UTILIZATION POTENTIAL FOR PULP AND PAPER OF SOUTHERN PINE HARVESTED FROM BEETLE-INFESTED FORESTS

by

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INTRODUCTION

The southern pine forests of the United States cover an estimated 100 million acres in 13 states, of which 5.4 million acres of pine timber lie in Virginia (1). Southern pines are susceptible to many forms of pathological and insect attack, the most notable being *Dendroctonus frontalis* Zimm, the southern pine bark beetle. Data collected by southeastern area state and private foresters reveal that from July, 1974, to June, 1975, 47% or 46.7 million acres throughout the southeast and 41% or 2.2 million acres in Virginia were affected by outbreaks of the southern pine bark beetle (one infested tree per acre would include that acre as infested) (1).

The structure of the timber market could be affected if management decisions called for quick removal of the infested stands. Presently, the true utilization potential and value of timber from these stands is unknown. No concerted effort has been made to determine properties of wood and fiber from beetle-infested trees allowed to remain dead on the stump for extended periods of time. Even if one assumes degradation of wood after the tree has been killed, the rate of change in properties from the point of the kill is open to conjecture. A knowledge of pulp and paper properties would assist landowners and managers in scheduling the harvesting of the affected stands.

SURVEY OF LITERATURE

Both stain and decay fungi rapidly attack a dead southern pine. Verral (31) states that infection in the form of wind- and insect-carried spores reached felled pines one to two days after death occurred. He also reported the _Ips_ beetle was particularly effective in inoculating trees with the bark still intact. Further evidence of the relationship between insects and fungi was illustrated in a study by Leach, et al. (17) on felled samples of Norway pine (_Pinus resinosa_ Ait.). They found that blue stain fungi and associated yeast fungi are introduced by _Ips pini_ and _Ips grandicollis_ bark beetles.

Conditions necessary for optimum fungal growth have been summarized by Kollman and Côté (16). These conditions include favorable temperature, oxygen supply, adequate moisture, and a suitable food supply. Baxter (4), in an extensive study of 147 species, determined that the optimum temperature for fungal growth occurs between 76^{o} and $86^{o}F$ with the lower limit of $40^{o}F$ and the upper limit of $100^{o}F$. Air is critical to the development of fungi because oxygen is consumed in the growth process. The availability of oxygen and the effective rate of carbon dioxide diffusion (given off during growth) from the wood are the key variables in the process.

Moisture in wood is essential for the germination of spores and for the growth of hyphae. Living trees of the southern pine species have a normal average moisture content of approximately 100%. This amount of moisture limits the rate of fungal growth, since it does not allow enough void space in the wood for air and thus oxygen. However, after the tree dies, it begins to dry out from the crown toward the butt. The tree may lose its moisture very rapidly if it dies in the spring or summer, or more slowly if it dies in the fall or winter. As this moisture loss occurs, the optimum moisture condition for fungi growth in encountered. This optimum level is slightly above the fiber saturation point (approximately 36% for southern pine) when a film of free water covers the inner cell walls leaving sufficient air space for the diffusion of gases. This helps facilitate enzymatic reactions (the spread of fungi is a chemical versus mechanical process).

These moisture content changes may adversely affect the pulping of wood. Barron (3) determined standing trees lost 22 to 53% of their moisture within the first month following their death. After six months, the loss was 62%. The effect of this decrease in moisture content may be important. The dryed-out pulpwood is lighter in weight per cord delivered to the woodyard, so the logger suffers a considerable price loss if he sells by weight. In the pulp digesters, a batch composed primarily of extra dry wood chips would contain a higher percentage of chemicals in the liquor, due to the lack of moisture in the chips. This may lead to overcooked chips, loss in pulp yield, and higher chemical consumption (22).

Staining fungi typically precede decay fungi in the sapwood (24). Stain fungi depend on parenchymatous tissues found primarily in the wood rays and on sugars and starches found in the cells for their early nourishment. The effect of blue stain on a living tree was observed by Nelson (21) on his study of shortleaf pine (Pinus echinata Mill.).

Once the sapwood was inoculated, the moisture content of the tree was lowered due to the fungus impeding the conduction of water up the bole of the tree. He found this led to a decrease in moisture content of the crown portion of the affected tree to the point where it became much dryer than the butt zone of the tree (the reverse of the condition in a healthy tree). However, once the moisture content of wood has fallen below the fiber saturation point, blue stain can rarely continue to survive.

Many studies have been undertaken to determine if blue stained pulpwood would return lower pulp yield and paper strength than normal wood (6,7,8,20). All have reached the same conclusion that stain in wood has no effect on pulp yield or on paper strength. This would seem to be the logical conclusion since the stain fungi does not attack the cellulose or lignin structure of the cell wall.

Wood-destroying fungi of southern pines fall into two categories, the white rots and the brown rots. Verral (31) states that Peniophora gigantea (contains properties of white and brown rot) attacks the wood initially, followed by Lenzites saepiaria (brown rot) which is especially destructive after six months.

A closer examination of the effect of white rot fungi on softwoods reveals that it attacks the tracheids and involves the progressive decomposition of both lignin and cellulose from the lumen outward. The result is a progressive thinning of the wood cell wall (16,32). Holzer (12) found lignin-destroying (white) rot retains some of the toughness of the original wood. Thus, the wood stands up under the mechanical process of turning it into chips, and the chips generally enter the pulp digesters intact.

Cowling, et al., (10) determined that paper tensile strength is frequently greater for wood decayed by white rot fungi than for normal undecayed wood because the fungus causes a gradual thinning of the wood cell walls. This allows the fiber to collapse more completely than those from sound wood during beating, which leads to stronger fiber-to-fiber bonds. Paper tear strength and pulp yield have been found to decrease with increases in white rot degradation of southern pine wood (19,23).

Brown rot fungi attack in a more diffuse manner throughout the entire cell wall than do white rots. Since they primarily metabolize the cellulose complex in wood, the residual lignin can maintain the cell shape so that little damage is apparent until the advanced stages of decay. At that stage, the residual wall materials collapse (16,32). Cellulose-destroying (brown rot) fungi cause the fibrous structure to break down into a soft, crumbly material, which is often sloughed off during the chipping process. It is believed pulp yield and paper strength (tensile and tear) are both decreased after southern pine is subjected to degradation by brown rot fungi (10,19,23).

Kraft pulp and paper studies performed on trees other than southern pine warn against the use of badly decayed wood. Hunt and Whitney (13) found that pulp from decayed balsam fir (Abies balsamea L.) gave significantly lower yields and paper strength than did sound wood.

They also surmised this loss could be virtually eliminated if the proportion of affected chips to normal chips was limited to approximately 10% of the digester volume. A five-year project by Shea, et al., (25) on Pacific silver fir (*Abies amabilis* D.) killed by the balsam woolly aphid revealed that pulp yield decreased steadily with increased time after tree death and the paper made from pulp of one-, three-, and five-year dead trees suffered a tear strength reduction of 5%, 15%, and 25%, respectively. Sheridan (26) discovered that *Fomes pini* infection of Jack pine (*Pinus banksiana* L.) caused a similar decrease in pulp yield and paper strength, as well as an increase in chemical consumption.

No investigation has been found that determined the physical properties of pulp and paper manufactured by the kraft process from southern pine infested by bark beetles and then allowed to stand dead on the stump for extended periods (up to 36 months) before being harvested, chipped, and utilized.

OBJECTIVES

The objectives of this investigation were to determine the kraft pulping characteristics and paper properties of southern pine infested by bark beetles and to relate these properties to the length of time since foliage fade was initially detected (time since death).

MATERIALS AND METHODS

The material studied was loblolly (*Pinus taeda* L.) and shortleaf pine (*Pinus echinata* Mill.) pulpwood from the central Piedmont and Coastal regions of Virginia. Nine sample plots (seven in the Piedmont, two on the coast) were located with the assistance of foresters from federal and state agencies and from private industry. These plots were accurately dated by the foresters as soon as death was detected by either aerial survey or on-the-ground inspection. Death is generally first detected in beetle-infested stands by a foliage fade from green to yellow. The number of trees per sample plot averaged 25 trees with the highest number being 50 and the lowest 20.

The trees chosen for use in the pulp and paper study were representative of the dbh range for the plot, having a reasonably straight bole with the stem portion of the crown still intact. Those selected were felled at appropriate intervals throughout the first year of study to correspond to one of the six kill classes selected: green control, dead 0 to 6 months, dead 6 to 12 months, dead 12 to 18 months, dead 18 to 24 months, and dead 24 months or more. Three one-foot bolts were taken from the trees selected; bolt number one was taken four feet above the stump, bolt two at the midbole position, and bolt three just below the minimum merchantable height in the crown. These bolts were hand debarked and chipped at the Doyle Lumber Company in Martinsville, Virginia. The chips from all three bolts of one tree were mixed in the same bag.

A batch of chips from each tree was processed through the cooking procedure with the following factors held constant throughout. Each digester wood charge was composed of 750 grams of wood chips (oven-dry basis) packed into an autoclave. The kraft cooking liquor was composed of sodium hydroxide (127 g/l) and sodium sulphide (42 g/l), the solutions being prepared within 12 hours of each cook. The liquor to wood ratio was 5:1. Thc charged autoclave was rotated in an oil bath for 30 minutes until the temperature stabilized at 173 C., and then for an additional two hours at this temperature (total cooking time, 2.5 hours). The autoclave was under a constant pressure of approximately 100 psi during the entire cooking process. After being removed from the oil bath, the autoclave was cooled for one half hour in a water bath. The spent liquor was decanted. The pulped chips were disintegrated for five minutes in clean water in a British disintegrator (TAPPI standard 200) (28), washed in clean water until all color traces were removed from the water and set out to air-dry. After drying to approximately 6% M.C., the gross pulp yield was determined for each tree.

To begin the paper making process, the dried pulp was disintegrated again in water for five minutes and beaten according to TAPPI standard T200 (28) for beater times 5, 15, 25, 30, 40 and 50 minutes (50 minutes only used when 40 minutes did not produce C.S.F. values below 300 ml.). These times were selected to produce Canadian Standard Freeness (C.S.F.) values between 750 and 200 ml. (TAPPI standard T227) (28). Handsheets were then formed (TAPPI standard 205) (28) for each beater time and conditioned in the atmosphere for several weeks before testing. The best five of six handsheets for each beater time of each tree were then tested for tear strength (TAPPI standard T414) (28) and tensile strength (TAPPI standard T404) (28). The average moisture content was determined from test scraps of all the handsheets that were tested each day in order to determine the average handsheet moisture free basis weight. Kappa number tests were performed on well-beaten pulp (TAPPI standard T236) (28) from each tree in order to determine the percent of residual lignin.

EXPERIMENTAL DESIGN

Two stipulations were made in this investigation which should be noted when evaluating the results. First, species variation between shortleaf and loblolly pine was neglected since previous investigations determined that southern pines have nearly the same pulp and paper properties when compared at similar specific gravity values (5,9). In fact, greater differences have been found in the pulps of sections from the same tree than exist between different species and growth rates. Moreover, these two species have exhibited essentially equivalent sapwood decay resistance in a study by Toole (30). The second condition set was Coastal and Piedmont trees were not evaluated separately for papermaking properties. This was necessary because of the difficulty encountered in locating Coastal plots; subsequently, sample trees were not available for each kill class.

The pulp and paper properties of southern pine infested by bark beetles in relation to the time since death was determined as follows:

Relationship Between Pulp Yield and Time Since Death

T-tests were performed on the mean gross pulp yields to determine if any of the classes of trees left dead on the stump (kill classes) were statistically significant from the green control class (27).

Replication of Paper Strength Tests

The number of paper strength tests performed for tensile and tear strength are shown in Table 1. This table indicates the possible sources of variation that may influence the results of this investigation.

Table 1. Replication and sources of variation of the paper strength tests performed

Source of Variation	Tensile	Tear
1. Time Since Death*	6	6
2. Digestion Method	1	1
3. Beating Times	5	5
4. Replications		
a) Trees**	13	13
b) Handsheets	5	5
c) Test	2	1
Total No. of Tests	3900	1950

*Levels

GC	Green Control
A	Dead 0-6 months
B	Dead 6-12 months
C	Dead 12-18 months
D	Dead 18-24 months
E	Dead 24+ months

**Represents the average number of trees per level.

Pulp and Paper Quality Versus Time Since Death and Beating Time

The means of Canadian Standard Freeness (C.S.F.), breaking length, and tear factor (dependent variables) for beating times of 5 and 20 minutes were compared for each kill class using the Duncan's Multiple Range Test (2). This test utilizes the error degrees of freedom and error mean square generated by the test replicates of the dependent variables to determine if there is a statistically significant difference between the means.

Inter-relationships Between Pulp Characteristics, Paper Strength, and Time Since Death

Tensile and tear strength (dependent variables) were related to Canadian Standard Freeness (independent variable) for each kill class according to the regression equation $y = ab^{x} x^{c}$. The correlation coefficient (r) of each line was tested to determine if the correlation between the variables concerned was significantly different from zero (27).

RESULTS AND DISCUSSION

The southern section of the United States is today the kraft pulping center of the world. The kraft mills of the South produce approximately 25% of the total pulps and 45% of the kraft pulps required in the world. The reasons for the emergence of kraft pulping in the South over the last 35 years are the vast renewable supply of southern pine trees and an abundance of fresh water. Of the ten southern pines, loblolly ranks first in kraft production, followed by shortleaf (which has the widest range of the southern pines and is found extensively in Piedmont and Coastal Virginia), longleaf, and slash pines (15).

Characteristics of Sample Trees

Age, diameter at breast height, and total height of each tree utilized in this pulp and paper study were recorded in the forest. The averages for each kill class are compiled in Table 2. The trees utilized were approximately 27 years of age, 8 inches dbh, and 54 feet in average total height. These statistics are representative for pulpwood in Virginia.

Relationship of Pulp Yield to Time Since Death

There are several variables influencing pulp yield in the kraft process. These include Kappa number (indication of residual lignin content of the pulp), effective alkali, sulfidity, and wood quality. Fungal degradation has been found to have a major effect on wood quality and subsequently, pulp yield.

For this study, gross pulp yield and Kappa number were determined according to the procedures outlined. The percentage of residual lignin remaining in the pulp after digestion was determined as follows:

Table 2. Growth variables of the sample trees

Kill Class	Symbol	No. of Trees	Age (yrs.)	St. Err. of Mean	DBH (in.)	St. Err. of Mean	Height (ft.)	St. Err. of Mean
Green Control	GC	15	29	2.7	8.3	0.3	55	2.4
Dead 0-6 mos.	A	4	27	5.3	7.9	0.1	59	2.9
Dead 6-12 mos.	B	21	30	2.0	7.8	0.3	56	2.1
Dead 12-18 mos.	C	15	30	2.4	7.7	0.3	52	1.3
Dead 18-24 mos.	D	15	26	2.3	9.0	0.3	59	2.0
Dead 24 mos. +	E	5	22	1.0	7.0	0.1	45	1.0
Average		13	27		8.0		54	

$$\text{Residual Lignin (\%)} = 0.15 \times \text{Kappa Number (15,29)} \qquad [1]$$

The net pulp yield was computed by the following equation:

$$\text{Net Pulp Yield (\%)} = \text{Gross Pulp Yield}\left(1 - \frac{\text{Residual Lignin}}{100}\right) \qquad [2]$$

Net pulp yield represents the percentage of fiber that remains from the original 750 grams (oven-dry weight) of wood that was introduced into the digester. The percentage of pulp fibers produced is of extreme importance to the commercial papermill since the yield of pulp per ton of wood is generally the major economic factor in the kraft process.

Evaluation of Table 3 leads to the conclusion that there is no statistically significant decrease of gross pulp yield with an increase in time since death up to 36 months. Net pulp yield also changes very little as wood degradation increases. Therefore, southern pine in Virginia infested by bark beetles and left dead on the stump for two years or more may produce a ratio by weight of pulp to wood equal to digester charges composed of sound wood. This result is in direct opposition to the majority of studies on the kraft process which indicate that as decay advances, pulp yield decreases. The percentage of residual lignin in the pulp exhibited no consistent trend between kill classes (Table 3). Evidently, lignin is not altered significantly enough to interfere with its digestion and removal during pulping as decay increases.

An explanation of these findings may be as wood decay progresses, the fiber cell wall becomes more porous and the cooking liquor is better able to permeate wood. This promotes more complete delignification of the cell wall so that less cellulose material is lost in

Table 3. Relationship among Kappa number, gross pulp yield, residual lignin, net pulp yield, and time since death

Kill Class	Symbol	No. of Cooks	Kappa No.	St. Err. Mean of Kappa No.	Gross Yield %	St. Err. Mean of Gross Yield	Resid. Lignin %	Net Yield %
Green Control	GC	15	36.05	1.38	46.09*	0.56	5.41	43.60
Dead 0-6 mos.	A	4	40.76	2.19	48.04*	0.50	6.11	45.10
Dead 6-12 mos.	B	21	38.89	1.37	46.60*	0.39	5.83	43.88
Dead 12-18 mos.	C	15	42.75	1.98	47.23*	0.71	6.41	44.20
Dead 18-24 mos.	D	15	37.99	1.46	46.94*	0.50	5.70	44.26
Dead 24 mos. +	E	5	41.63	2.61	46.14*	0.35	6.24	43.26

*Means not significantly different at .01 level.

the cooking process. Therefore, despite the loss of cellulose to wood destroying brown rot, more may be freed from lignin, not lost with the black liquor, due to the increased effectiveness of the cooking process. Pulp yield may remain essentially the same until a significant amount of cellulose has been completely degraded by the fungi.

Influence of Time Since Death on Canadian Standard Freeness

The drainage rate of pulp, as measured by the Canadian Standard Freeness (C.S.F.) test, is related to the surface conditions and swelling of the fibers and is a useful index for the amount of beating action performed on the pulp. Refining or beating is probably the most fundamentally important process in paper making. The principal effects of beating are fracture and partial removal of the primary wall of the fiber, increase in the external surface of the fiber, increase in the fiber flexibility, decrease in fiber length (cutting), and the formation of fibrils (crushing or fibrillation) (18). Wood fibers in the presence of water exposed to this process (hydration) undergo all the physical changes which make the fibers more reluctant to allow the drainage of water through a slurry of pulp. That is, as beating time increases, C.S.F. decreases.

Table 4 lists the mean C.S.F. values for each kill class by beating time. The first result that should be noted is all pulps, independent of the origin of the wood they were made from, have a C.S.F. value of 750 milliliters after 5 minutes of beating. Further, it is shown that increasing beater time reduces C.S.F. These conclusions were expected

Table 4. Mean Canadian Standard Freeness values with corresponding beating times and kill classes

Kill Class	Symbol	No. of Tests Per Beater Time	Beating Times (Minutes)									
			5		15		25		30		40*	
			Mean (ml.)	St. Err. Mean	Mean (ml.)	St. Err. Mean	Mean (ml.)	St. Err. Mean	Mean (ml.)	St. Err. Mean	Mean (ml.)	St. Err. Mean
Green Control	GC	30	756	2.9	690	5.1	545	9.9	435	12.1	219	11.6
Dead 0-6 mos.	A	8	757	2.1	693	6.1	544	21.6	456	26.0	236	30.0
Dead 6-12 mos.	B	42	757	2.1	701	3.9	580	10.5	481	15.5	270	14.2
Dead 12-18 mos.	C	30	764	1.5	705	3.7	569	12.9	464	16.3	240	14.6
Dead 18-24 mos.	D	30	769	1.8	719	4.0	601	9.7	503	13.2	278	14.4
Dead 24 mos. +	E	10	749	3.4	685	4.5	534	22.6	431	27.1	215	23.0

*In cases when 40-minute beating did not produce C.S.F. values less than 300 milliliters, beating time was extended to 50 minutes.

from the knowledge of the behavior of kraft pulps in refining (18). However, the increase in the standard error of the mean with increasing beating time, which is even more striking when expressed as a fraction or percentage of the mean, needs explanation. Ifju, et al. (14) in a study of loblolly pine growth increments, concluded that latewood pulps require appreciably less energy of refining to attain a particular freeness level than earlywood pulps. Applied to this study, an unequal earlywood-latewood ratio that most likely occurred between trees from different plots and regions, would appreciably increase the variability in C.S.F. between pulps as refining increased.

For the purpose of further evaluation, C.S.F. was analyzed at 5 and 30 minutes beating to discern why wood decay has an effect on the fiber refining. Figure 1 (beating time = 5 minutes) illustrates the trend that as the level of decay in wood increases up to 24 months since death, the fibers showed an increase in drainage time. After 24 months the C.S.F. values fall again. None of the means are statistically different at this beating level, so this trend can only be suspected at this point.

In Figure 2, the same general trend is noted again. After 30 minutes beating time, C.S.F. exhibits a statistically significant increase as decay increases past 18 months since death. Kill Class E (after 24 months) once again returns a lower mean C.S.F. following the gradual increase in freeness values at the earlier stages of wood deterioration.

The trend detected in Figures 1 and 2 may be due to an interaction between fiber beating characteristics and the effect of decay on wood.

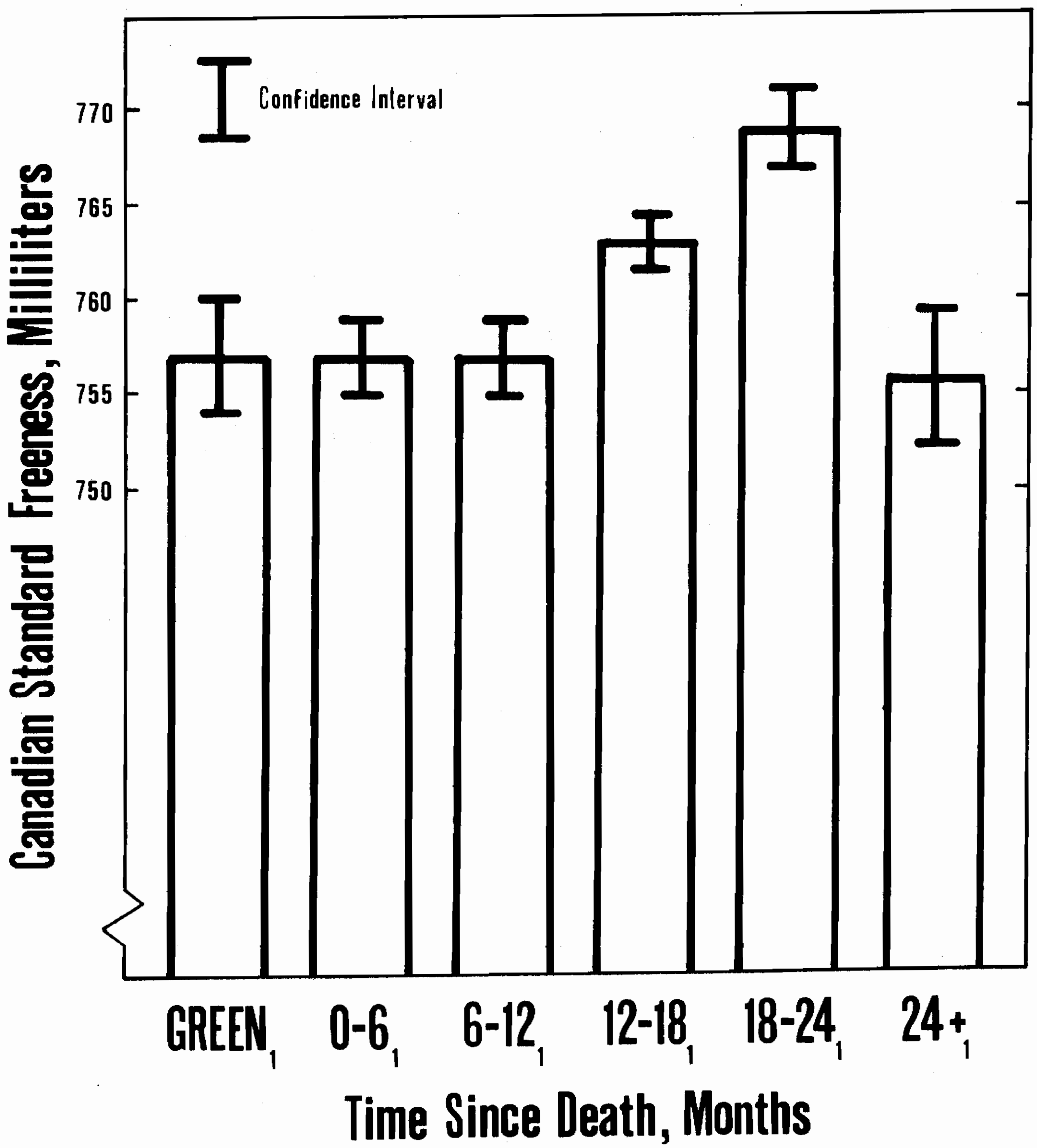
As previously described, beating produces a change in the physical characteristics of pulp fibers, most notably fiber shortening (cutting) and fiber fibrillation, which have major effects on the drainage rate of pulp. When wood degradation increases, fibers become brasher and more easily cut then crushed; therefore, fiber fibrillation decreases and fiber cutting increases. The increase in the number of fiber segments as decay increases allows the pulp to drain faster due to less contact between the segments than if fibrillation were the primary mode of refining as with fibers from sound wood. Once the fibers have reached the severely advanced stage of decay (Kill Class E), the fibers have become so weak and brittle that as beating takes place the individual fibers are shattered into short microfibrillar bundles which may effectively clog up the apparatus screen, causing a sharp decline in C.S.F.

Influence of Time Since Death on the Tensile Strength of Paper

The amount and quality of fiber bonding is the most important factor affecting tensile strength in paper. Tensile strength is traditionally measured as breaking length, which is the length of paper in meters that would represent a weight sufficient to cause failure. During the tensile test mostly fiber-to-fiber bonds are ruptured, so the more bonds the paper has per unit area the higher the tensile strength will be.

In this investigation two distinct factors would have an affect on fiber bonding: beating time (inversely related to C.S.F.) and wood degradation. Beating time was found to be directly related to tensile strength (illustrated in Table 5). The beating process causes physical changes in the character of wood fibers that lead to an increase in

FIGURE 1: Relationship between mean Canadian Standard Freeness and time since death after 5 minutes beating



Classes With Same Subscript Are Not Significantly Different At The .05 Level (Duncan's Test)

FIGURE 2: Relationship between mean Canadian Standard Freeness and time since death after 30 minutes of beating

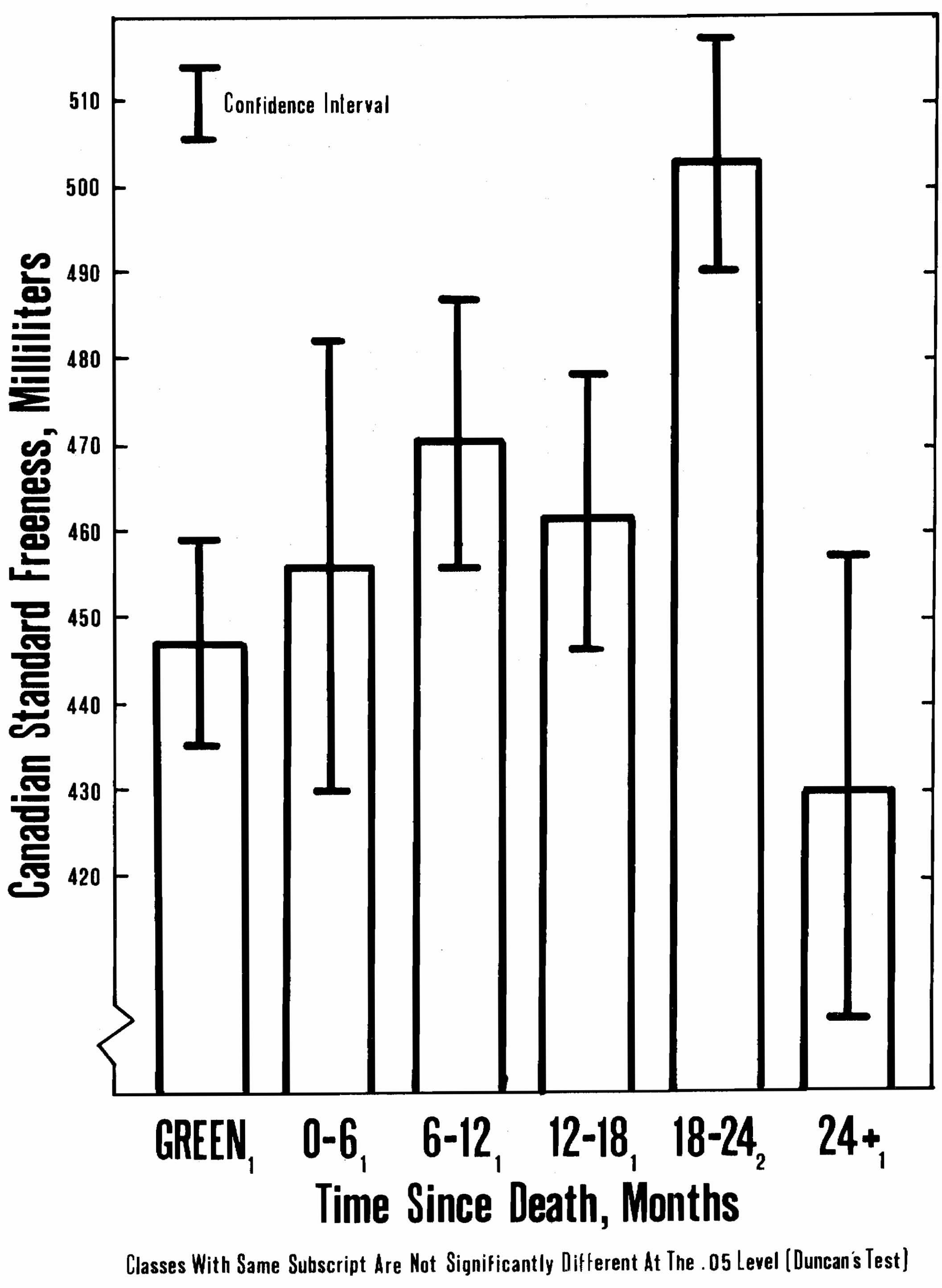

Confidence Interval
510
500
490
480
470
460
450
440
430
420
Canadian Standard Freeness, Milliliters
GREEN1
0-6 1
6-12 1
12-18 1
18-24 2
24+ 1
Time Since Death, Months
Classes With Same Subscript Are Not Significantly Different At The .05 Level (Duncan's Test)

Table 5. Mean breaking length values with corresponding beating times and kill classes

Kill Class	Symbol	No. of Tests Per Beating Time	5 Mean (meters)	5 St. Err. Mean	15 Mean (meters)	15 St. Err. Mean	25 Mean (meters)	25 St. Err. Mean	30 Mean (meters)	30 St. Err. Mean	40* Mean (meters)	40* St. Err. Mean
Green Control	GC	150	5186	53.9	6979	63.2	8031	78.5	8252	74.0	8416	64.5
Dead 0-6 mos.	A	40	5424	103.9	7541	103.4	8366	119.0	8469	120.4	8575	121.8
Dead 6-12 mos.	B	210	5249	50.1	7075	66.4	8055	60.9	8184	57.2	8419	55.0
Dead 12-18 mos.	C	150	5050	54.7	7111	65.2	7870	74.2	8288	67.3	8331	65.1
Dead 18-24 mos.	D	150	4648	67.1	6699	72.6	7604	65.8	7860	62.0	8147	62.3
Dead 24 mos. +	E	50	5345	82.7	6947	95.4	7668	114.9	7922	106.4	8406	83.9

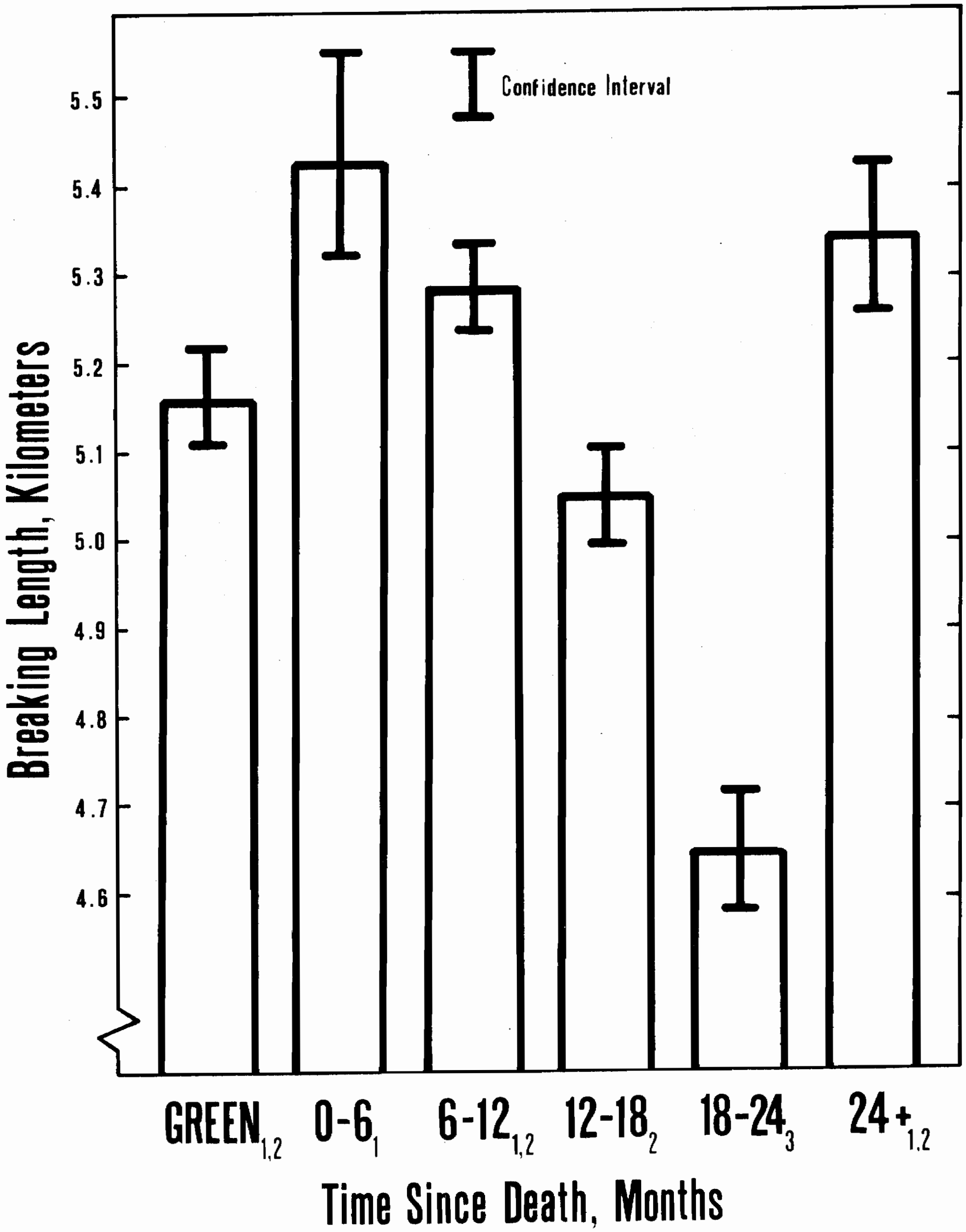
(Beating Time (Minutes): 5, 15, 25, 30, 40*)

*In cases when 40-minute beating did not produce C.S.F. values less than 300 milliliters, beating time was extended to 50 minutes.

fiber bonding, thereby tensile strength. The high breaking length values of trees dead for a short period, 0 to 6 months, illustrate that initial forms of wood decay, such as white rot, may increase fiber bonding through the progressive thinning of the wood cell wall. The large standard error of the mean for Kill Class A may indicate that the extent of white rot degradation varies significantly from tree to tree. The smaller number of tests per beater time could also explain this trend since trees dead more than 24 months also have a large standard error and fewer than average tests. Table 5 also shows that as more severe forms of decay, such as brown rot, decimate the structure of the cell wall the tensile strength begins to decrease after 12 months since death.

In order to more completely analyze the effect of successive stages of wood decay on tensile strength in paper, the beating times of 5 and 30 minutes were thoroughly examined. After 5 minutes the effect of wood decay on mean breaking length was already apparent (Figure 3). Referring to Figure 1, a comparison of the mean C.S.F. for each kill class found them to be not significantly different. C.S.F. is generally considered to be a good indicator for fiber flexibility and the ability of the fibers to bond together. But in Figure 3, the paper made from green trees and trees dead up to 18 months have a significantly higher mean breaking length value than paper made from trees dead 18 to 24 months. Therefore, even though the fibers have the same ability to bond together in the pulp form; apparently, a point comes when the individual fiber strength in the handsheet deteriorates so much that it

FIGURE 3: Relationship between mean breaking length and time since death after 5 minutes beating



Classes With Same Subscript Are Not Significantly Different At The .05 Level (Duncan's Test)

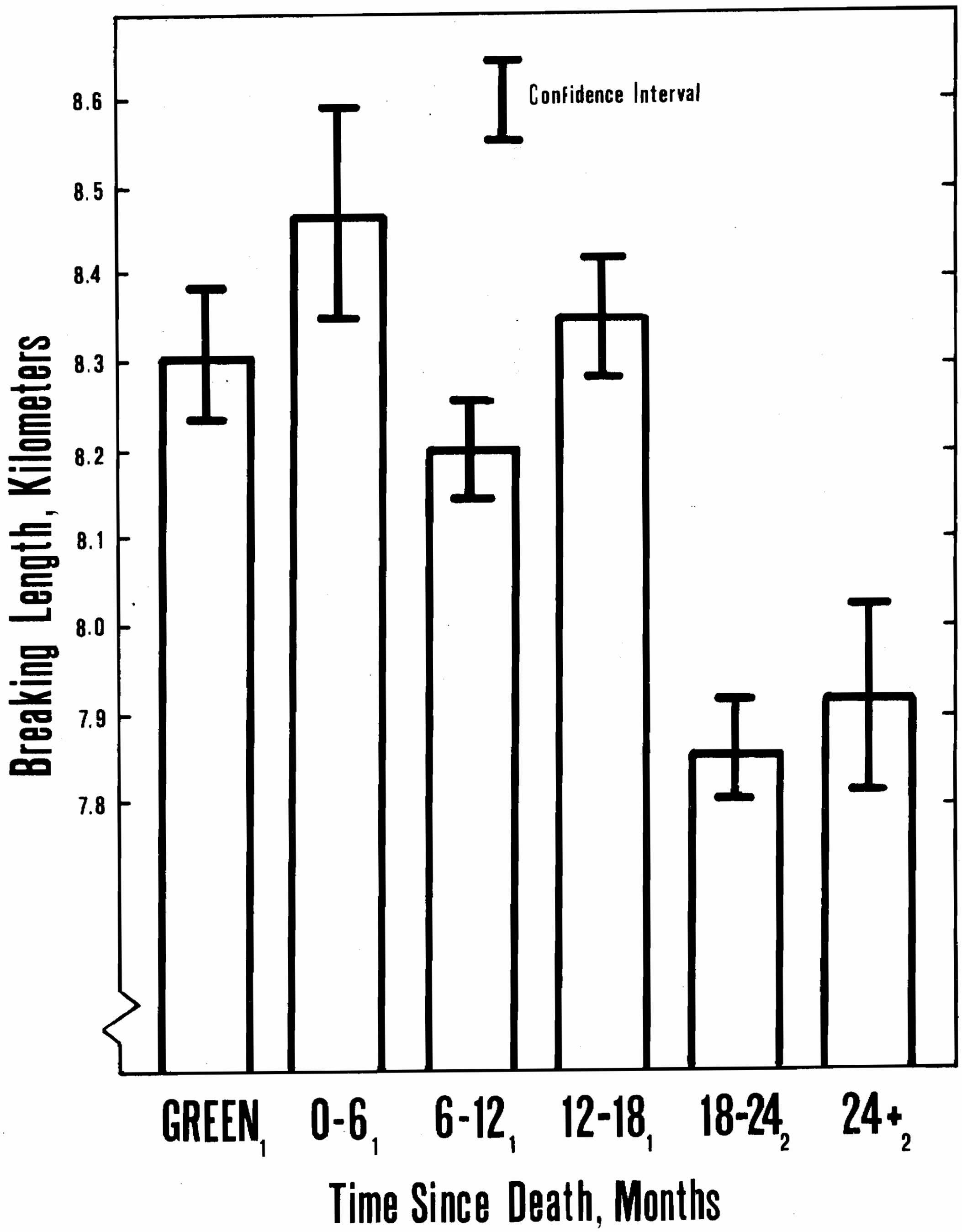
becomes the determining factor in tensile strength instead of bonding. The case of trees dead for over 24 months is more difficult to resolve. Perhaps the existence of individual fibers, even after a small amount of refining, is greatly reduced. The separate microfibrillar bundles (fines) that once made up a fiber may possess sufficient individual strength and bonding capabilities to resist tensile stresses (fiber strength no longer restrictive) after a brief beating period.

Figure 4 clearly indicates the response of the paper after 30 minutes of beating the pulp. Green trees and those dead up to 18 months exhibit an ability to maintain the integrity of their fiber bonds which results in good tensile strength. The low mean breaking length for trees dead 18 to 24 months may be explained by a loss in individual fiber strength or by the significantly large C.S.F. values encountered at this level of beating (Figure 2). However, the trees dead over two years, which exhibited no difference from trees dead up to 18 months in freeness, now yield significantly lower tensile strength results. Evidently, as beating progresses, the fines generated from the fibers of these trees are able to clog the screen mechanism of the freeness tester but are unable to resist rupture and bond failure.

Influence of Time Since Death on the Tear Strength of Paper

Tearing resistance in paper is dependent on four properties: total number of fibers participating in sheet rupture, fiber length, fiber coarseness, and number and strength of fiber-to-fiber bonds. The energy consumed in tearing a sheet of paper consists of two components, work involved in pulling fibers out of the paper and work involved in rupturing the fibers.

FIGURE 4: Relationship between mean breaking length and time since detected death after 30 minutes of beating



Classes With Same Subscript Are Not Significantly Different At The .05 Level (Duncan's Test)

The tearing resistance of paper made from unbeaten pulp is very low since the only work involved is overcoming the frictional resistance of fibers being pulled from the paper. At this stage, the total area of fiber contact is small, so the tear resistance is small. After a slight amount of beating, interfiber bonding is increased and the tearing resistance is greater because of the increased frictional resistance in pulling fibers out of the sheet. As beating continues to increase, the fibers no longer slip past one another readily and, therefore, there is an increase in the number of fibers that rupture in tension. This mechanism is more nearly a shearing action than a pulling action. Since the work involved in rupturing a fiber is much less than the energy involved in pulling a fiber out of the sheet, the energy required to tear the sheet decreases with increased beating time.

Table 6 illustrates the relationship between the mean tearing resistance of each kill class and beating time. Beating time exhibits an inverse relationship to tear; therefore, C.S.F. has a direct relation to tear strength (as C.S.F. decreases so does tear strength). It should also be noted that the handsheets were quite different in tear resistance after 5 minutes of beating; that is, healthy fibers exhibited much greater strength. However, as beating increased the papers became more homogeneous in strength. The exception to this trend is found in trees dead more than 24 months which remained consistently lower in tear strength, relative to healthy trees, at all beating times.

Table 6. Mean tear values with corresponding beating times and kill classes

			Beating Time (Minutes)									
			5		15		25		30		40*	
Kill Class	Symbol	No. of Tests Per Beater Time	Mean (dm^2)	St. Err. Mean	Mean (dm^2)	St. Err. Mean	Mean (dm^2)	St. Err. Mean	Mean (dm^2)	St. Err. Mean	Mean (dm^2)	St. Err. Mean
Green Control	GC	60	209	6.2	155	3.9	124	2.9	115	2.9	96	3.0
Dead 0-6 mos.	A	16	160	5.9	132	4.0	107	3.7	95	3.3	82	2.9
Dead 6-12 mos.	B	84	160	2.5	132	2.1	109	1.7	103	1.6	85	1.7
Dead 12-18 mos.	C	60	175	3.9	136	2.7	111	2.4	102	2.6	86	2.2
Dead 18-24 mos.	D	60	168	2.7	136	2.2	115	1.8	106	1.9	90	1.9
Dead 24 mos. +	E	20	137	2.4	112	3.4	90	2.5	83	2.7	70	3.0

*In cases when 40-minutes beating did not produce C.S.F. values less than 300 milliliters, beating time was extended to 50 minutes.

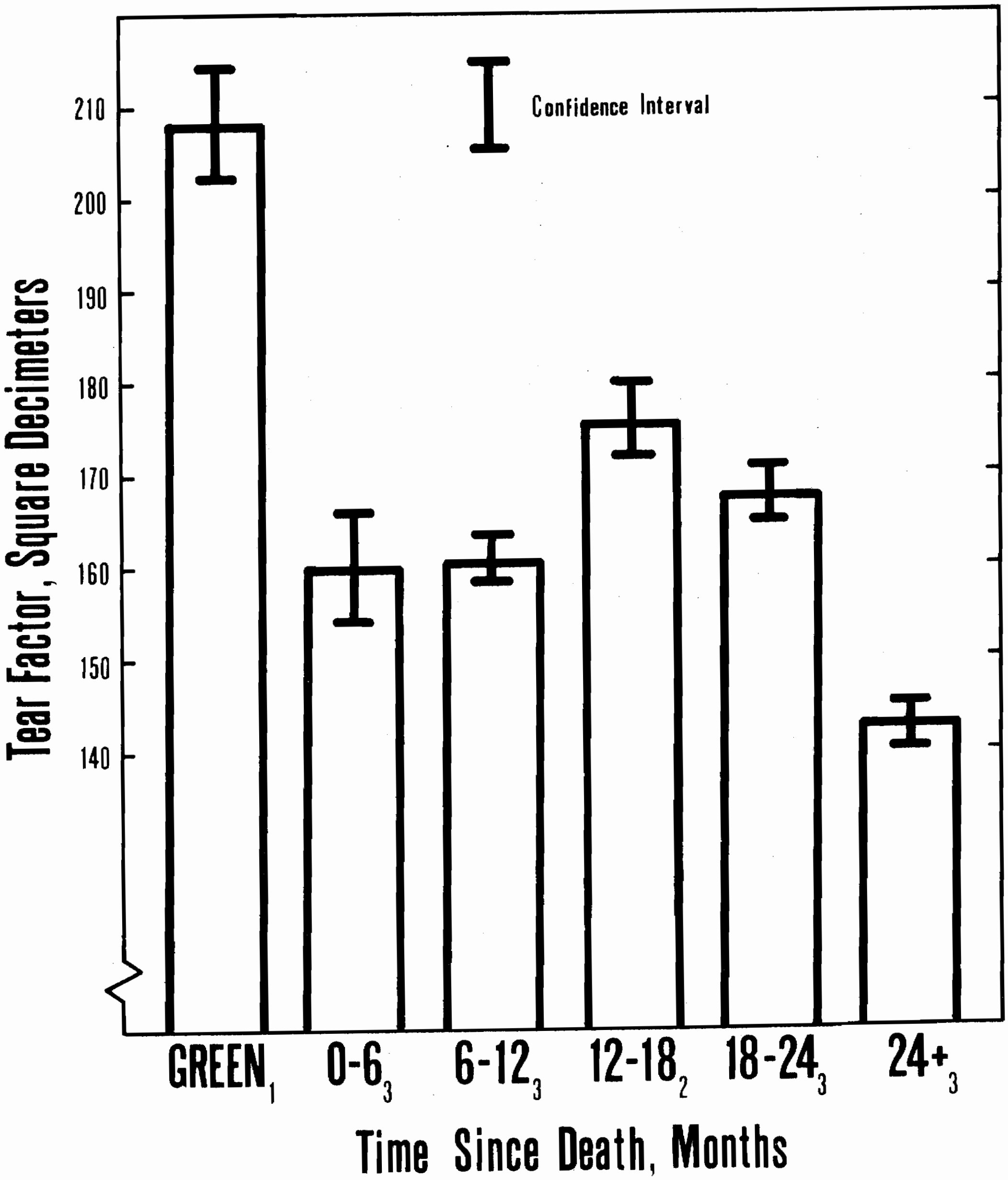
For the purpose of thorough evaluation of the effect of wood degradation on tear strength, tear values at beating times of 5 and 30 minutes were analyzed. Beating the pulp for 5 minutes was enough to show that even slightly decayed fibers offer less tear resistance than fibers from healthy trees (Figure 5). Apparently, cutting and breaking of fibers occurs so rapidly when decayed fibers are refined that the shortened fibers offer less frictional resistance when they are pulled from the handsheet due to their reduced length. As was the case with tensile strength, the nonsignificance between the mean C.S.F. values in Figure 1 can be misleading in the evaluation of tear strength.

As beating increased to 30 minutes, the fibers no longer slipped past each other, the rupture of individual fibers became the dominant mode of failure and tear resistance decreased. The healthy fibers still exhibited statistically significant superiority in tear strength (although less than after 5 minutes of beating), probably because the individual fibers are stronger and more able to resist rupture in tension than the fibers from decayed wood (Figure 6).

Inter-relationship Among Paper Strength Properties, Canadian Standard Freeness (C.S.F.), and Wood Degradation

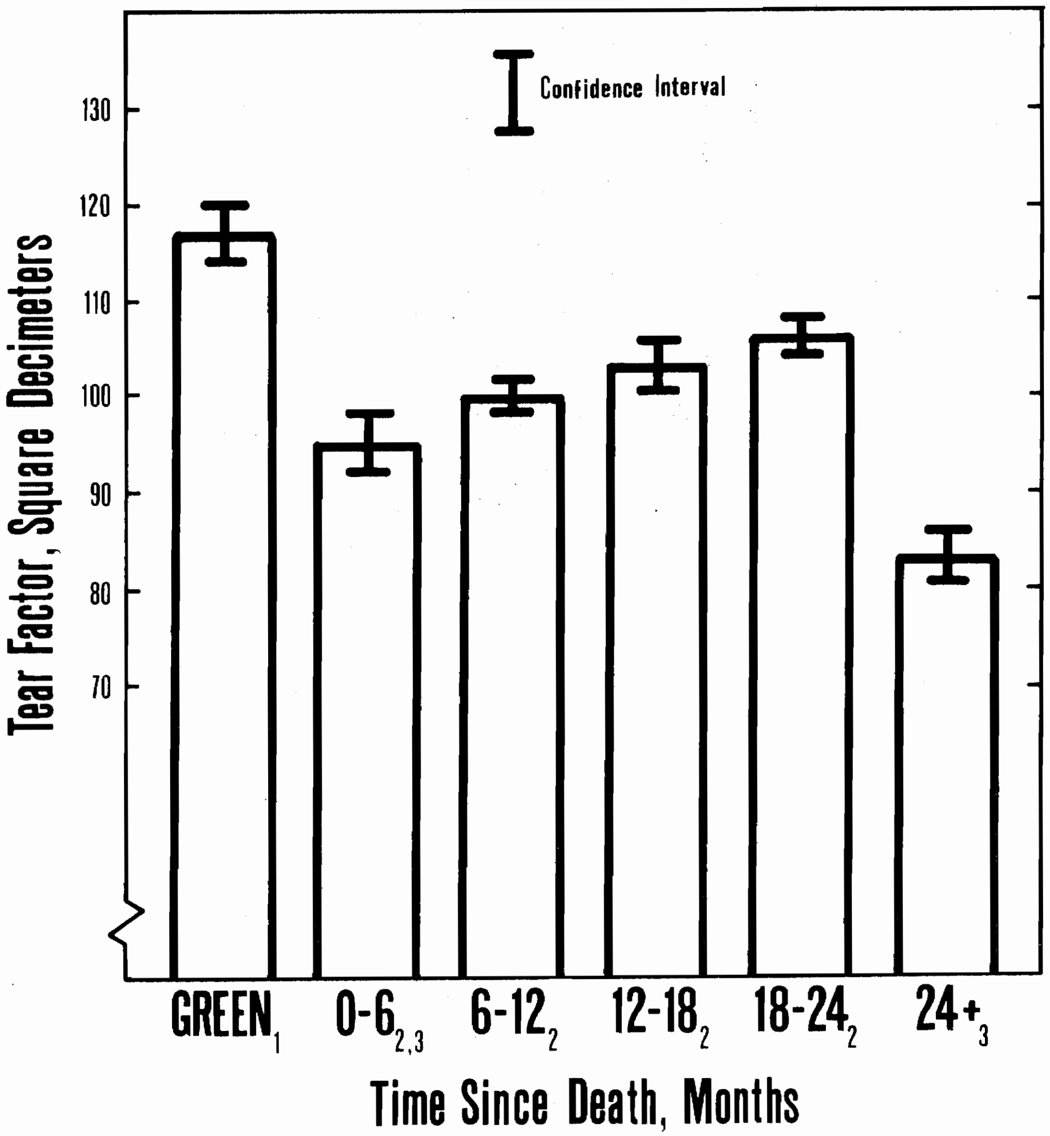
The correlation between paper tensile and tear strength and C.S.F. of pulp sheets is very important to paper makers. They rely on the fact that tensile strength increases with decreasing C.S.F., and conversely tear resistance decreases with the decrease of C.S.F. Therefore, the experienced paper maker who knows the freeness of a particular batch of pulp can predict the relative strength of the paper that will be produced. As noted previously in the evaluation of the

FIGURE 5: Relationship between mean tear factor and time since death after 5 minutes of beating



Classes With Same Subscript Are Not Significantly Different At The .05 Level [Duncan's Test]

FIGURE 6: Relationship between mean tear factor and time since death after 30 minutes beating



Classes With Same Subscript Are Not Significantly Different At The .05 Level [Duncan's Test] experimental results, wood degradation may have a misleading effect on the prediction of physical properties of paper on the basis of C.S.F. Evidently this is the result of the varied reaction of wood fibers to beating when they have been previously subjected to progressive stages of decay in the solid wood form.

Examination of the patterns of the data for tensile (breaking length) and tear (tear factor) strengths versus C.S.F. led to the conclusion that the following regression equation would best transform the data to a curvi-linear form:

$$y = ab^{x}x^{c}$$

$$\text{or:} \quad \log y = \log a + x \log b + c \log x \qquad [4]$$

$$= b_o + b_1 + b_2 \log x \qquad [5]$$

where: y = breaking length or tear factor

x = Canadian Standard Freeness

$\log a = b_o,\ a = 10^{b_o}$

$\log b = b_1,\ b = 10^{b_1}$

$c = b_2$

Utilizing the SAS 76 statistical computer package (2), values for the coefficients a, b, and c were determined for each kill class (Tables 7, 8) and regression lines were then plotted for breaking length versus C.S.F. (Figure 7) and tear factor versus C.S.F. (Figure 8). Tables 7 and 8 also contain the correlation coefficient (r) between the dependent paper strength properties and the independent C.S.F. variable. The correlation between both tear and tensile strength and

FIGURE 7: Relationship between breaking length and Canadian Standard Freeness by time since death

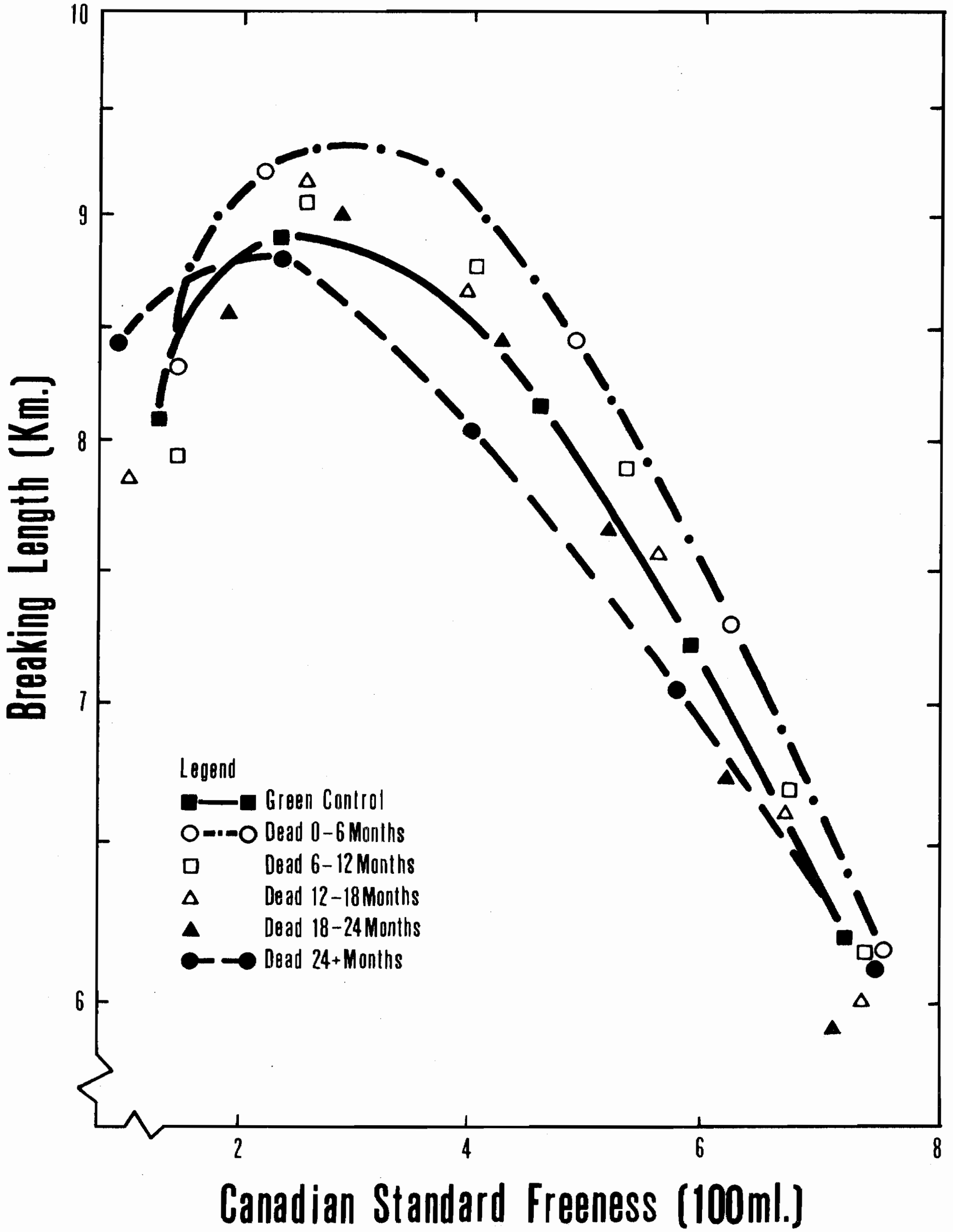
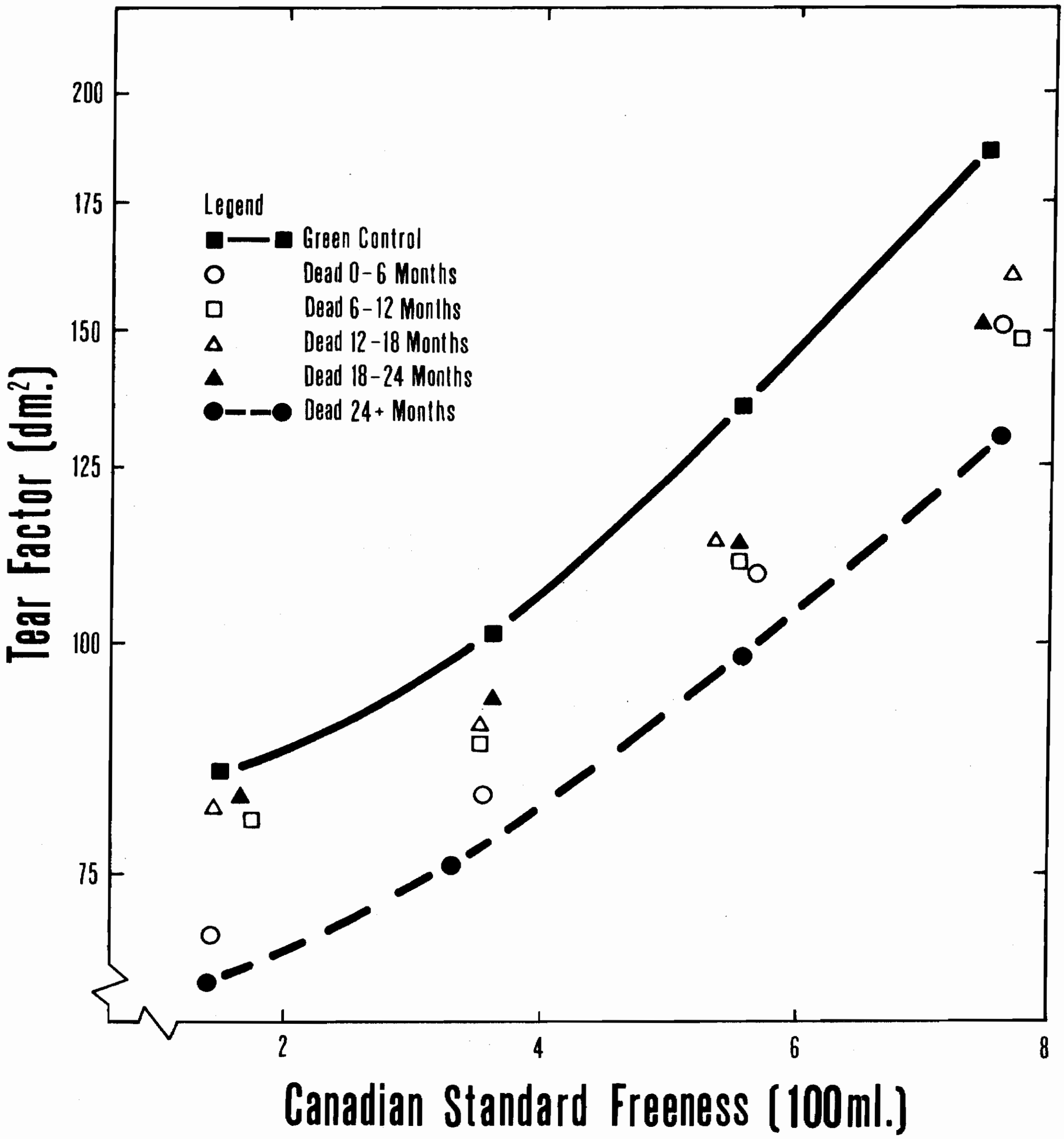

Breaking Length (Km.)
10
9
8
7
6
Legend
Green Control
Dead 0-6 Months
Dead 6-12 Months
Dead 12-18 Months
Dead 18-24 Months
Dead 24+ Months
2
4
6
8
Canadian Standard Freeness (100ml.)

FIGURE 8: Relationship between tear factor and Canadian Standard Freeness by time since death


Legend
Green Control
Dead 0-6 Months
Dead 6-12 Months
Dead 12-18 Months
Dead 18-24 Months
Dead 24+ Months
Tear Factor (dm²)
200
175
150
125
100
75
2
4
6
8
Canadian Standard Freeness (100ml.)

C.S.F. for all kill classes was statistically significant at the .01% level. Examples of the data scatter about the predicted regression line for breaking length versus C.S.F. and tear factor versus C.S.F. are shown in Figures 9 and 10, respectively.

Figure 7 illustrates the inverse relationship that as C.S.F. decreases tensile strength (expressed as breaking length) increases. The reason is that as beating time increases the ability of the fibers to bond together increases, and a greater stress is required to separate the fibers in tension. Tensile strength exhibits a slight decline for all six kill classes when the pulp is excessively beaten (approximately 300 milliliters C.S.F.) due to the destruction of fiber structure. This result causes an increase in the proportion of individual fiber failures to fiber-to-fiber bond ruptures.

Analysis of the kill class regression lines over the full range of freeness yields some interesting conclusions. At the initially high freeness level, the effect of wood decay on tensile strength appears to be negligible. As C.S.F. decreases, it becomes apparent that fibers subjected to limited fungal degradation (trees dead up to 24 months) may indeed be stronger (6% higher tensile strength for trees dead up to 6 months) or equivalent in tensile strength to healthy fibers. However, thinner, weaker fibers and fines from trees attacked by decay organisms eventually lose their toughness and strength (trees dead over two years) and begin to display a decrease in breaking length (approximately 5%).

The direct relationship that exists between paper tear strength, measured as tear factor, and C.S.F. is shown in Figure 8. A small amount of beating (5 minutes) is sufficient to produce maximum tear strength at the high levels of freeness. Fiber-to-fiber bonding is increased significantly after slight refining although fibers exposed to even limited fungal degradation exhibit an inability to resist fiber cutting. The increase in cut fibers significantly lowers the tear resistance relative to unaffected normal fibers. Trees dead on the stump up to 24 months suffer a tear strength loss of approximately 20%, and trees deteriorating for over two years, a 30% loss. This trend of decreasing tear resistance of paper with increasing decay of southern pine continues over the full range of freeness values although some of the kill classes begin to approach the strength of paper from healthy fibers at the lower freeness levels.

FIGURE 9: Scatter of breaking length data versus Canadian Standard Freeness around the computed regression curve (data from Kill Class C)

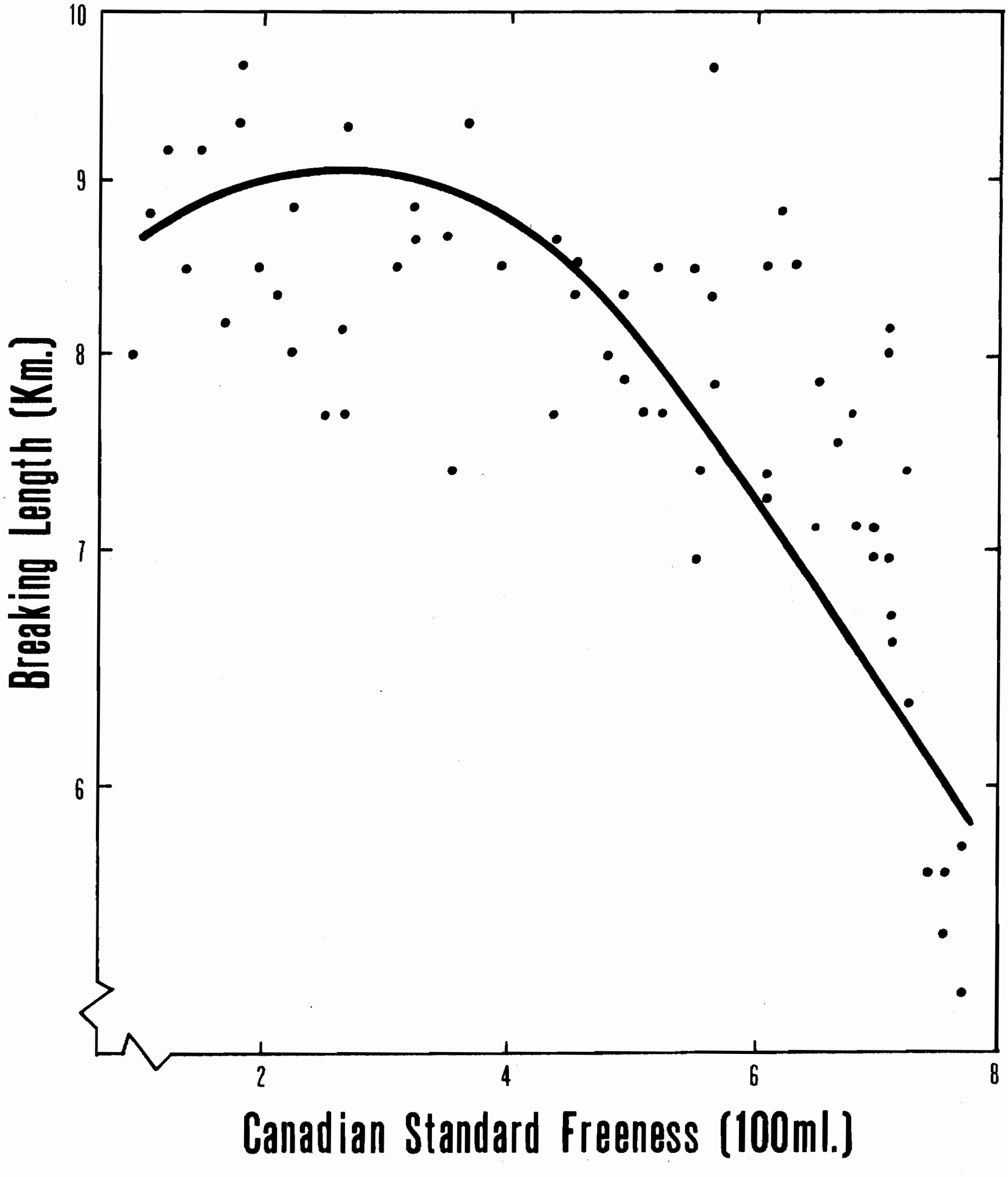

10
9
8
7
6
Breaking Length (Km.)
2
4
6
8
Canadian Standard Freeness (100ml.)

FIGURE 10: Scatter of tear factor data versus Canadian Standard Freeness around the computed regression curve (data from Kill Class D)

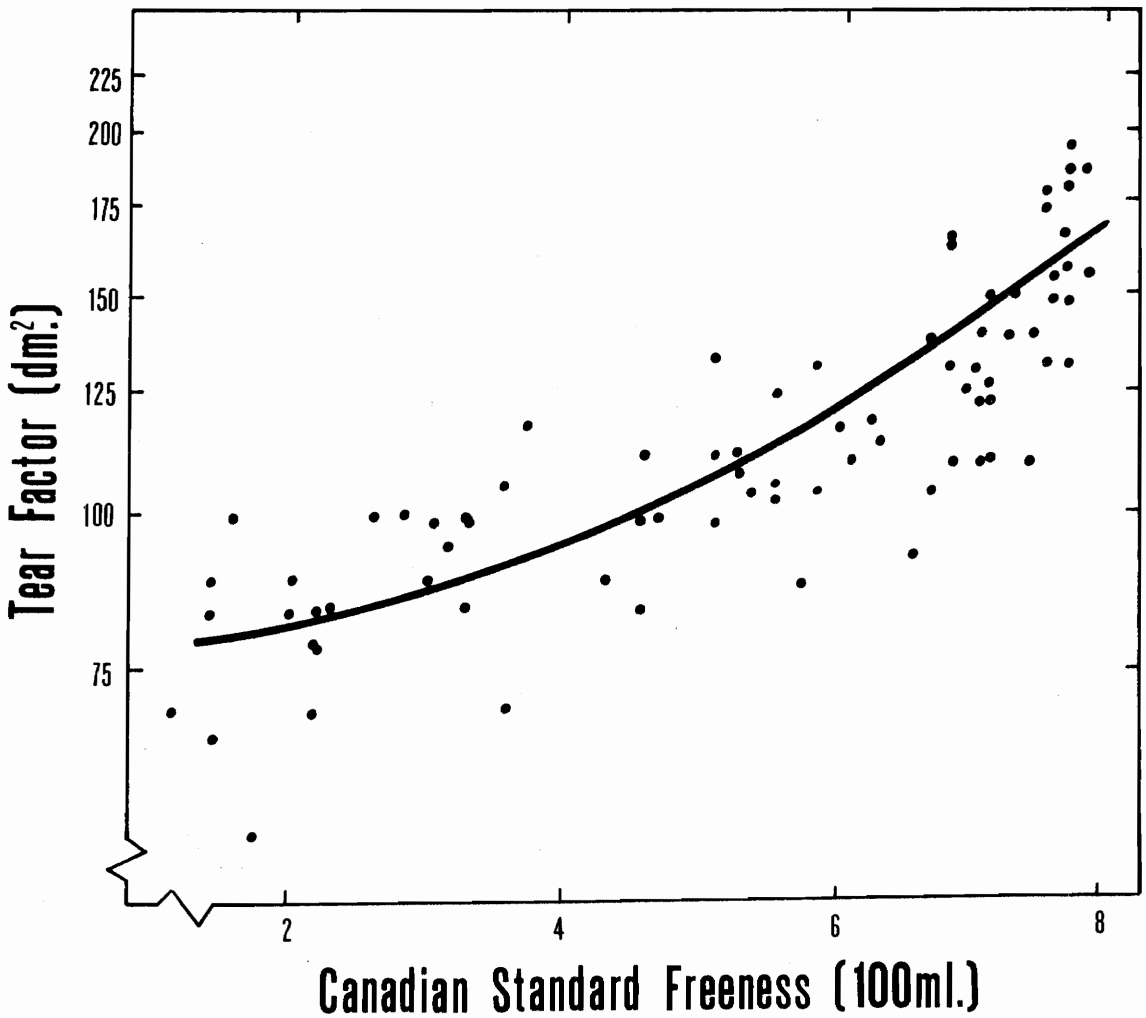

225
200
175
150
125
100
75
Tear Factor (dm²)
2
4
6
8
Canadian Standard Freeness (100ml.)

Table 7. Regression and correlation coefficients for breaking length versus Canadian Standard Freeness by time since death

Kill Class	Symbol	r	a	b	c
Green Control	GC	0.78*	696.63	1.00	0.55
Dead 0-6 mos.	A	0.81*	283.79	1.00	0.74
Dead 6-12 mos.	B	0.79*	266.93	1.00	0.75
Dead 12-18 mos.	C	0.79*	594.98	1.00	0.59
Dead 18-24 mos.	D	0.79*	260.68	1.00	0.76
Dead 24 mos. +	E	0.81*	2698.98	1.00	0.27

*Correlation significant at .01 level

Table 8. Regression and correlation coefficients for tear factor versus Canadian Standard Freeness by time since death

Kill Class	Symbol	r	a	b	c
Green Control	GC	0.82*	249.57	1.00	-0.28
Dead 0-6 mos.	A	0.94*	1818.86	1.00	-0.70
Dead 6-12 mos.	B	0.85*	493.97	1.00	-0.43
Dead 12-18 mos.	C	0.84*	262.48	1.00	-0.30
Dead 18-24 mos.	D	0.86*	316.52	1.00	-0.33
Dead 24 mos. +	E	0.94*	135.43	1.00	-0.20

*Correlation significant at .01 level

CONCLUSIONS

From the results of this study, the following conclusions may be drawn:

(1) Pulp yield is not affected significantly by allowing the dead trees to remain on the stump for extended periods of time (three years).

(2) Canadian Standard Freeness increases significantly at high beating times as wood deteriorates (up to 24 months) until a large amount of fines exist in the pulp because of the refining of extremely decayed fibers (after 24 months). These fines effectively reduce the freeness of the pulp by clogging the apparatus screen.

(3) Tensile strength of paper is reduced significantly (after an initial increase) as the wood deteriorates on the stump beyond 24 months.

(4) Tear strength of paper is reduced significantly after the initial attack of wood destroying fungi which follows closely the death and drying out of the tree.

(5) A thorough summary relating the gross external characteristics of southern pines infested by bark beetles to various periods of time since death would be a valuable supplement to this investigation for the practicing forester.

(6) Whenever the tear resistance of paper made from the kraft process is a critical determinate for the utility of that paper, the usefulness of deteriorated southern pine should be carefully evaluated by the pulpmill operator.

RECOMMENDATIONS

(1) Analysis of chip size distribution may prove valuable since it appeared that a high percentage of fines and dust were produced when severely decayed wood was chipped.

(2) Modification of the fibers by refining decayed material was probably different from that of fibers found in sound wood. Thus, a microscopic examination of the fibers after various beating periods is needed to shed light on the apparent anomalies in the strength--C.S.F. relationships.

(3) Decay, especially by brown-rot fungi, results in partial depolymerization of cellulose which, in turn, influences paper properties related to fiber strength. Evaluation of cellulose degree of polymerization would be essential to find the basic reasons for changes in refining and strength characteristics of the pulp and paper produced from them.

(4) Identification of the specific micro-organisms degrading the wood in the dead trees would result in a better understanding of the changes occurring due to decay.

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Paul C. Ferguson

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UTILIZATION POTENTIAL FOR PULP AND PAPER
OF SOUTHERN PINE HARVESTED FROM BEETLE-INFESTED FORESTS

by

Paul Charles Ferguson

(ABSTRACT)

Southern pine trees left dead on the stump for up to three years following southern pine bark beetle infestations in the Virginia Piedmont and Coastal regions were felled, chipped and pulped in an experimental Kraft digester. The 75 trees included in the study were stratified according to the length of time they had been standing dead after the infestation. The following six "kill classes" were studied: Green control (15 trees), dead 0-6 months (4 trees), dead for 6-12 months (21 trees), dead for 12-18 months (15 trees), dead for 18-24 months (15 trees) and dead for longer than 24 months (5 trees). A small batch of chips from each tree was individually cooked, the yield was determined, and handsheets were prepared and tested for tear and breaking length after five different beating periods.

It was observed that deterioration of the wood in the standing dead trees occurred due to decay. The extent of the decay was not evaluated but was observed to increase with increasing time after the death of the trees. In spite of the apparent decay, especially of wood in the trees left dead on the stump for over two years, no drop in kraft pulp yield was found compared with the green control material.

However, tearing resistance of the handsheets decreased after as soon as 0-6 months (20% for 6 months, and 30% for more than two years) following the beetle attack. Paper tensile strength increased slightly (approximately 6%) after six months following foliage fade and then began to decrease gradually until it reached a small loss (approximately 5%) after 24 months on the stump.