NBSIR 76-1148 (A)

Characterizing the Inter-Fiber Bond Strengths of Paper Pulps in Terms of a Breaking Energy

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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, ***Secretary***

Edward O. Vetter, ***Under Secretary***

Dr. Betsy Ancker-Johnson, ***Assistant Secretary for Science and Technology***

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Acting Director***

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SUMMARY

Two of the most important factors influencing paper strength are fiber strength and inter-fiber bond strength. Although tedious, the average fiber strength can be determined by testing a large number of single pulp fibers. However, the measurement of inter-fiber bond strength is considerably more difficult to achieve. In order to fully characterize a pulp, the quality of bondability must be known, especially for pulps produced from a mixture of waste paper in the paper recycling process.

If a fiber network consists of a relatively small number of fibers (2.5 g/m^2) such that the area covered by more than two fibers intersecting at a given point is negligible, then the forces generated when a specimen is elongated will be significantly lower than necessary to break fibers in the specimen. When the elongation is performed in a sensitive tensile tester, the force-elongation curve consists of jagged peaks. Each peak signifies the breaking of a bond between two fibers. Integration under the curve produces values for a second curve in which the cumulative work done on the specimen is plotted against the number of bond breaks that have occurred. Segments of this curve, usually occurring near the end, have minimum slopes. The values of these slopes are equal to the average energy dissipated per bond break by a few fibers near the site of the break, and can be considered a measure of bond strength.

Handsheets (2.5 g/m^2) were prepared from beaten and unbeaten Northern and Southern softwood kraft pulps. Specimens were tested to tensile failure on a sensitive tensile tester. Plots of work

done as a function of the number of bonds broken were prepared and slopes were determined.

The average energy dissipated per bond was similar for the two unbeaten pulps, but differences were observed in the tensile behavior of samples made from the two different pulps. Beating resulted in approximately an eight-fold increase in the energy dissipated per bond break. The bond strength for the beaten Northern pulp appeared to be slightly higher than for the beaten Southern pulp.

These preliminary results indicate that the proposed method for measuring interfiber bond strength is feasible. However additional work will be necessary to confirm the applicability of the method and establish its usefulness. As a first step it is proposed to test additional samples prepared from pulps subjected to various degrees of beating. If sufficient time is then available, tests will be performed on samples of different basis weights. These latter tests should help determine whether the fiber density of the sample influences its tearing behavior. These tests thus might help explain the differences in tearing behavior observed in samples made from the two unbeaten pulps.

INTRODUCTION

Consider a random fibrous network formed from the pulp to be evaluated. The network should be thin; i.e., the number of fibers constituting it shall be so small that the area covered by more than two fibers intersecting at a given point is negligible. The concept and statistical geometry of such "2-dimensional" networks has been discussed by Kalmes and Corte [1].

If a specimen cut from this network is stretched to break in a sensitive tensile tester, the force-elongation curve obtained often looks something like the curve depicted in Figure 1. Each jagged peak on this curve signifies the breaking of a bond between fibers. (It is assumed the fibers are much stronger than the bonds between them, so that the fibers themselves do not break.) By integrating under the curve, Figure 1, it is possible to obtain values for a second curve, Figure 2, in which is plotted the cumulative work, U, done on the specimen as a function of the number of bond breaks, n, that have occurred. It should be noted that the slope dU/dn of this curve decreases and approaches a constant value as n increases. This constant value is the characteristic energy E proposed by Dodson as a measure of bond strength.

During the straining operation the following behavior sequence is observed in the fibrous network. The fibers gradually align themselves in the direction of strain with the straightest and most perfectly aligned fibers bearing most of the load. Initially breaks occur at random points throughout the network, but eventually they become concentrated in the vicinities of pre-

existing or developing flaws. As the extension continues the network is gradually destroyed. In the final stages of the breaking process, portions of the network often coalesce into long thread-like structures that sustain relatively large elongations before breaking.

In order to provide some understanding of this extensional behavior the following network response mechanics is postuated. It is assumed that initially the force borne by the network is sustained by a relatively small number of fiber segments roughly oriented in the direction the network is being stretched. The forces in these fiber segments range from small values up to magnitudes large enough to break the bond at either end of the segment. Most of the fiber segments in the network bear no load at all, because they are unaligned, or because the load is borne by adjacent fibers with shorter segments between bonds. When a bond breaks the network opens up in the vicinity of the break. This permits new fibers to become better aligned and to carry some of the load. During early stages of the extension the number of load bearing fibers increases as a result of this process, the load distribution among the fibers becomes more uniform, and the force sustained by the network tends to increase.

During the stretching process part of the work done is stored as potential energy and part is dissipated when bonds break. Initially most of the work is stored as energy in the network. When a bond breaks some of this energy is dissipated, but if the level of force after break then increases in a series of successive breaks, there is a net increase in energy stored. Because of this increase in stored energy, the curve of work done U versus number of breaks n has a large positive slope during the initial stage of the stretching process. At higher forces the fiber bonds tend to break more readily, and the increase in force before another break occurs is not so great. Less additional energy is stored between breaks, and the slope of the U,n curve becomes less positive.

In those stages of the extension when the stretching force is large and the network remains intact, each time a bond is broken other previously unloaded fiber segments in the vicinity assume some of the load. Under these conditions there is an approximate one-to-one relationship between the level of force and the energy stored in the network. In particular, if during extension the force sustained by the network returns to the same value after each of a series of breaks, the average energy stored in the network remains constant. The work of extension is completely dissipated; that is, it merely replaces the stored energy lost by each bond break of the series. The slope of the U,n curve then has a constant minimum value, and represents the average energy dissipated per bond break. This dissipated energy is the energy that was stored in a few fibers near the site of a broken bond, and is equal to Dodson's characteristic energy E.

If during extension the force sustained by the network diminishes appreciably between two consecutive breaks a flaw has probably developed and the network has become partially destroyed. The functional relationship between force and stored energy that held in the previously intact network no longer applies, but it is still true that the energy stored has been diminished, and consequently all of the work done in extending the network between breaks has been dissipated. Thus if the force after break has a decreased value in each of a series of successive breaks, the cumulative work done to produce the breaks is all dissipated, and the average value of the work of extension that is dissipated per break is given by the slope of the U,n curve in this region. This slope will have a decreased value, but this value may be greater than Dodson's characteristic energy E.

Often after a network has been partially destroyed it again begins to store energy, and the level of force rises åfter each of a series of successive breaks until further deterioration occurs. The force-elongation curve thus may rise and fall through a series of peaks, and the corresponding U,n curve will have a scalloped appearance. The decreased slopes at each scallop can be used to estimate E; the minimum of these slopes is ordinarily a good estimate. However the regions of the force-elongation curve corresponding to these decreased slopes should always be carefully studied in order to judge, in the light of this discussion, how good this estimate is.

In the final stages of the extension portions of the network may coalesce into long threadlike structures consisting of several strands of fibers bonded end to end and cross linked at intervals by other fibers. The presence of these structures would be manifest in the force-elongation curve as a series of breaks at low forces with relatively large elongations between breaks. The curve of percent elongation versus number of breaks would have a sharp increase in slope when these structures occur.

In the long narrow networks of these threadlike structures the stretching force is sustained along a straight-line path consisting of fiber segments bonded together in series. When one of these bonds is broken, other slightly longer and previously unstressed segments in the vicinity assume the load. The energy stored in a structure such as this is a function of the applied force. Thus by using the previous arguments it is seen that if the force after break has the same or a decreased value in each of a series of successive breaks, the cumulative work done to produce the breaks is all dissipated, and the slope of the U,n curve will have a decreased value. Ordinarily these final threadlike structures do not suffer drastic deterioriation as a result of bond breaks, nor are they often capable of storing energy over a successive series of breaks; thus the forces after break stay within reasonable bounds. In most cases, then, the final portion of a U,n curve should have a long constant minimum slope that would provide a reliable measurement of E.

EXPERIMENTAL

Handsheets having a weight of 2.5 g/m^2 (2-D sheets) were prepared from beaten and unbeaten Northern and Southern softwood kraft pulps. Beating was performed in a PFI laboratory beater at a consistency of ten percent for 10,000 revolutions with no clearance between bed plate and roll at a force of 33N (3.4 kg) and a relative velocity of roll to bed plate of 6 m/s.

The standard method for preparing handsheets was unsatisfactory for the preparation of 2-D sheets. A microscopic study indicated that the fibers followed the undulations of the wire xcreen used as the forming medium resulting in an entanglement of the fibers with the wire screen. This made it virtually impossible to remove the handsheet from the wire without damaging it. It became obvious a smoother forming medium was necessary in order to prepare the 2-D handsheets uniformly and reproducibly.

In the course of evaluating several different forming media, it was found that cotton linters pulp was superior to the ordinary forming wire. Its performance was further enhanced by treating its surface with a fluorocarbon release agent.

The procedure for forming 2-D handsheets is as follows: A 33 x 33 cm piece of cotton linters pulp treated with a fluorocarbon release agent is placed on top of the support wire of the deckle box of the handsheet machine and wetted. The pulp expands upon wetting. The deckle box is then closed, clamping the pulp firmly at the bottom. Water is then added to the box from the top being careful not to damage the pulp surface.

An appropriate amount of pulp to be tested is placed in approximately one liter of water and disintegrated on a British Disintigrator for 7,500 revolutions for beaten pulp or 25,000 revolutions for unbeaten pulp. Whenever unbeaten pulp is used it is first soaked in one liter of water overnight prior to disintegration. The disintegrated pulp is added to the water in the deckle box, agitated carefully and then drained through the pulp sheet.

The pulp sheet is removed from the deckle box and placed on top of a fresh sheet of pulp. A 33 x 33 cm ferrotype plate is then placed carefully over the top of the wet pulp sheet so as not to disturb the fibers of the 2-D sheets. After placing another pulp sheet over the ferrotype plate the entire sandwich is placed in a hydraulic press and pressed at 0.66MPa (96 lbs/in^2) for five minutes.

During the pressing the 2-D sheet is transferred to the ferrotype plate. It is allowed to dry while still adhered to the ferrotype plate. When dry, the 2-D handsheet is carefully removed from the plate without any damage to the sheet.

The handsheet samples were fragile so special handling and mounting procedures were used to prepare and test the specimens. The sample to be tested was sandwiched between two sheets of paper and a 1 cm ribbon cut using a scalpel guided by a straight edge. The ribbon was transferred, using forceps, to a paper mounting frame, and taped at top and bottom with masking tape. A frame for mounting the 1 x 2 cm specimens tested is shown in Figure 3.

The frame and specimen were mounted in the tensile tester. The top of the frame was held between two small strips of aluminum suspended by a wire from the load cell. The bottom was held in an air clamp. After mounting, the strips of paper on each side of the frame were carefully cut with scissors.

All tests were conducted using a cross-head speed of 0.2 cm/min and a chart speed of 20 cm/min. For tests on the unbeaten samples of Northern and Southern pulps, the load cell sensitivity was 0.02N (2 g) full scale. Load cell sensitivity was 0.2N

(20 g) full scale for tests on the beaten samples of Northern pulp and 0.1N (10 g) full scale for beaten samples of Southern pulp.

RESULTS

Results of the tests are given in Tables 1 through 4. In these tables the quantities labeled E are the estimates of average energy dissipated per bond break by a few fibers near the site of the break. The values of E were determined from the constant slope portions of the U,n curve. N is the number of breaks that occurred in the specimen tested. The quantity U_t/N is the total amount of work done in breaking a specimen divided by the number of breaks that occurred. Its value provides an upper bound to the estimate of E. Most of the energy U_t is dissipated by the collapsing network rather than by the fibers located at the breaking sites. This is why the value of U_t/N is greater than E.

The fifth and sixth columns in the tables provide qualitative information about the force-elongation curves and the U,n plots respectively. The fifth column gives estimates of the number of peaks apparent in the force-elongation curve. This should correlate roughly with the number of flaws in the specimen about which the breaks were concentrated, and the number of scallops that might appear in the U,n plot. In those cases where the symbol ∞ is given, the force at which breaks occurred was approximately constant throughout most of the curve, and no peaks could be distinguished. The U,n plots derived from these curves usually contained many scallops.

The quality of the U,n plot as graded in the sixth column is a rough evaluation of the reliability of the E value determined from the U,n plot. For instance, a plot graded A usually resulted from a test in which bond breaks occurred in the vicinity of a single flaw, and a long portion at the end of the U,n plot was linear. In contrast, a plot graded D contained many scallops in which the linear portions were not well defined.

Figures 4 through 7 are tracings of typical force-elongation curves obtained in the tests. Each curve represents the behavior of a different pulp sample. For instance, Figure 4 is a curve of two peaks obtained in a test of specimen 4 of the unbeaten Northern pulp sample. Column 5 of Table 1 indicates that multipeak curves are usually obtained in tests of this sample. The corresponding U,n curve is shown in the plot of Figure 8. Two pronounced scallops corresponding to the two peaks in Figure 4 are the dominant features of this plot. As the character of this plot was so definite the quality of the plot was assigned a grade of A.

In tests on the beaten Northern pulp, single-peak force-elongation curves are frequently obtained. Figure 5 is a tracing of one of these curves. The corresponding U,n plot is given in Figure 9 The monotonic dependence of U upon n culminating in a long region of constant minimum slope provides a good illustration of breaking behavior in the vicinity of a single flaw.

Tests on specimens from the unbeaten Southern pulp sample resulted in curves in which the magnitude of the breaking force remained the same over much of the elongation. A force-elongation curve of this type is given in Figure 6. The corresponding U,n plot, shown in Figure 10, has many scallops of short duration.

The value of E derived from this plot is not very reliable, and the quality of the plot was graded D.

Tests on beaten Southern pulp spcimens yielded multi-peak force-elongation curves similar to the one shown in Figure 7. The corresponding U,n curve plotted as Figure 11 shows multiple scallops.

Plots of elongation versus number of breaks are given in Figures 12 through 15, for the same specimens whose force-elongation and U,n curves were given previously. The curves for the unbeaten and beaten Northern pulps tend to be linear throughout most of the range of the number of breaks n, and to have a gradually increasing slope when n is large. The increased slope at the end of the test indicates that in the final stages the breaks are occurring within a long thread-like structure formed by the specimen. Curves for the beaten and unbeaten Southern pulps usually have two linear portions with an abrupt change in slope occurring near the middle of the range of n. This indicates that the Southern pulp specimens have a greater tendency to form thread-like structures than do the Northern pulp specimens.

Elongation is more compactly presented in columns 7 and 8 of Tables 1 through 4. In column 7 total elongations are given, and in column 8 elongations per break are tabulated. The values of elongation per break were found from slopes of the elongation-break curves. Those curves with two slopes have two values tabulated. If the change of slope is gradual or occurs near the end of the range of n values as in Figure 12, the value of the second slope is not given in the tables. Similarly as in Figures 14 and 15 the very large slopes occurring at the end of the n value range have been omitted from the tables.

DISCUSSION

According to Tables 1 and 3 it is not possible to distinguish between the unbeaten Northern and Southern pulps by comparing their E values, as the Northern pulp average value of 0.85 x 10^{-7}J is almost the same as the Southern pulp average value of 0.82 x 10^{-7}J. Nor do the average U_t/N values afford a clear cut distinction, as the U_t/N value of 1.72 x 10^{-7}J for the unbeaten Southern pulp is only slightly but not significantly higher than the value of 1.30 x 10^{-7}J for the unbeaten Northern pulp.

The breaking behaviors of the two pulp samples however are quite different. Breaking in the unbeaten Northern pulp specimens usually occurred only in the vicinity of a few flaws, as may be seen from the small number of peaks observed in the force-elongation curves, and the good reliability with which E could be determined from the U,n curves. The low value of elongation per break averaging to 0.15% break suggests that the network was firmly connected with only short distances between fiber bonds. Thread-like structures, if they developed at all, occurred only near the end of a test, as only one set of values of elongation per break is tabulated in column 8 of Table 1.

In contrast, the unbeaten Southern pulp specimens had many breaks occurring at random throughout the network. The U,n curves had many scallops and E values could not be determined with good reliability. The high initial values of elongation per break of 0.43 %/break suggest that in many of the specimens the network was not firmly connected; that is, there was a longer distance on the average between fiber breaks. The occurance of multiple values of elongation per break tabulated in column 8 of Table 3 suggests that thread-like structures frequently developed about midway through the breaking process.

It was noted during sample preparation that the unbeaten Southern pulp sample was very fragile and difficult to handle. It is therefore possible that further tests on different samples will give results different from the ones obtained here.

Beating the pulp strongly affects the ability of the fibers to bond together. In the case of the Northern pulp, the beating treatment produces a rise in the values of E from 0.85×10^{-7}J for the unbeaten pulp to 7.3×10^{-7}J for the beaten pulp. There were also minor changes in the character of the force-elongation curves and U,n plots. Beating tends to reduce the number of random fiber breaks throughout the network and localize them to the vicinity of a flaw. Fewer flaws develop in the beaten pulp network, and the number of scallops appearing in the U,n plots are less, so that more reliable values of E can be obtained.

Beating produces similar changes in the Southern pulp samples. The value of E is increased from 0.82×10^{-7}J for the unbeaten pulp to 6.8×10^{-7}J for the beaten pulp specimens. The beaten pulp network has more of a tendency to break in the vicinity of a flaw, and the U,n curves have fewer scallops so that better determinations of the value of E can be made. For the southern pulp beating also causes the network to be more firmly connected, as noted by the significant decrease in the value of 0.43 percent elongation per break for the unbeaten pulp to 0.18 percent elongation per break for the beaten pulp.

Although beating produces more strongly bonded networks in both the Northern and Southern pulp samples, the breaking behaviors of the two pulps are still different. The beaten Southern pulp specimens have multiple-peak force-elongation curves, and the reliability of the E values determined from the correspondingly scalloped U,n curves is only fair. Moreover the beaten Southern pulp specimens frequently form threadlike structures midway through the tests. In the beaten Northern pulp specimens the force-elongation curves have fewer peaks, the U,n curves have fewer scallops and the thread-like structures that form do not appear until the end of the test. Evidently the differences in behavior between the Northern and Southern pulp networks cannot be completely overcome by a beating treatment.

CONCLUSIONS

From the preliminary work reported here it appears that interfiber bond strength can be characterized by Dodson's energy parameter E. Definite differences in bond strength have been observed between beaten and unbeaten soft wood kraft pulps. The effect of beating on bond strength therefore should be studied by additional tests on samples prepared from pulps subjected to various degrees of beating.

No significant difference in bond strength was observed between samples prepared from Northern and Southern soft wood kraft pulps, although differences in tensile behavior were observed in the tests. The differences in tensile behavior may be due to differences in the morphology and coarseness of the two pulp samples, so these quantities should be characterized to help interpret the test results. The effect of fiber coarseness should also be investigated by tests performed on samples of different basis weight.

REFERENCES

1. O. Kallmes and H. Corte, TAPPI 43, 737 (1960).

2. C. T. J. Dodson, Brit. J. Appl. Phys. 18, 1199 (1967).

Table 1

Tests on Sample 1, Northern Pulp Unbeaten

Specimen	E	N	U_t/N	No. of Peaks	Quality of U,n Plot	Total Elong.	Elong. per Break
	$10^{-7}J$		$10^{-7}J$			%	%
3	0.73	52	1.70	1	A	11.	0.15
4	0.64	63	1.03	2	A	15.	0.13
7	1.04	99	1.66	3	B	22.	0.12
9	0.74	66	0.96	∞	C	20.	0.20
10	1.08	97	1.54	∞	D	52.	0.18
11	0.88	86	1.47	2	A	22.	0.12
12	0.71	95	1.48	4	B	26.	0.11
13	0.92	112	0.99	>3	C	31.	0.12
14	0.71	80	0.88	∞	D	20.	0.14
15	1.08	113	1.29	∞	D	42.	0.20

Average E 0.85 x 10^{-7}J, standard deviation 0.17 x 10^{-7}J
Average U_t/N 1.30 x 10^{-7}J, standard deviation 0.31 x 10^{-7}J
Average elongation per break 0.15%, standard deviation 0.03%

Table 2

Tests on Sample 2, Northern Pulp Beaten

Specimen	E	N	U_t/N	No. of Peaks	Quality of U,n Plot	Total Elong.	Elong. per Break
	$10^{-7}J$		$10^{-7}J$			%	%
1	7.0	148	16.2	>3	C	28.	0.14
2	8.2	160	22.7	1	A	31.	0.11
3	6.4	119	14.6	1	A	30.	0.15
4	10.1	161	21.7	>3	D	34.	0.12
5	6.8	95	22.4	>2	B	20.	0.12
6	7.2	73	24.1	>2	B	15.	0.12
7	8.7	88	20.7	1	A	19.	0.13
8	6.0	94	18.7	>1	A	29.	0.13-0.75
9	6.8	108	17.7	3	A	21.	0.13
10	6.0	163	20.3	>1	A	29.	0.12

Average E $7.3 \times 10^{-7}J$, standard deviation $1.3 \times 10^{-7}J$

Average U_t/N $19.9 \times 10^{-7}J$ standard deviation $3.1 \times 10^{-7}J$

Average elongation per break 0.13%, standard deviation 0.01%

Table 3

Tests on Sample 3, Southern Pulp Unbeaten

Specimen	E	N	U_t/N	No. of Peaks	Quality of U,n Plot	Total Elong.	Elong. per Break
	10^{-7}J		10^{-7}J			%	%
1	0.81	99	1.85	∞	D	51.	0.32 - 0.73
3	0.80	27	1.96	∞	D	29.	0.80
4	0.80	92	1.97	∞	D	53.	0.35 - 0.55
5	0.96	38	1.56	∞	D	36.	0.49 - 1.33
6	0.92	47	1.85	∞	D	54.	0.47 - 0.72
7	0.94	61	1.59	∞	D	46.	0.27 - 1.04
8	0.80	45	1.53	∞	C	31.	0.60
9	0.60	120	1.62	∞	D	75.	0.22 - 0.61
10	0.66	61	1.97	∞	D	46.	0.50
11	0.86	127	1.29	∞	B	44.	0.24 - 1.10

Average E 0.82 x 10^{-7}J, standard deviation 0.12 x 10^{-7}J

Average U_t/N 1.72 x 10^{-7}J, standard deviation 0.23 x 10^{-7}J

Average initial elongation per break 0.43%, standard deviation 0.17%.

Table 4

Tests on Sample 4, Southern Pulp Beaten

Specimen	E	N	U_t/N	No. of Peaks	Quality of U,n Plot	Total Elong.	Elong. per Break
	10^{-7}J		10^{-7}J	!		%	%
1	6.4	76	16.2	>5	D	24.	0.19
2	5.3	104	11.3	8	B	24.	0.18
3	5.6	158	12.1	>10	B	51.	0.16 - 0.34
4	8.1	141	17.3	>5	D	32.	0.13 - 0.42
6	7.1	153	19.2	>7	B	44.	0.14 - 1.15
7	7.6	143	17.8	>10	D	37.	0.20
9	7.1	133	16.5	>7	B	28.	0.16
10	8.5	112	15.7	>7	D	24.	0.16
11	5.4	77	14.6	>5	D	34.	0.29 - 0.66
16	6.8	110	14.0	>7	C	51.	0.16 - 0.85

Average E 6.8 x 10^{-7}J, standard deviation 1.1 x 10^{-7}J

Average U_t/N 15.5 x 10^{-7}J, standard deviation 2.5 x 10^{-7}J

Average initial elongation per break 0.18%, standard deviation 0.05%

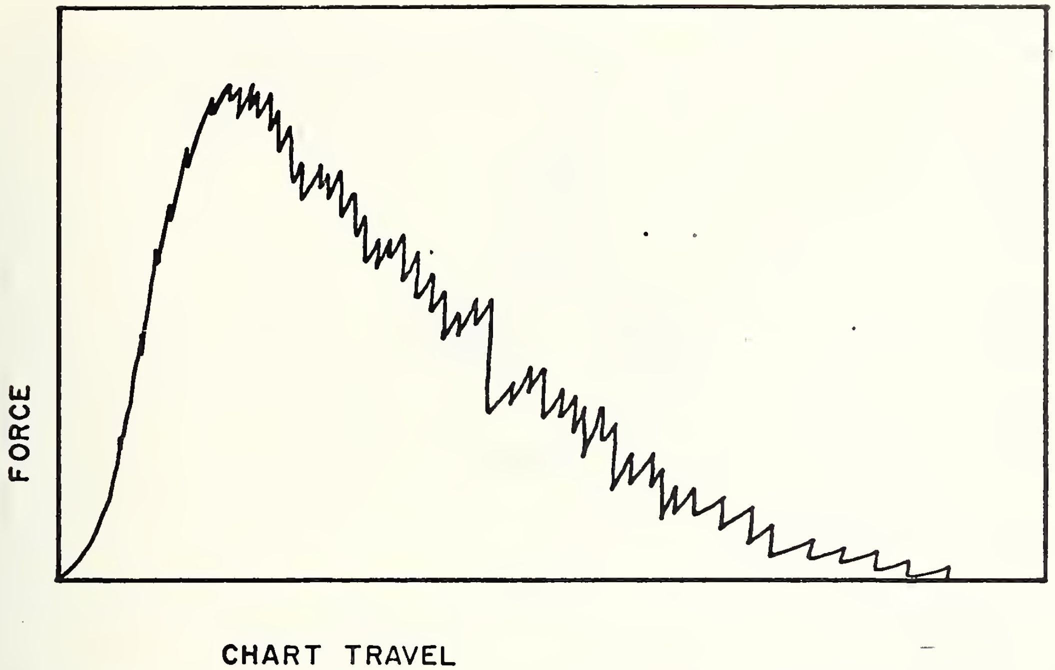


Figure 1: Idealized force-elongation curve for a "2-dimensional" paper network.

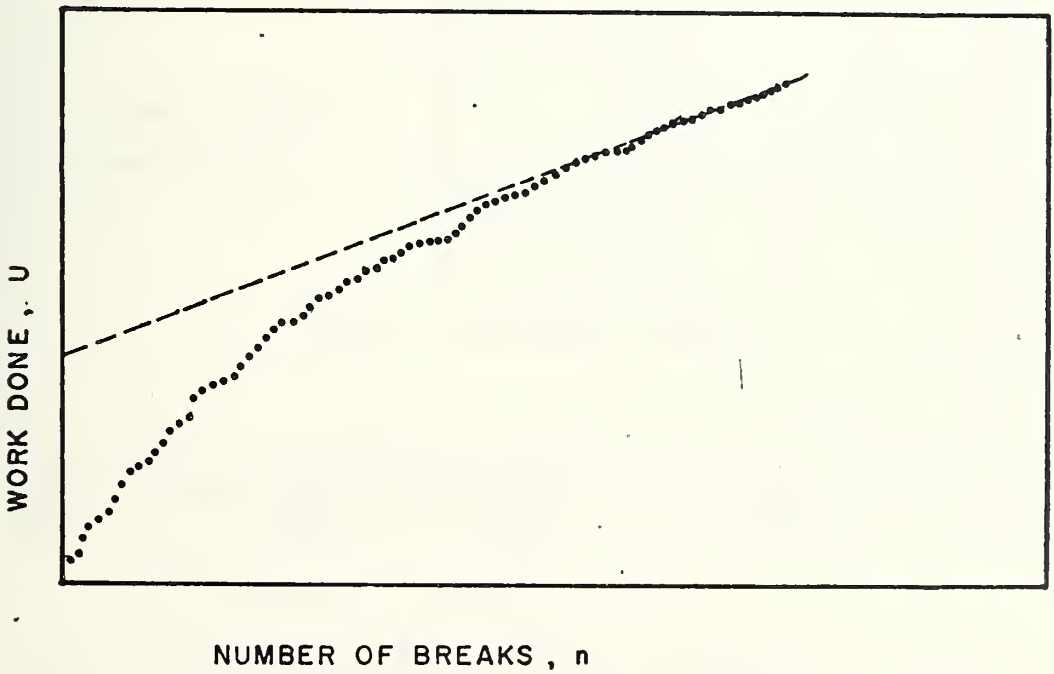
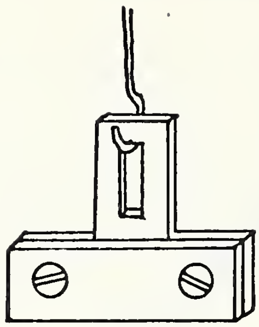
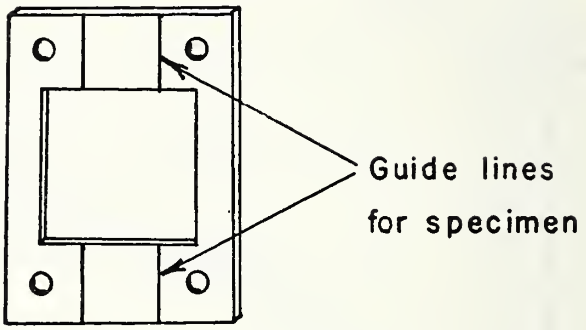


Figure 2: Plot of work of extension U versus number of bond breaks n for the force-elongation data of Figure 1.



TOP CLAMP



PAPER MOUNTING FRAME

Figure 3: Mounting frame and clamp for testing paper specimens.

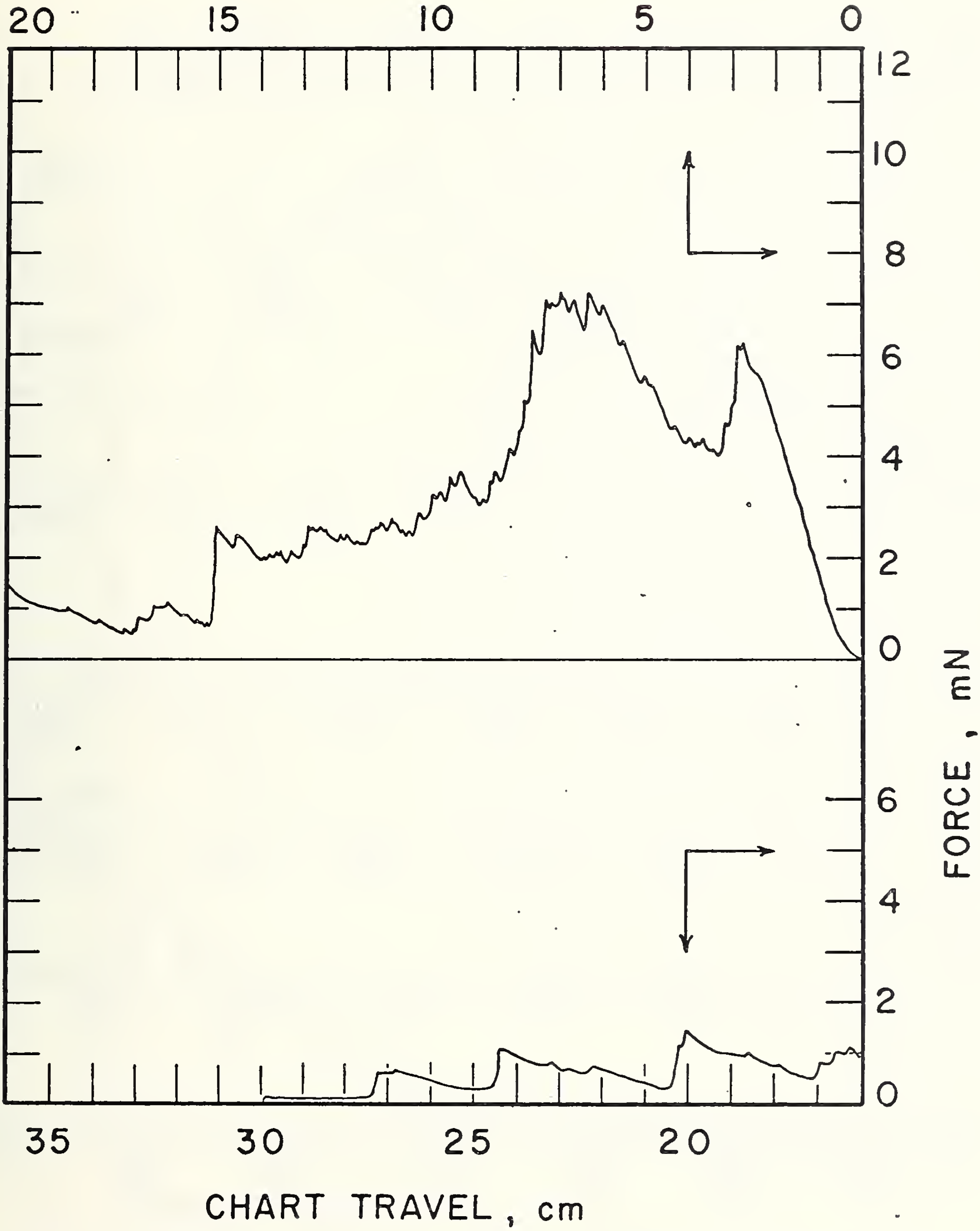


Figure 4: Tracing of force-elongation curve for specimen 4 of the unbeaten Northern pulp sample.

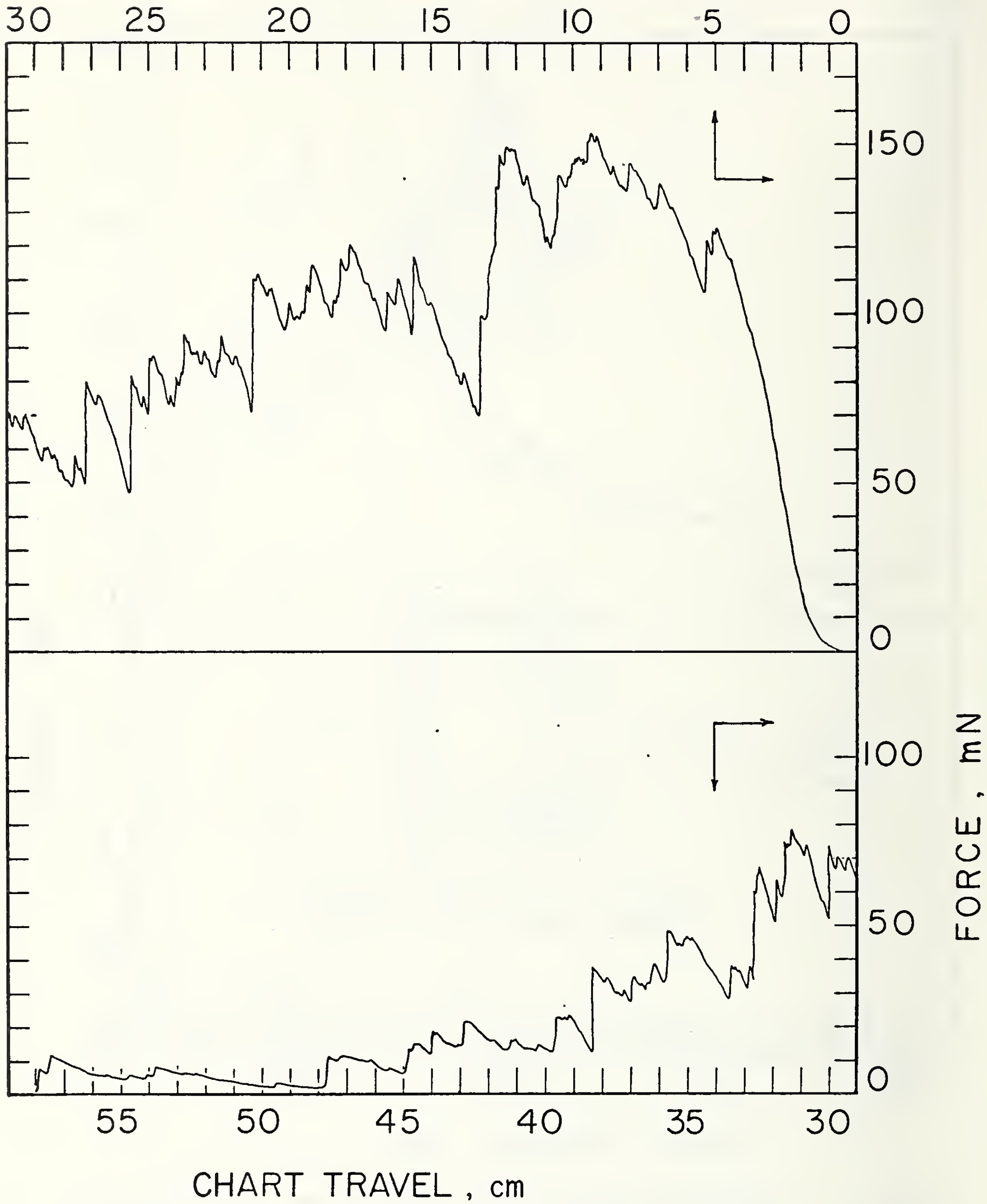


Figure 5: Tracing of force-elongation curve for specimen 10 of the beaten Northern pulp sample.

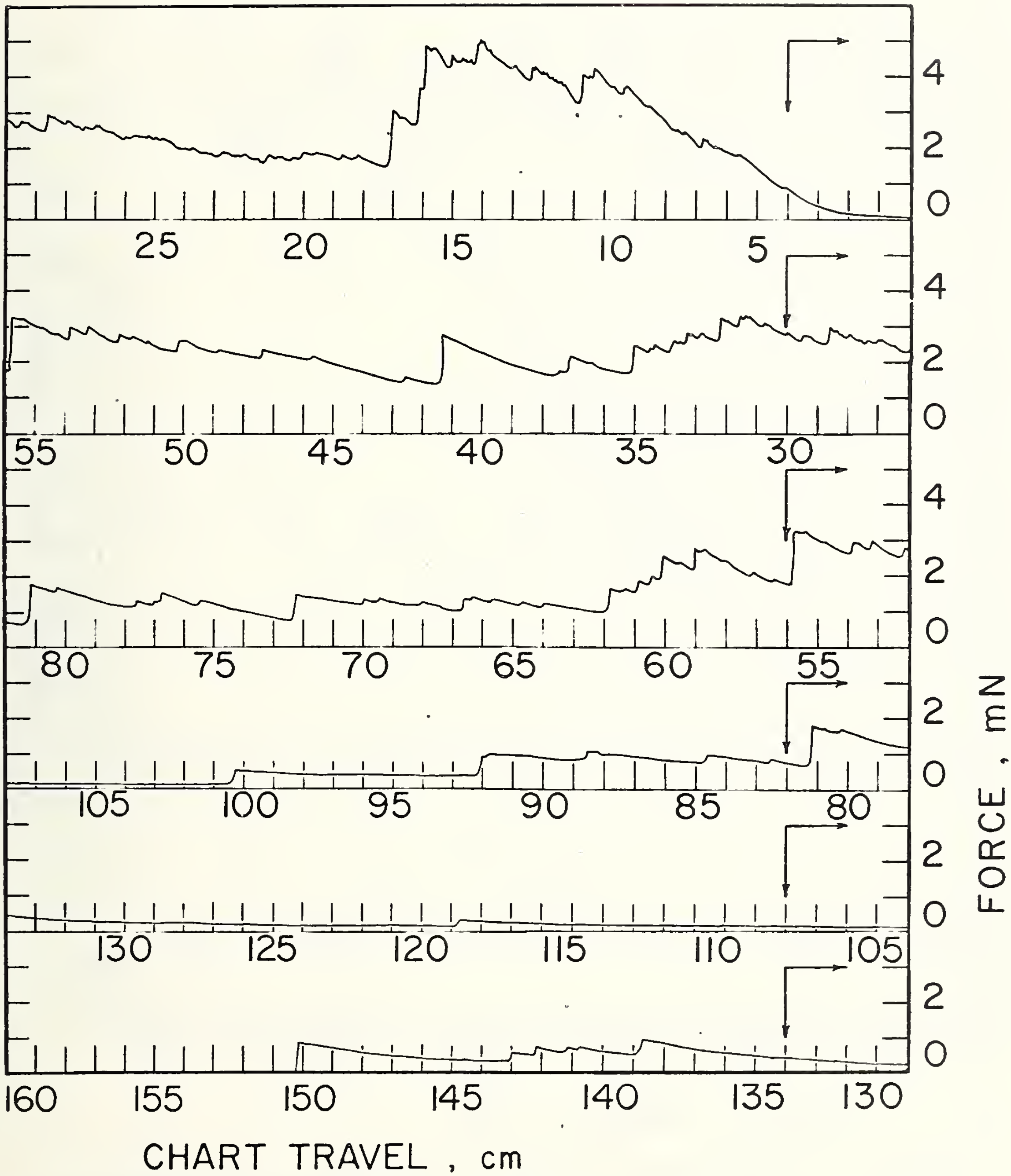


Figure 6: Tracing of force-elongation curve for specimen 9 of the unbeaten Southern pulp sample.

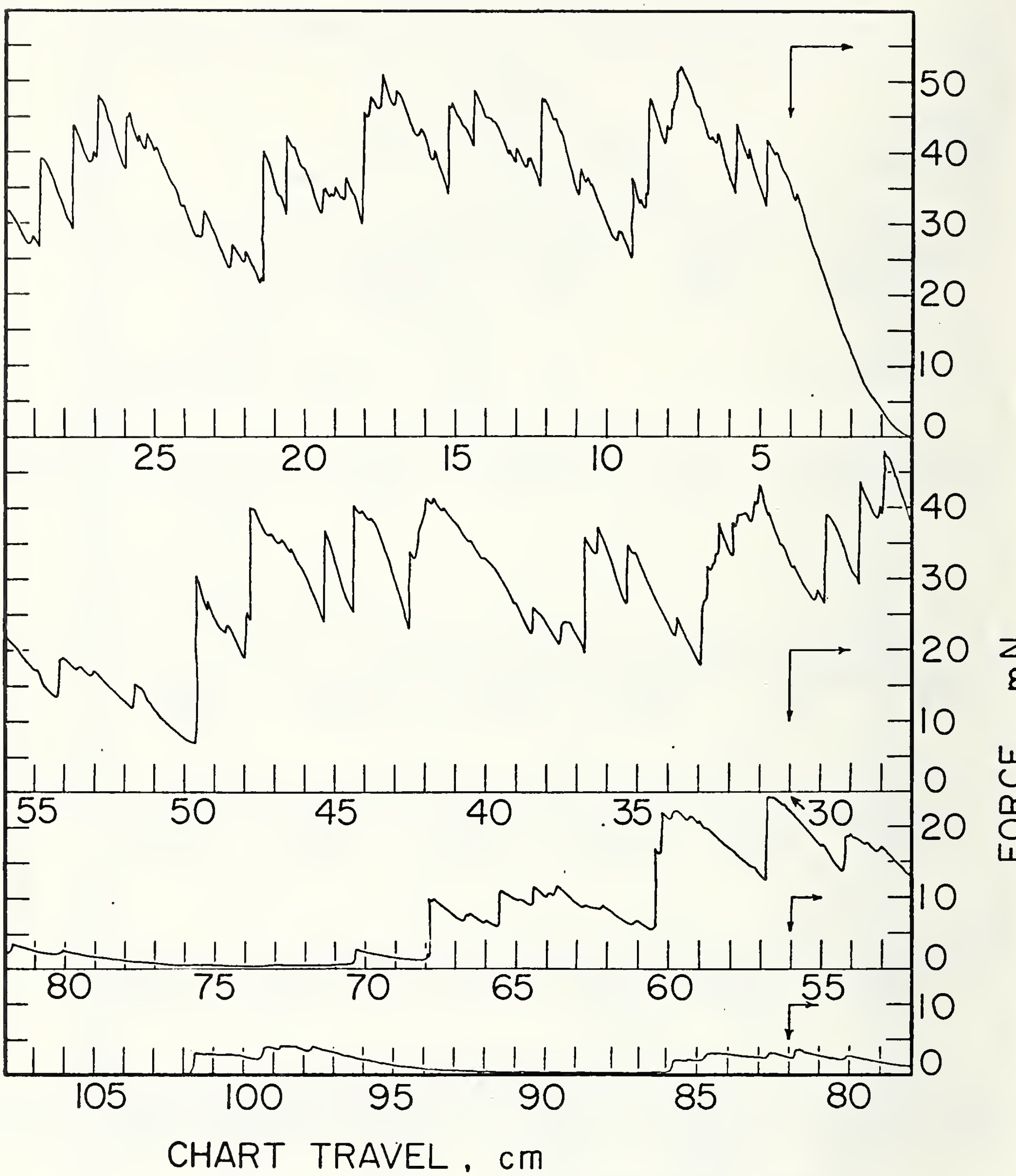


Figure 7: Tracing of force-elongation curve for specimen 3 of the beaten Southern pulp sample.

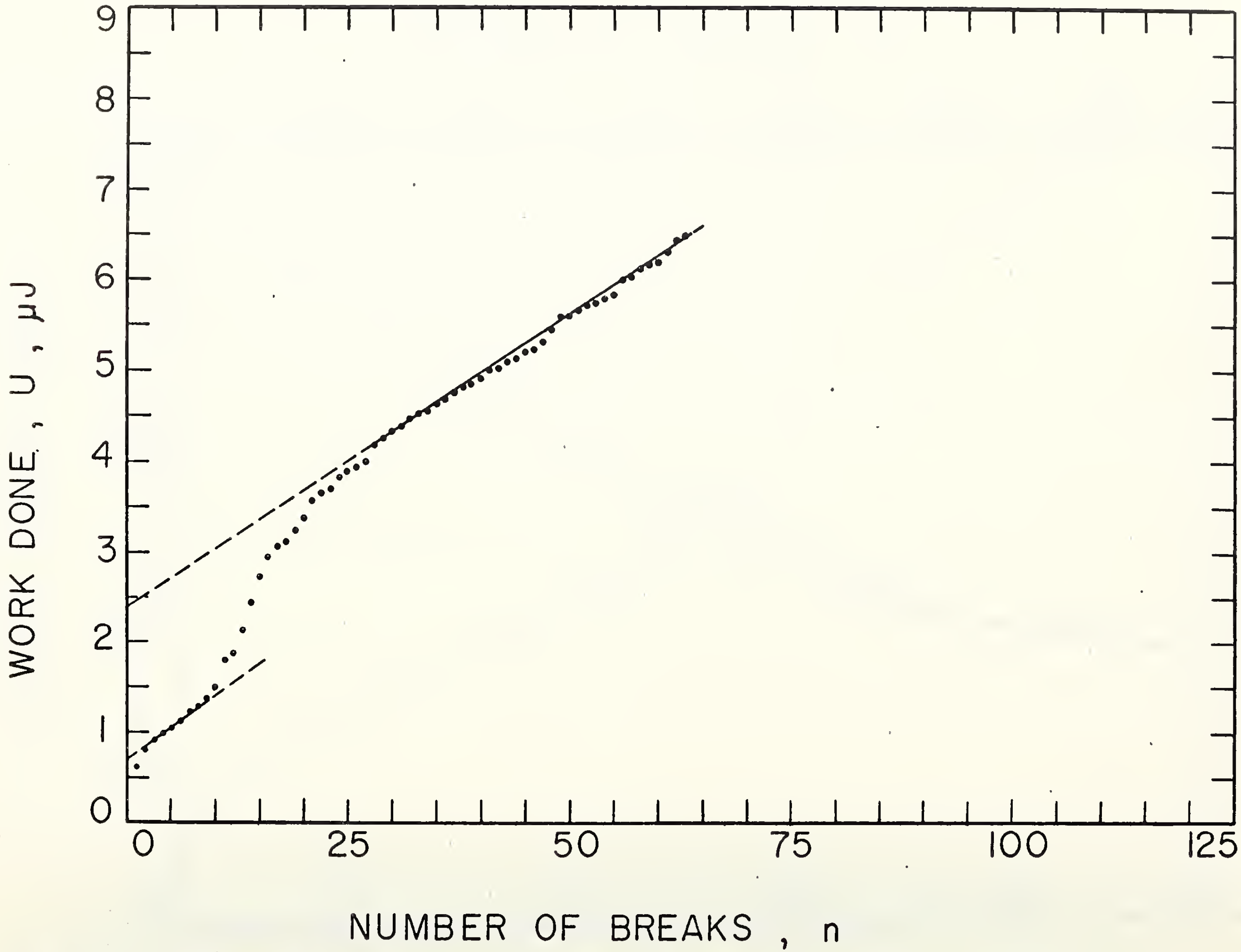


Figure 8: Plot of work of extension U versus number of bond breaks n for specimen 4 of the unbeaten Northern pulp sample.

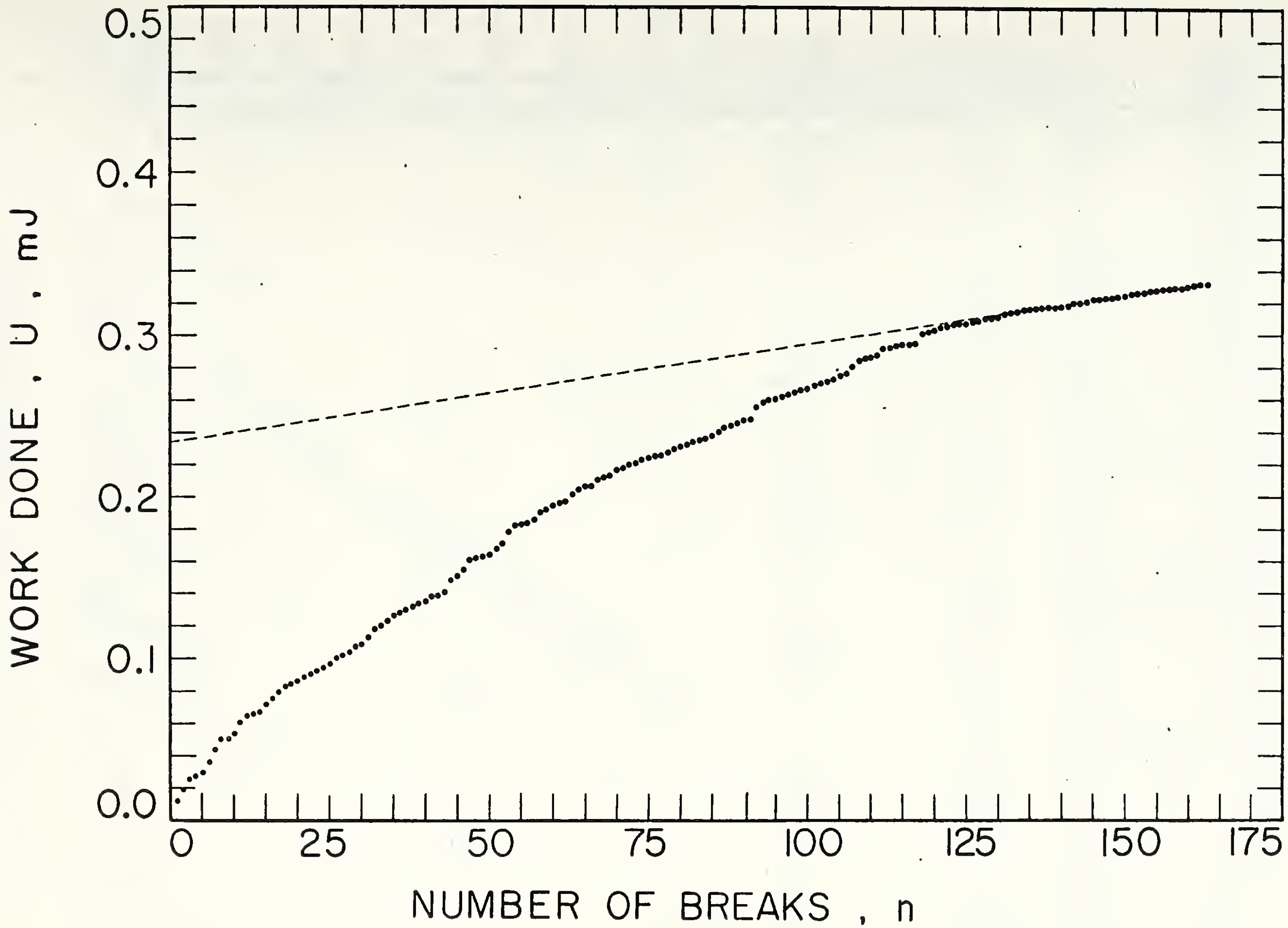


Figure 9: Plot of work of extension U versus number of bond breaks n for specimen 10 of the beaten Northern pulp sample.

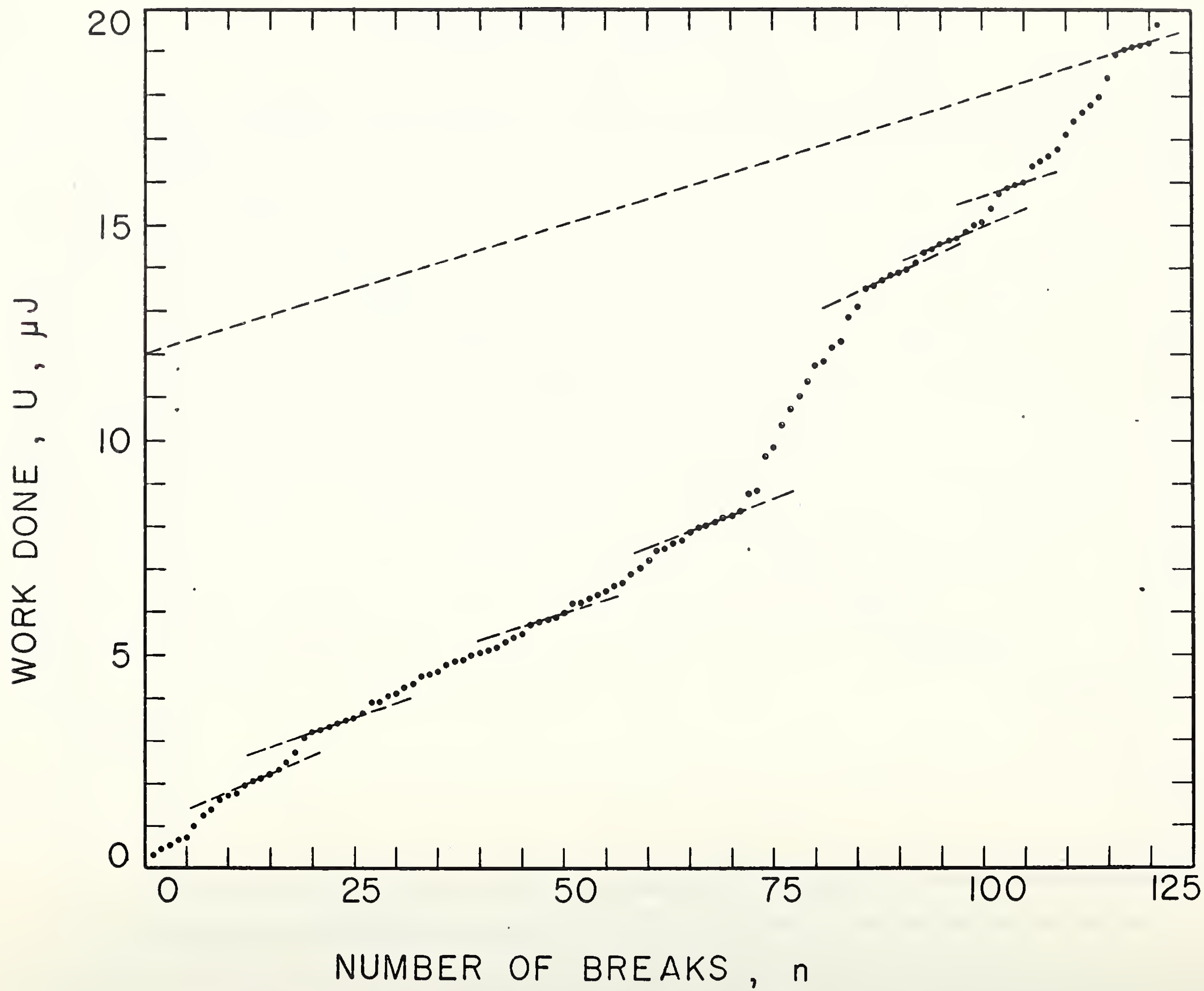


Figure 10: Plot of work of extension U versus number of bond breaks n for specimen 9 of the unbeaten Southern pulp sample.

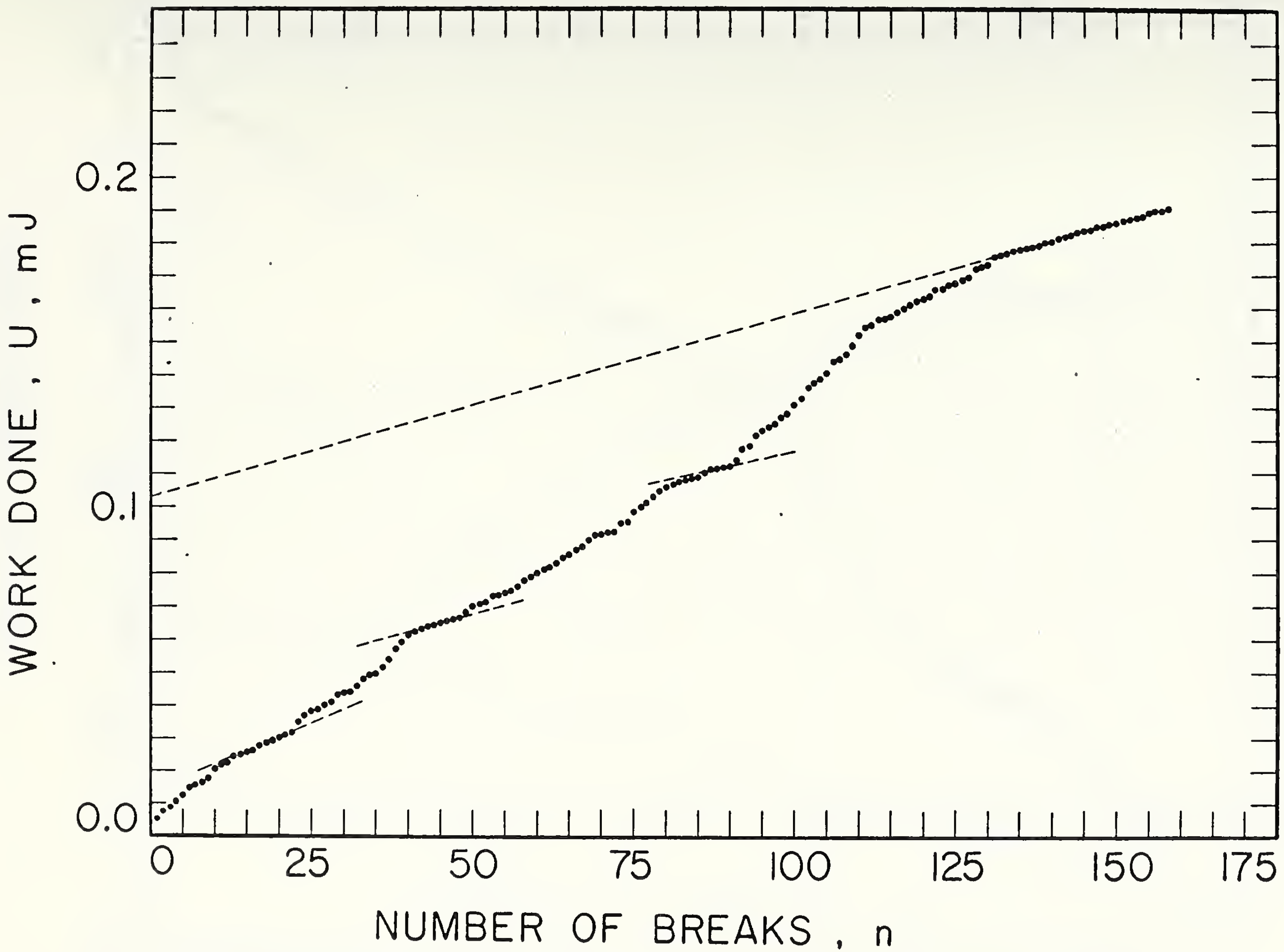


Figure 11: Plot of work of extension U versus number of bond breaks n for specimen 3 of the beaten Southern pulp sample.

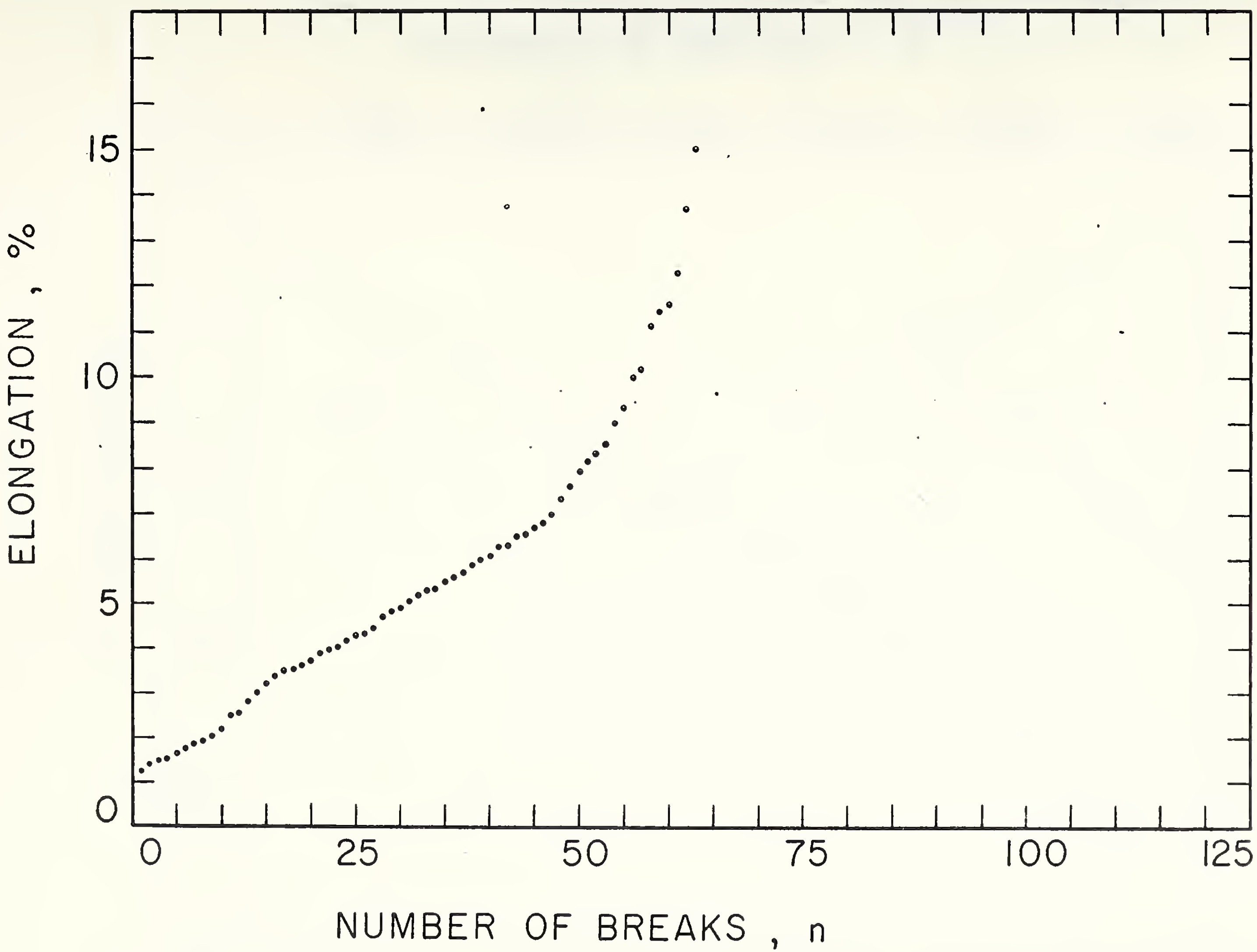


Figure 12: Plot of elongation versus number of bond breaks n for specimen 4 of the unbeaten Northern pulp sample.

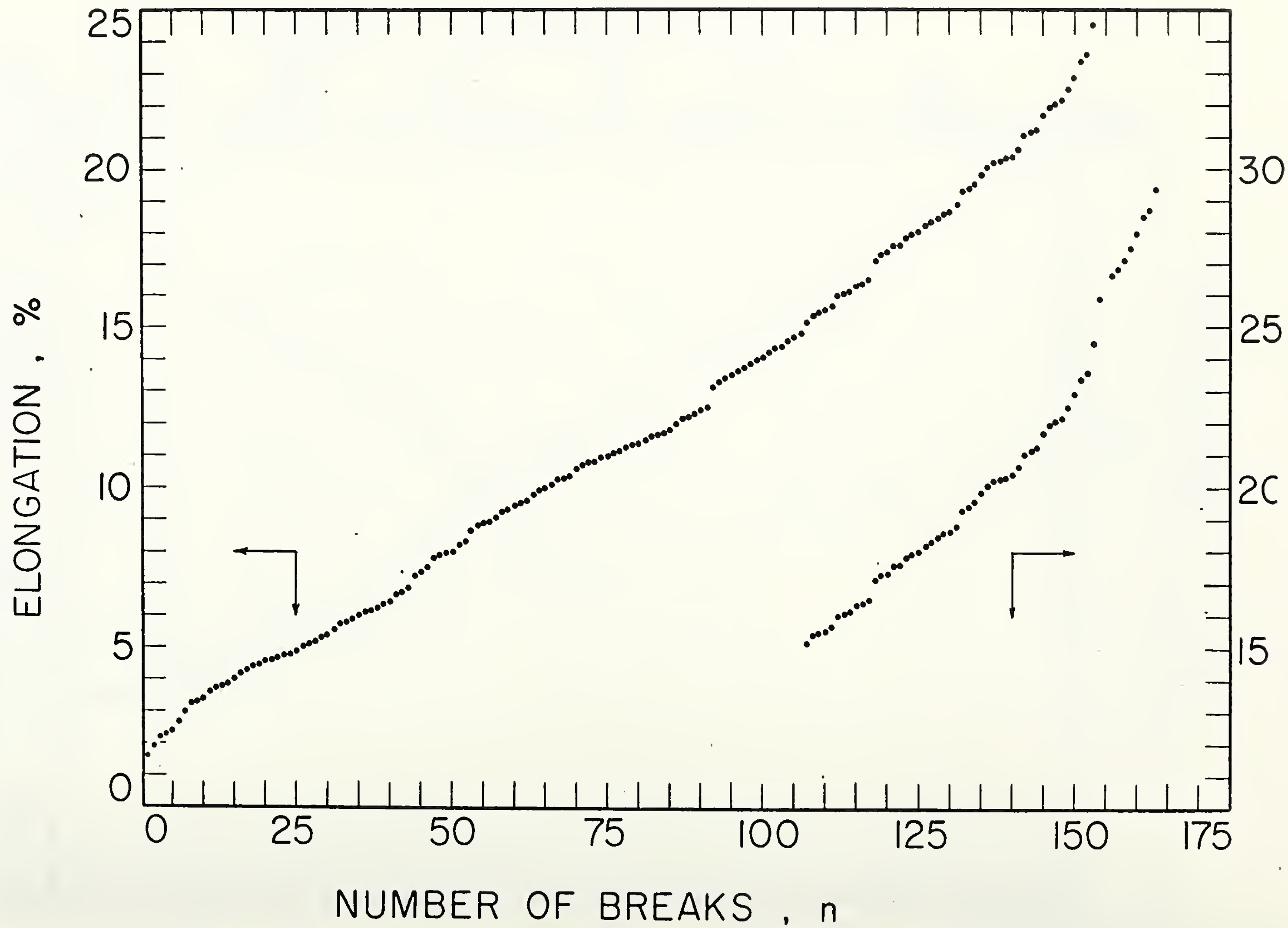


Figure 13: Plot of elongation versus number of bond breaks n for specimen 10 of the beaten Northern pulp sample.

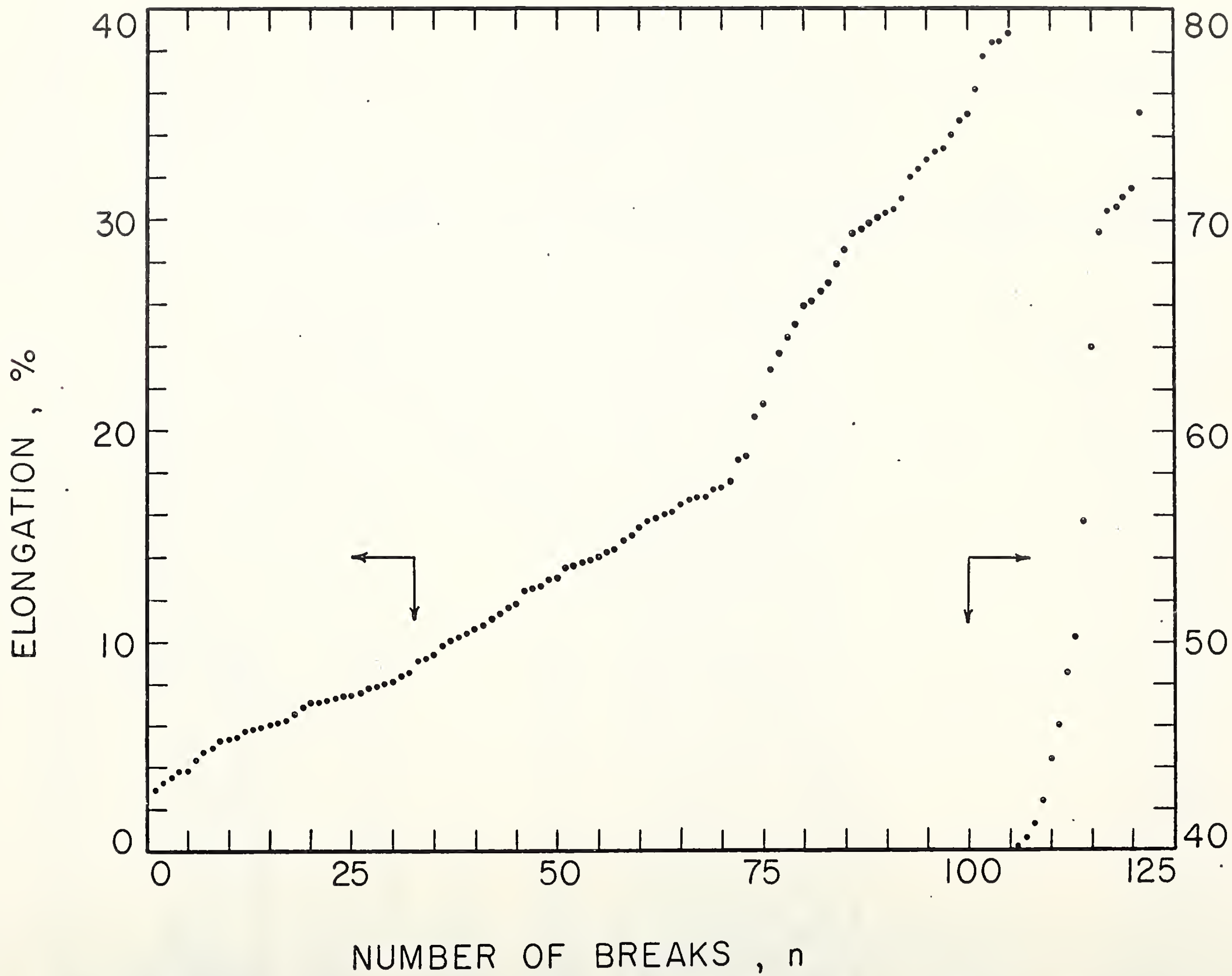


Figure 14: Plot of elongation versus number of bond breaks n for specimen 9 of the unbeaten Southern pulp sample.

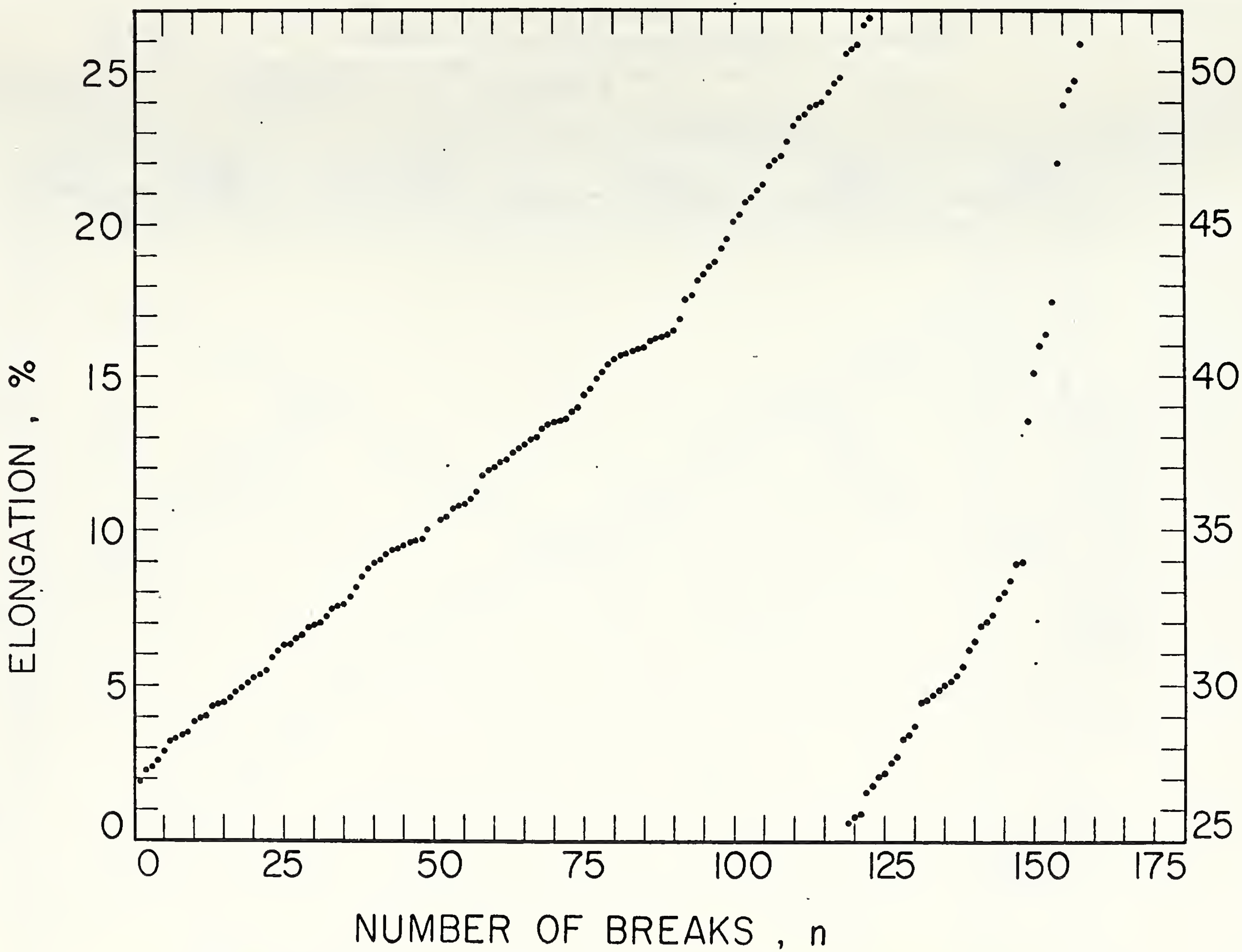


Figure 15: Plot of elongation versus number of bond breaks n for specimen 3 of the beaten Southern pulp sample.

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 76-1148	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Characterizing the Inter-Fiber Bond Strengths of Paper Pulps in Terms of a Breaking Energy

5. Publication Date October 15, 1976

6. Performing Organization Code

7. AUTHOR(S) Jack C. Smith and Edmond L. Graminski

8. Performing Organ. Report No. NBSIR 76-1148

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No. 3110443

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

U. S. Energy Research and Development Administration
Washington, D. C. 20234

13. Type of Report & Period Covered Progress Rpt Jan 1, 1976 - June 30, 1976

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The inter-fiber bond strength of paper is an important but an arduous property to measure. In order to characterize a pulp completely, the quality of bondability must be known especially for pulps produced from a mixture of waste paper. It has been postulated that a measure of bond strength can be obtained by measuring 2.5 g/m^2 handsheets to tensile failure, recording the number of bonds broken with a sensitive tensile tester and plotting a curve of number of bonds broken as a function of cumulative work done on the system. The value of the minimum slope of this curve is equal to the average energy dissipated per bond break. Results obtained on two different softwood kraft pulps indicate the proposed method may be useful in assessing bond strengths.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Breaking energy; inter-fiber bond strength; mixed waste paper; paper recycling; pulp characterization; 2.5 g/m^2 handsheets

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21. NO. OF PAGES 38

22. Price $4.00

USCOMM-DC 29042-P74