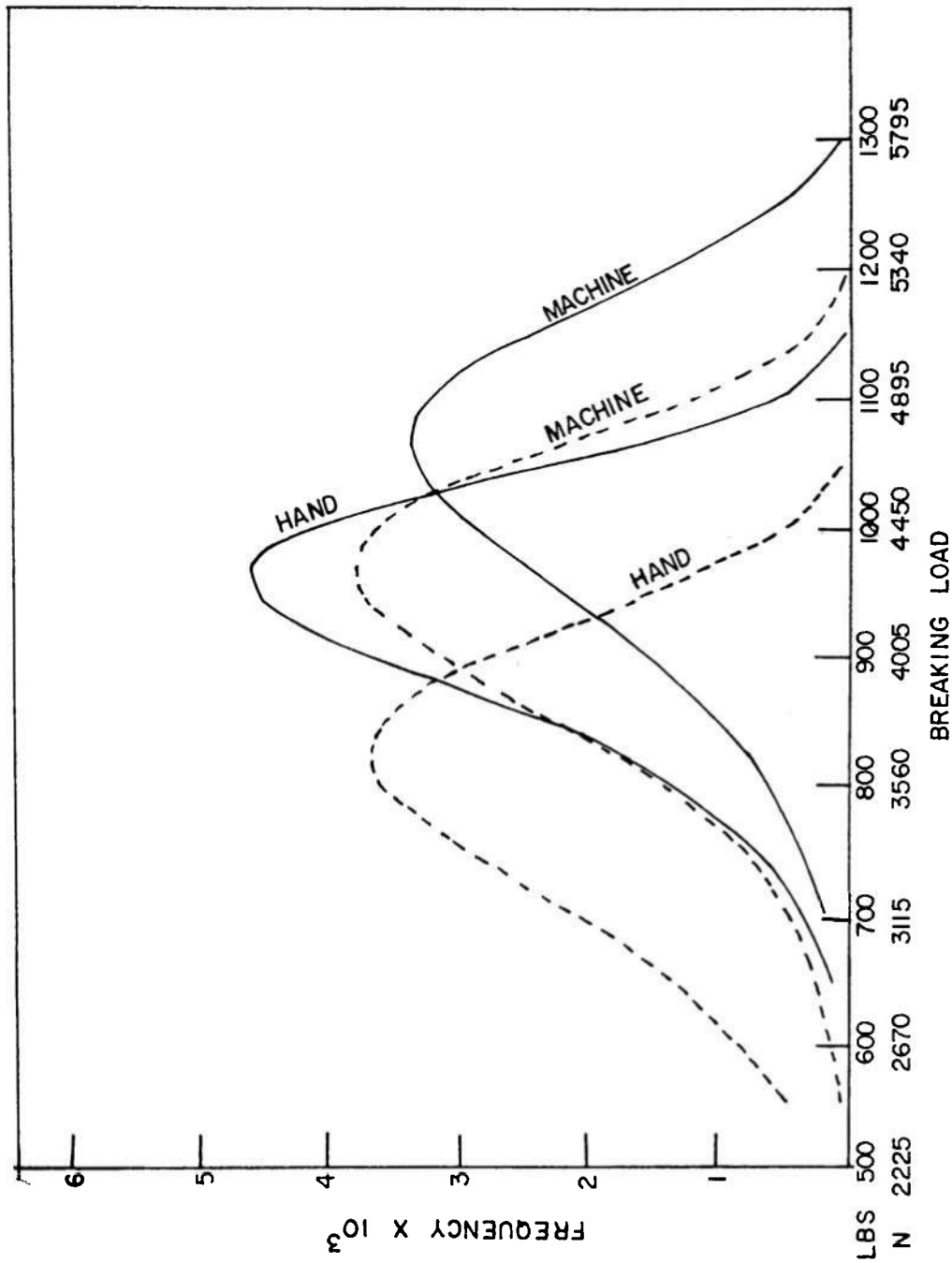


Figure 5. Differential Weibull distribution curves for EC-2214, — = 1-4 hrs SET; ---- = 1-14 days SET.

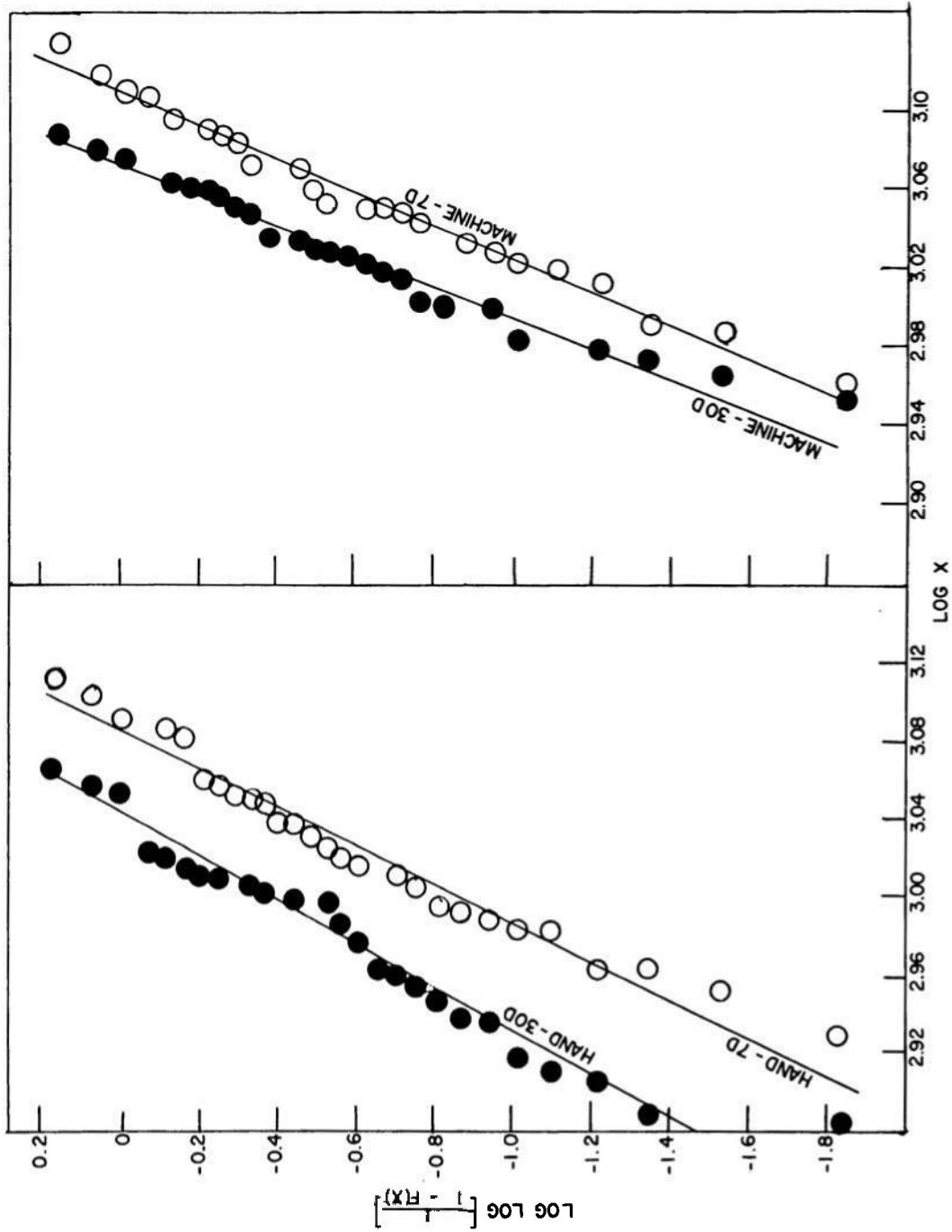


Figure 6. Linear Weibull distribution for AF-126.

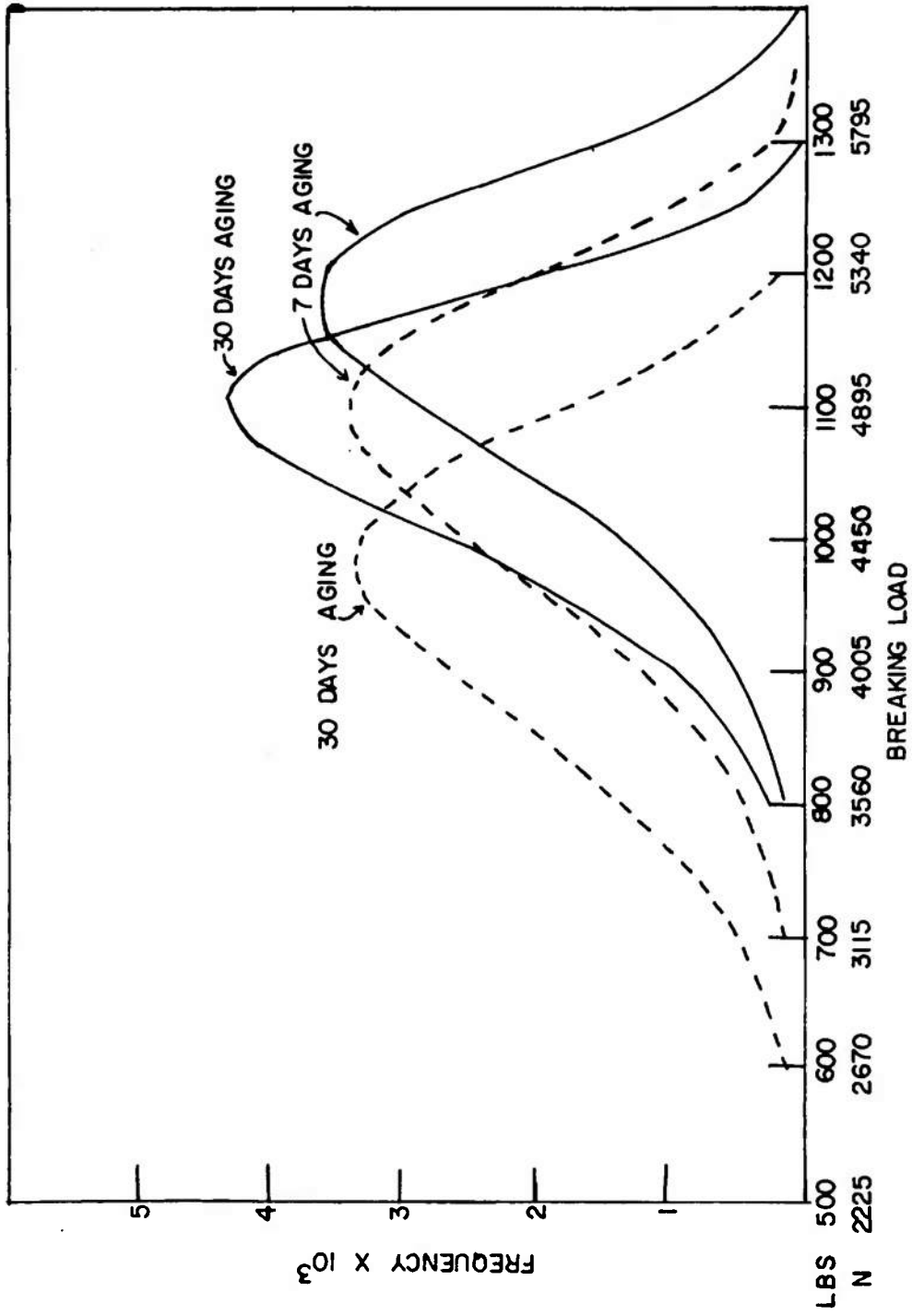


Figure 7. Differential Weibull distribution curves for AF-126. — = machine sanding; ---- = hand sanding.

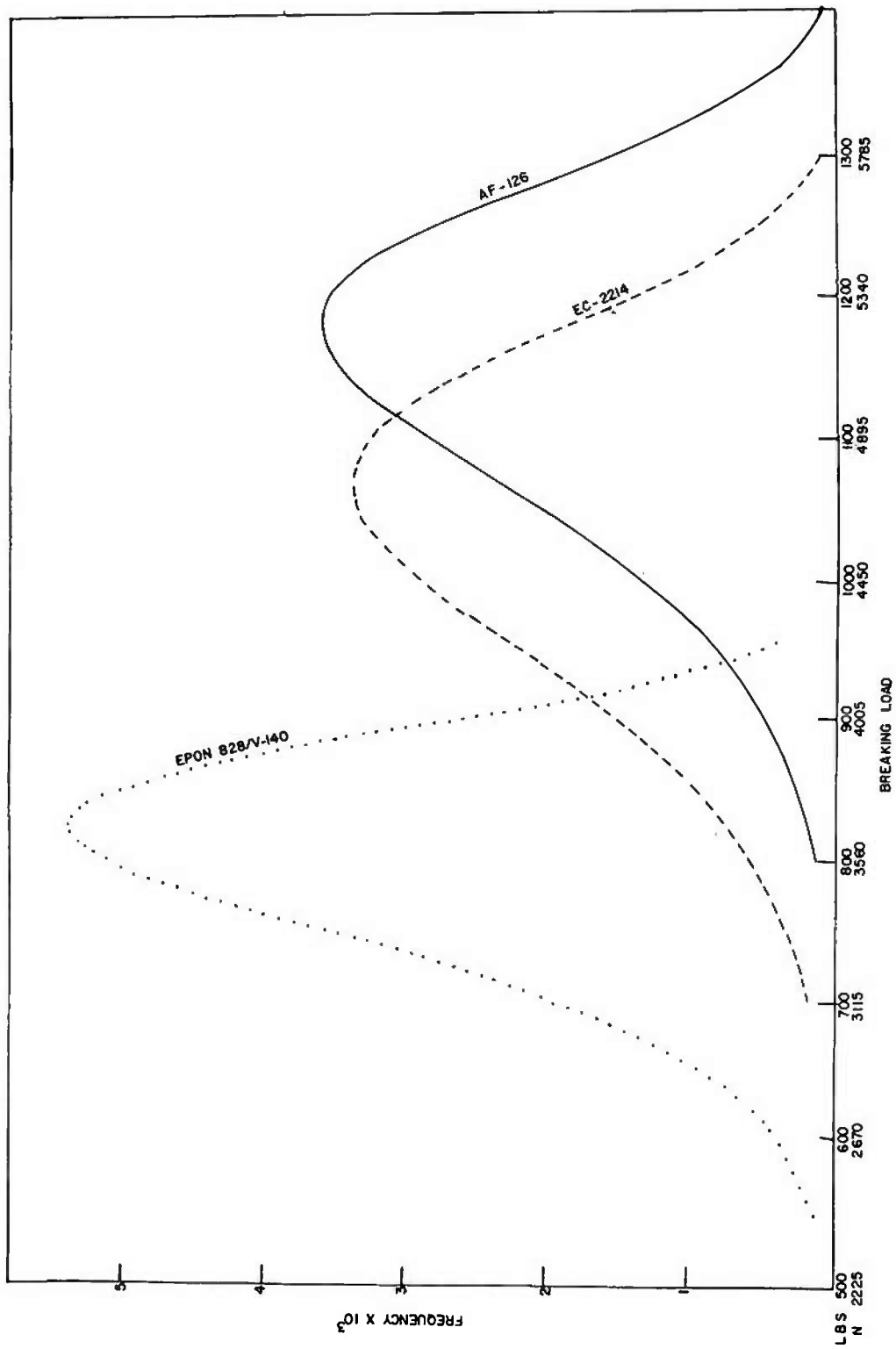
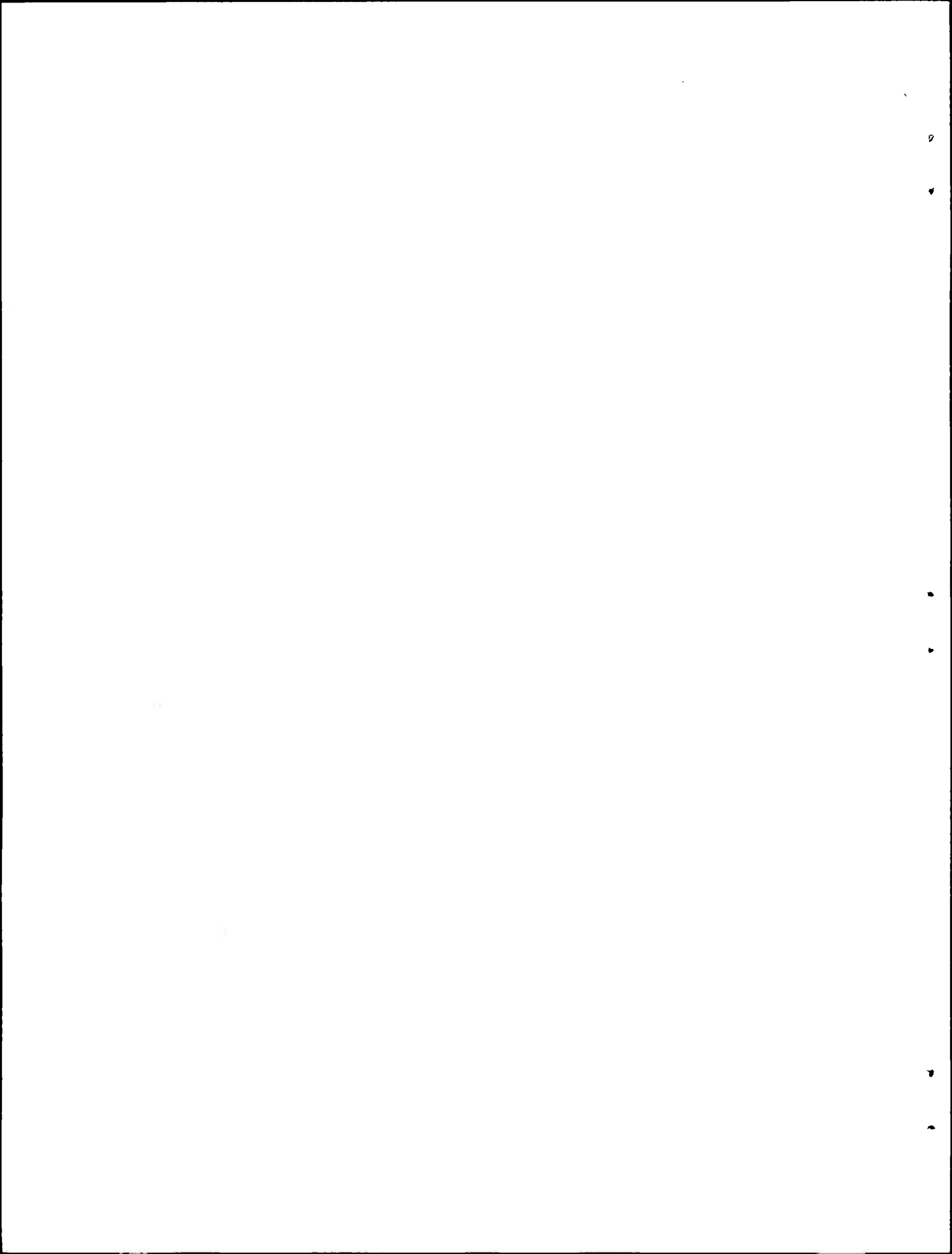


Figure 8. Comparison of adhesives under optimum conditions.



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DRSEL-TL-ME, Mr. G. Platau
DRSEL-PP-EM2, Sarah Rosen
Fort Monmouth, NJ 07703

Director
U.S. Army Tank-Automotive Research
and Development Command
ATTN: DRSTRA-KMD
Warren, MI 48090

Commander
U.S. Army Materials and Mechanics
Research Center
ATTN: DRXMR-FR, Dr. G. Thomas
DRXMR-PL
Technical Information Section
Watertown, MA 02172

Director
U.S. Army Production Equipment Agency
Rock Island Arsenal
ATTN: DRXPE-MT, Mr. H. Holmes (2)
Rock Island Arsenal, IL 61201

Commander
USA Troop Support and Aviation Materiel
Readiness Command
ATTN: DRSTS-MEU(2) Mr. E. Dawson
DRSTS-ME(2) Mr. C. Sims
DRSTS-MEN(2) Mr. L. D. Brown
DRSTS-MEL(2) Mr. Bell
DRSTS-MET(2) Mr. Ceasar
PO Box 209, Main Office
St Louis, MO 63166

Commander
Corpus Christi Army Depot
ATTN: DRSTS-MES (STOP 55) (2)
DRSTS-MESA, Mr. T. Tullos (2)
DRSTS-MESP, Mr. Bulloch
Corpus Christi, TX 78419

Commander/Director
Chemical Systems Laboratory
USA ARRADCOM, Bldg E5101
Aberdeen Proving Ground, MD 21010

Chief
Benet Weapons Laboratory
LCWSL, USA ARRADCOM
ATTN: DRDAR-LCB
DRDAR-LCB-TL
Watervliet, NY 12189

Director
U.S. Army Engineer Waterways
Experiment Station, PO Box 631
Corps of Engineers
ATTN: Mr. Hugh L. Green - WE SSS1
Vicksburg, MS 39180

Commander
U.S. Army Medical Bio-Engineering Research
and Development Laboratories
Fort Deterick
ATTN: Dr. C. Wade
Frederick, MD 21701

Commander
USA Aviation R&D Command
ATTN: DRDAV-EQA, Mr. W. McClane
4300 Goodfellow Blvd
St Louis, MO 63120

Plastics Technical Evaluation Center
ATTN: Mr. H. Pebly
Mr. A. Landrock
U.S. Army ARRADCOM
Dover, NJ 0780]

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Harry Diamond Laboratories
ATTN: Mr. N. Kaplan
Mr. J. M. Boyd
Library
Washington, DC 20438

Commander
Chemical Systems Laboratory
ATTN: DRDAR-CLB-PM, Mr. Dave Schneck
DRDAR-ACW
Aberdeen Proving Ground, MD 21010

Commander
Tobyhanna Army Depot
ATTN: Mr. A. Alfano
Tobyhanna, PA 18466

Director
U.S. Army Ballistic Research Laboratory
USA ARRADCOM Bldg 328
Aberdeen Proving Ground, MD 21005

Commander
U.S. Army Materiel Development
and Readiness Command
ATTN: DRCPM-UA, Mr. C. Musgrave
DRCPM-LH, Mr. C. Cioffi
DRCPM-HLS-T, Mr. R. E. Hahn
PO Box 209
St Louis, MO 63166

Commander
Natick Research and Development Command
Natick, MA 01760

Commander
U.S. Army Engineer Research and
Development Labs
Fort Belvoir, VA 22060

Department of the Navy
Naval Air Systems Command
ATTN: Mr. John J. Gurtowski (AIR 52032C)
Washington, DC 20360

Naval Ordnance Station (NOSL)
ATTN: Mr. W. J. Ryan Code 5041
Southside Drive
Louisville, KY 40214

Naval Avionics Facility
ATTN: Mr. B. D. Tague, Code D/802
Mr. Paul H. Guhl, D/033.3
21st and Arlington
Indianapolis, Indiana 46218

Commander
U.S. Naval Weapons Station
ATTN: Research and Development Division
Yorktown, VA 23491

Commander
Aeronautical Systems Division
ATTN: Mr. W. Scardino, AFML/MXE
Mr. T. J. Aponyi
Composite and Fibrous Materials Branch
Nonmetallic Materials Division
Wright-Patterson Air Force Base, OH 45433

U.S. Army Air Mobility R&D Laboratory,
Headquarters
Advanced Systems Research Office
ATTN: Mr. F. Immen, MS 207.5
Ames Research Center
Moffet Field, CA 94035

Naval Ship Engineering Center
ATTN: Mr. W. R. Granger, SEC 6101E
Prince George's Center
Hyattsville, MD 20782

Mare Island Naval Shipyard
Rubber Engineering Section
ATTN: Mr. Ross E. Morris, Code 134.04
Vallejo, CA 94592

Hanscom Air Force Base
ATTN: Mr. R. Karlson, ESD/DE, Stop 7
HQ, ESD
Bedford, MA 01731

Naval Air Development Center
Materials Laboratory
ATTN: Mr. Coleman Nadler, Code 30221,
Div, AVTD
Warminster, PA 18974

Defense Documentation Center (12)
Cameron Station
Alexandria, VA 22314

Dr. Robert S. Shane, Staff Scientist
National Materials Advisory Board
National Academy of Science
2101 Constitution Avenue, NW
Washington, DC 20418

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