United States
Department of
Agriculture

Forest
Service

North Central
Forest Experiment
Station

Research
Paper NC-296

Reducing Particle Dimensions of Chunkwood

Robert C. Radcliffe

Radcliffe, Robert C.
1990. **Reducing particle dimensions of chunkwood.** Res. Pap. NC-296. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 17 p.

Presents and compares the chunkwood sizes obtainable with the USDA Forest Service prototype wood chunker using four different blade configurations, and the results of further chunkwood reduction with three methods totally separate from the chunking process.

KEY WORDS: Flakeboard, chunkwood particle size, size reduction, comminution, fingerlings.

North Central Forest Experiment Station
Forest Service—U.S. Department of Agriculture
1992 Folwell Avenue
St. Paul, Minnesota 55108
Manuscript approved for publication November 7, 1990
1990

Reducing Particle Dimensions of Chunkwood

Robert C. Radcliffe

BACKGROUND

In 1972 the USDA Forest Service began a 5-year effort to reduce residues on Forest Service lands. Under the umbrella of the Close Timber Utilization Project, researchers sought ways to utilize logging residues and small, low-quality trees recovered from thinnings. A potential target for the resulting fiber was the composite wood products industry.

Because of prior involvement with whole-tree chipping, research engineers at the Forestry Sciences Laboratory in Houghton, Michigan, were commissioned to develop a machine to produce wood particles from low-quality trees or logging residues. The wood particles were to have a greater length in the fiber direction than conventional pulp chips and be suitable for flaking. The prototype machine that resulted from this research produces chunky-shaped particles (chunkwood) (fig. 1) with an average fiber length of 2 to 4 inches that can have any cross section, including round pieces the full diameter of the tree or log.

PROBLEM STATEMENT AND STUDY OBJECTIVE

If the technique of producing elongated flakes, which in turn are produced from chunkwood, is to gain commercial acceptance, practical methods must be developed to reduce the unacceptably large chunks into "fingerlings" of an acceptable size (Gardner *et al.* 1978). In an effort to determine if the individual particle size of chunkwood could be further reduced while maintaining fiber length, we conducted a series of experiments using different blade configurations on the prototype chunker, and on three methods of particle size reduction totally apart from the chunking process. The results are reported here.

CHUNKER DESCRIPTION

The mobile prototype wood chunker (Arola *et al.* 1988b, Barwise *et al.* 1984) (fig. 2) uses three curved, triangular cutting blades attached to a 36-inch carrier disc. The disc is driven by a 180-horsepower diesel engine through a speed reduction unit to obtain a disc speed of about 200 revolutions per minute (rpm). The disc allows for blade replacement and has facilities to mount blades of different thicknesses. The log is fed through a tubular anvil by hydraulically powered feed rollers that control the log feed rate. This machine is capable of processing tree-length material up to 9 inches in diameter. Because of the physical difficulties encountered when transporting and handling whole trees, only 8-foot logs were chunked to supply material for the following tests.

DETERMINATION OF PARTICLE SIZE AND METHODS OF ANALYSIS

A rotary square-hole screen classifier (Arola *et al.* 1988a) (fig. 3) was used to determine the particle size distributions of the chunkwood samples. The screens are rotated about their longitudinal axes to impart a tumbling action on the chunks, facilitating discharge. The screens were used in descending order, the screen with the largest opening first. The particles that passed through the first screen were further classified by the screen with the next smaller opening. The classifier screen was inclined at an angle of 5 degrees from the horizontal, and the screen surface rotational speed was set at 78 feet per minute. The screens are composed of bars running the length of the screen. On all except the fines screen (0.2 inch), bands were placed around the circumference at

---

Robert Radcliffe is an Electronic Technician with the North Central Forest Experiment Station, Houghton, Michigan.

Figure 1.—*Unreduced chunkwood.*

distances corresponding to the bar spacing, to give an approximate square opening. The combination of slots and bands gave openings of 1.0, 2.0, and 2.5 inches. The 2.5-inch screen opening was later increased to 3.0 inches.

ANALYSIS TECHNIQUES

Although the chunks had a continuous distribution of sizes, the data consist of the percent by weight of chunks in discrete size fractions. The size categories depend on the screen selection and the size interval between screens. Therefore, nonlinear regression techniques were used to fit a continuous Weibull probability function of the form

$$E(Y) = 1 - \exp(-b_1 X^{b_2})$$

to the data to provide continuous curves for each treatment, reflecting the distribution of actual chunk weights. Because the primary focus of this research was the reduction of large particles, we defined a dependent variable "OVERSIZE" as the percent (by weight) of the particles that were retained on the screens with holes 2 inches and larger, for analysis of the difference among treatments.

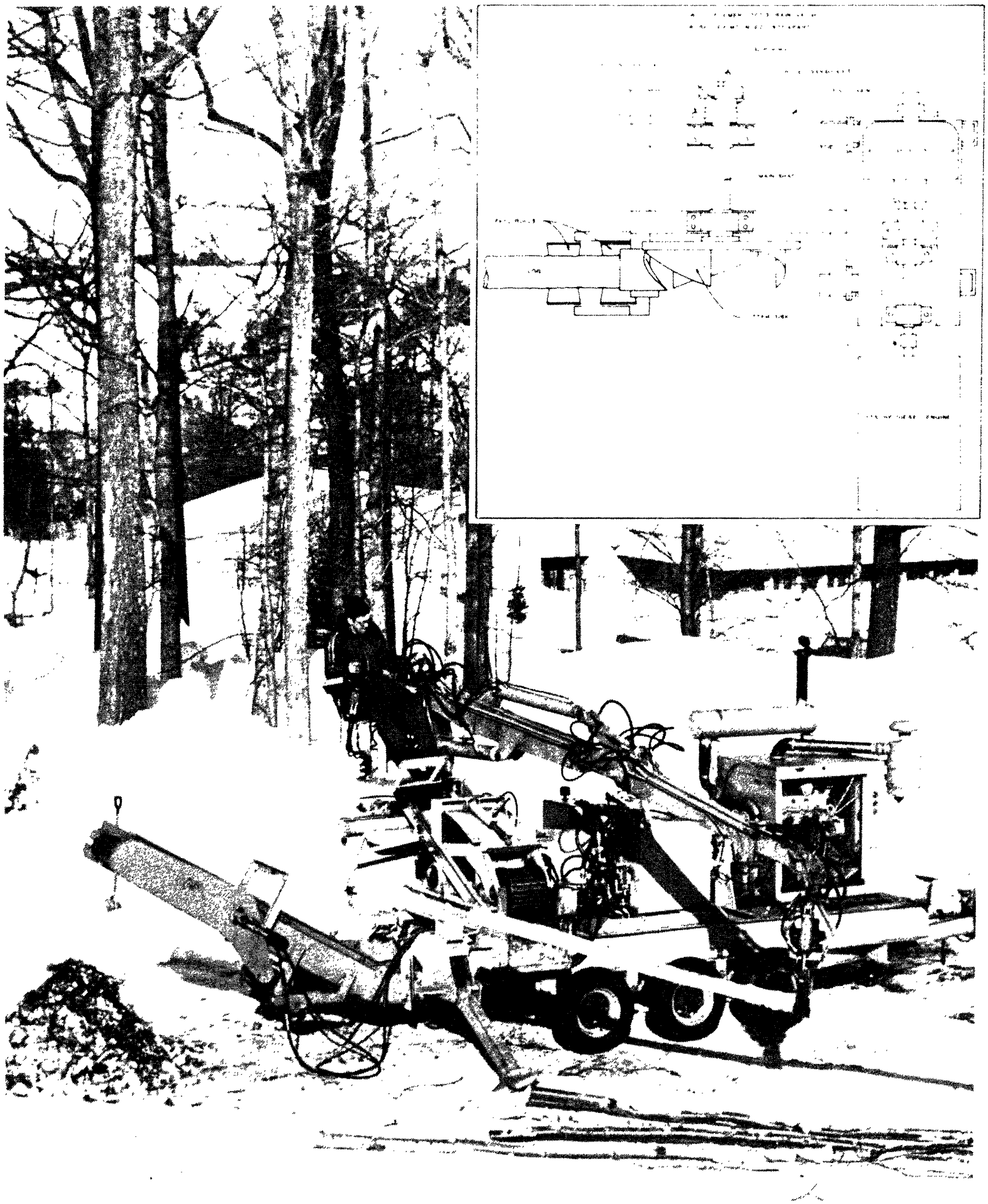

Figure 2.—*Photo and schematic of chunker.*

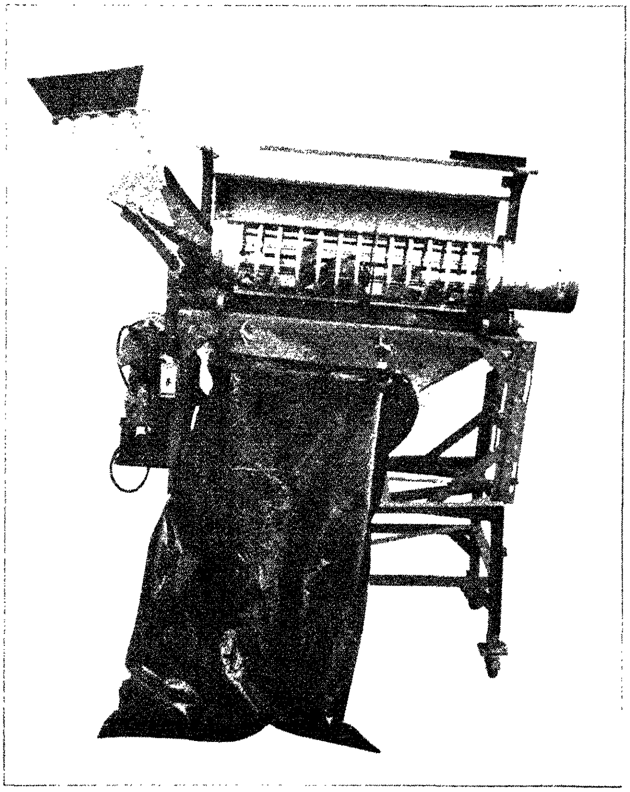

Figure 3.—*Rotary square-hole screen classifier.*

CHUNKER BLADE CONFIGURATION TESTING

From prior work, we knew that blade thickness (1/4- vs. 3/8-inch) and cutting edge geometry (single- vs. double-bevel) have a significant effect on the resulting particle size (Arola *et al.* 1983). Because the 3/8-inch blades tend to break up the large discs more than the 1/4-inch blades, we theorized that a 3/8-inch-thick ramp attachment positioned at the cutter edge would augment particle breakup, producing even smaller particles. We tested each of the following blade configurations: 3/8-inch-thick single-bevel blades, 1/4-inch-thick single- and double-bevel blades, and 1/4-inch-thick double-bevel blades with a ramp attachment (fig. 4). The chunkwood produced by each blade set was quantitatively analyzed for particle comminution.

Test Procedure

During the initial testing of the laboratory version of the chunker, log diameter appeared to influence chunk size. For that reason, the test logs were split

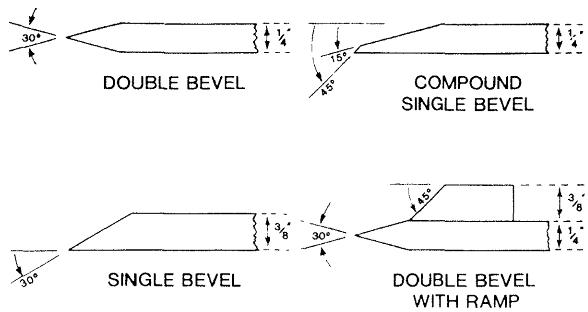

Figure 4.—*Schematic of chunker blades.*

into two size classes by average diameter: 2.8 to 4.7 inches for the small size category and 4.8 to 6.8 inches for the large. Forty 8-foot red maple (*Acer rubrum*) logs were numbered, measured for end diameters, and weighed. Ten logs were randomly selected, five in each size category for each blade set. The chunker blades were sharpened and installed prior to the testing sequence. The test logs were chunked and the output collected for subsequent classification, discarding the chunks that came from the ends of the log. After classification screening of the chunks (table 1), moisture content samples were taken from each screen fraction. Because moisture content was essentially constant across screen fraction sizes, an average moisture content is reported for each treatment.

Analysis

Analysis of variance (ANOVA) was used to determine if a difference in the percentage of large chunks (OVERSIZE) existed due to blade set or test log diameter (table 2). No statistically significant difference resulted from test log diameter, contrary to expectations based on previous chunking studies. This was probably due to the relatively small diameter range of the test logs. The interaction term between log diameter and blade set was not significant. The difference in the OVERSIZE category due to blade configuration was, however, significant at the 99-percent confidence level. Based on the ANOVA results, the diameter classes were combined for regression analysis to determine the Weibull cumulative distribution curves for the blade tests (fig. 5). R^2 values for the regressions were 0.97 or higher, indicating good fits. The actual regression coefficients obtained are presented in the Appendix. Examination of the curves shows that the double-bevel ramp blade

Table 1.—*Effect of chunker blade configuration on chunk size distribution*

Blade type	Input weight	Moisture content	Percentage of chunks (by weight) falling to pass the following screen openings				
			Fines	OVERSIZE +0.2[1]	+1.0[1]	+2.0[1]	+3.0[1]
	Pounds	*Percent*	- - - - - - - - - *Inches* - - - - - - - -				
3/8" Single-bevel							
Mean	28.1	39	3.1	8.3	29.0	36.4	23.0
Std. dev.[2]	3.9		0.8	2.3	5.5	5.8	7.8
1/4" Single-bevel							
Mean	28.4	39	1.8	3.2	15.8	48.7	30.1
Std. dev.	2.8		0.6	1.7	4.6	13.5	15.4
1/4" Double-bevel							
Mean	27.5	37	2.2	3.7	23.8	37.0	32.8
Std. dev.	5.0		0.5	1.5	5.9	7.9	13.4
1/4" Double-bevel ramp[3]							
Mean	23.6	41	3.4	8.7	38.1	39.0	10.2
Std. dev.	5.1		1.0	2.4	5.2	5.2	5.9

[1] Size of screen opening.
[2] Standard deviation.
[3] Only four large logs were chunked with the 1/4-inch double-bevel ramp blades because of chunker malfunctions, resulting in nine observations for this treatment.

Table 2.—*Analysis of variance for blade configuration tests*[1]

Source	Degrees of freedom	Sum of squares	Mean square	F
Blade set (B)	3	4,666.8	1,555.6	29.3
Log size (S)	1	18.2	18.2	0.3
Interaction				
B x S	3	285.8	95.3	0.2
Error	31	1,647.3	53.1	
Total	38	6,618.1		

[1] Dependent variable was OVERSIZE.

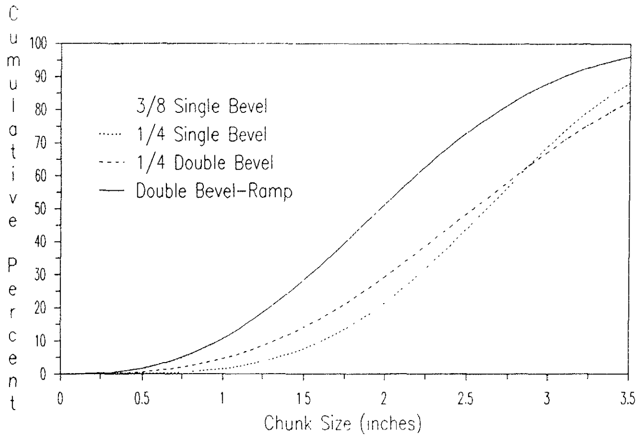

Figure 5.—*Weibull curves for blade data.*

produced the most small particles, with only 49 percent being in the OVERSIZE class. The 3/8-inch single-bevel blades left 59 percent of the chunks in the OVERSIZE category, whereas the 1/4-inch double- and single-bevel blade sets left 70 percent and 79 percent, respectively.

PARTICLE SIZE REDUCTION METHODS

We tested three mechanical methods of chunkwood particle size reduction. Two of the methods broke up the chunks, whereas the third crushed the log prior to processing by the chunker. The postchunking methods included a small, commercially available hammermill and an experimental device called the spiked roll assembly that broke down the chunks by forcing a pointed rod through the wood pieces. The third, the prechunking approach, was an experimental crusher (roll crusher) developed by the Forest Engineering Research Institute of Canada (FERIC), Pointe Claire, Quebec (Barnett *et al.* 1986).

Sample Preparation

Each reduction method was tested on green logs of two species: red maple (*Acer rubrum*) and aspen (*Populus tremuloides*). All logs were 8 feet long and less than 8 inches in diameter. The logs were chunked using the USDA Forest Service chunker equipped with the 3/8-inch-thick single-bevel blades. Each log was numbered and chunked individually, and the chunks were collected and bagged separately.

For all test procedures, samples of the material were collected from each size fraction during screening for moisture content determinations made according to TAPPI Standard T 18m-53 (Technical Association of the Pulp and Paper Industry 1967). Moisture content is reported on a green-weight basis. Chunks and reduced material were screened by size with the rotary square-hole screen classifier, and results were analyzed using the same technique that was applied to the blade testing.

HAMMERMILL

The Holmes model ADX[1] is a small hammermill (fig. 6) powered by a 3-horsepower, three-phase electric motor with a synchronous speed of 1,750 rpm. The material to be reduced is fed into a chamber enclosing three pivoted, weighted bars mounted on a rotating shaft. As the shaft rotates, the weighted bars impact the material entering the chamber, fracturing the larger pieces. To prevent overreduction of the chunkwood, the bottom retaining grate was removed, limiting particle residence time and facilitating particle discharge.

Test Procedure

Five randomly selected logs of each species were chunked individually, and the resulting output was divided into two samples: 25 percent for a control and 75 percent for processing by the hammermill. After the control sample was removed, the remaining chunks were weighed and dumped into the feed hopper of the hammermill. After one pass through the mill, the reduced particles were collected and reweighed to determine losses. Both the control and the hammermilled samples were screened for particle size distribution.

Analysis

Two-way analysis of variance (table 3), using OVERSIZE as the independent variable, indicated a significant difference due to treatment (F = 156 with 1 and 16 d.f.). The ANOVA also indicated a significant difference due to species at the 95-percent level (table 4). The data show that more small particles were produced when chunking or hammermilling red maple than aspen, but the difference was not great enough to be of concern from a practical standpoint (fig. 7). Therefore, the two species were combined for the rest of the analysis.

[1] *The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the United States Department of Agriculture to the exclusion of others that may be suitable.*

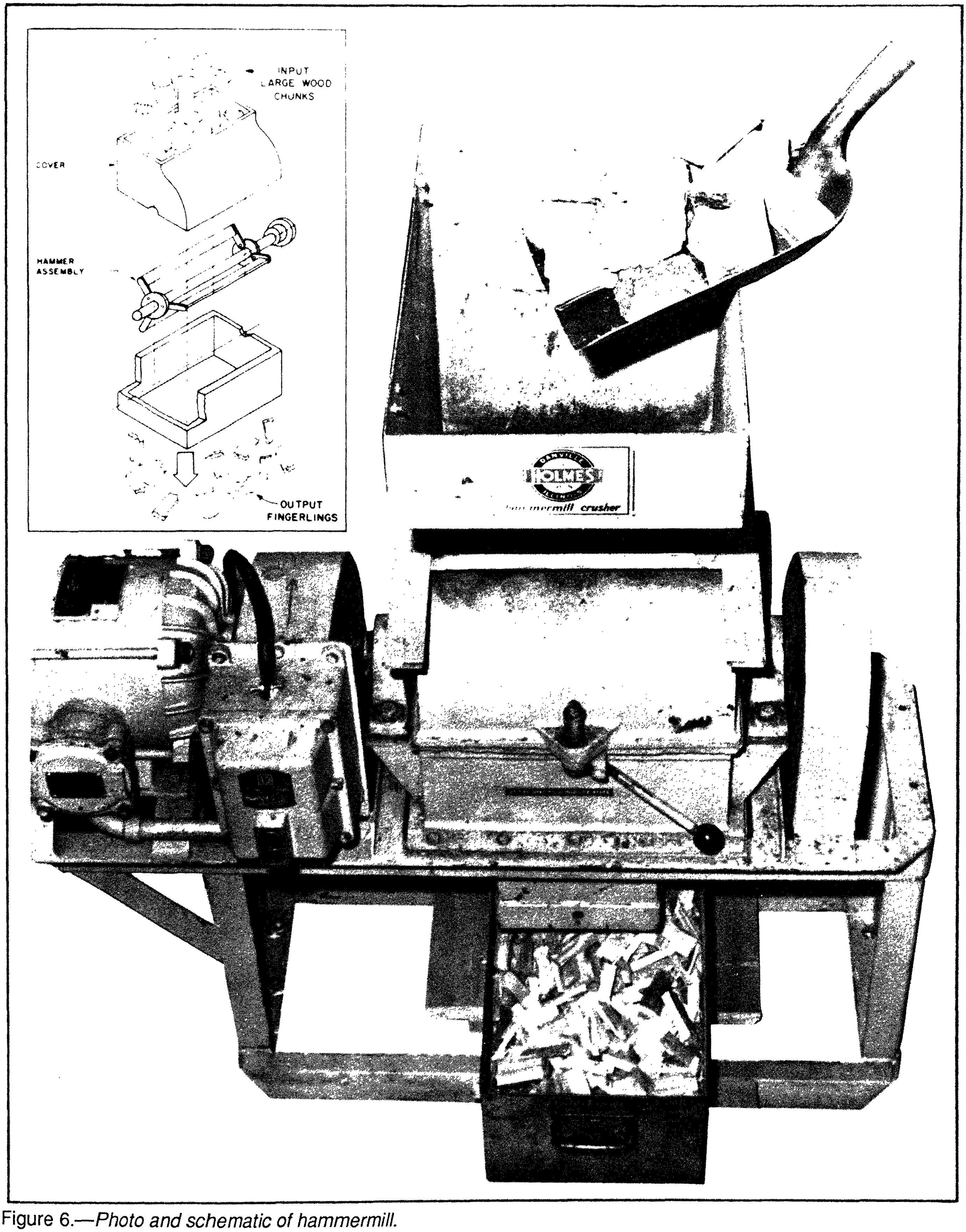

Figure 6.—*Photo and schematic of hammermill.*

Table 3.—*Analysis of variance for hammermill tests*[1]

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatment (T)	1	13,772.8	13,772.8	156.4
Species (S)	1	459.5	459.5	5.2
Interaction T x S	1	52.6	52.6	0.6
Error	16	1,408.6	88.4	
Total	19	15,693.5		

[1] Dependent variable was OVERSIZE.

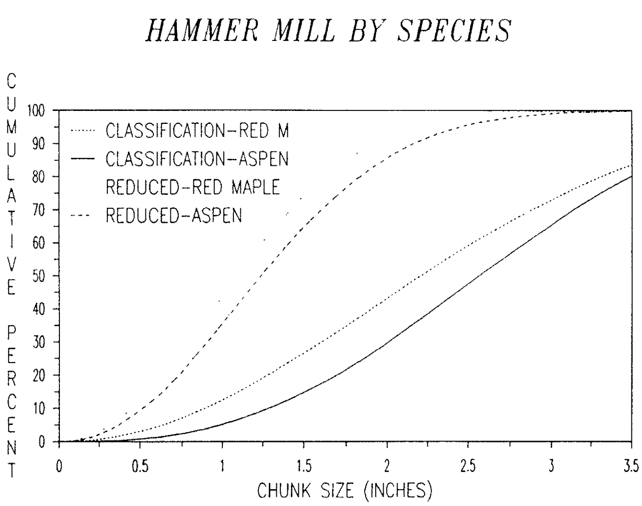

Figure 7.—*Weibull curves for hammermill data.*

EXPERIMENTAL SPIKED ROLL ASSEMBLY

The spiked roll concept was initially developed by researchers at Michigan Technological University's Institute of Wood Research (Haataja *et al.* [1984]). The machine was designed by Michigan Tech mechanical engineering students under the guidance of a Forest Service engineer. The spiked roll assembly's principal feature is two opposing rolls with attached 6-inch-long spikes (fig. 8). The spikes were made from hardened 3/4-inch hex-head bolts with the threaded end sharpened to a 45-degree cone. The bolts were welded to the rolls on a 2- by 3-inch grid and placed so that the spikes of the opposing roll would intermesh. At the widest roll spacing, the spikes do not actually intermesh; the tips of the spikes of one roll are about 1 inch from the tips of the spikes of the opposing roll. The roll spacing, and hence the degree of intermeshing, was adjustable in 1-inch increments. The adjustments allowed settings of 1-inch separation between the tips of the rods, tips of the rods even with each other, and a 1- or 2-inch intermesh. The spikes are slightly inclined in the direction of rotation, providing easier spike penetration and a more aggressive feed. A 50-horsepower hydraulic power unit supplied power to a hydraulic motor, which in turn drove the rolls through a sprocket/chain assembly. An industrial version of this machine is envisioned as having multiple opposing roll pairs, adjusted so that the chunks would be progressively reduced to smaller particles as they pass through succeeding stages.

Table 4.—*Effect of hammermilling on particle size distribution*

	Input weight	Moisture content	Percentage of chunks (by weight) failing to pass the following screen openings: Fines	OVERSIZE +0.2[1]	+1.0[1]	+2.0[1]	+2.5[1]
	Pounds	*Percent*		*Inches*			
Untreated							
Mean	24.8	39	4.6	8.9	22.4	15.4	48.0
Std. dev.[2]	0.3		2.6	4.7	7.2	3.0	15.2
Treated							
Mean	74.5	39	11.1	28.5	49.1	8.3	2.6
Std. dev.	0.3		1.6	4.0	2.9	2.6	1.5

[1] Size of screen opening.
[2] Standard deviation.

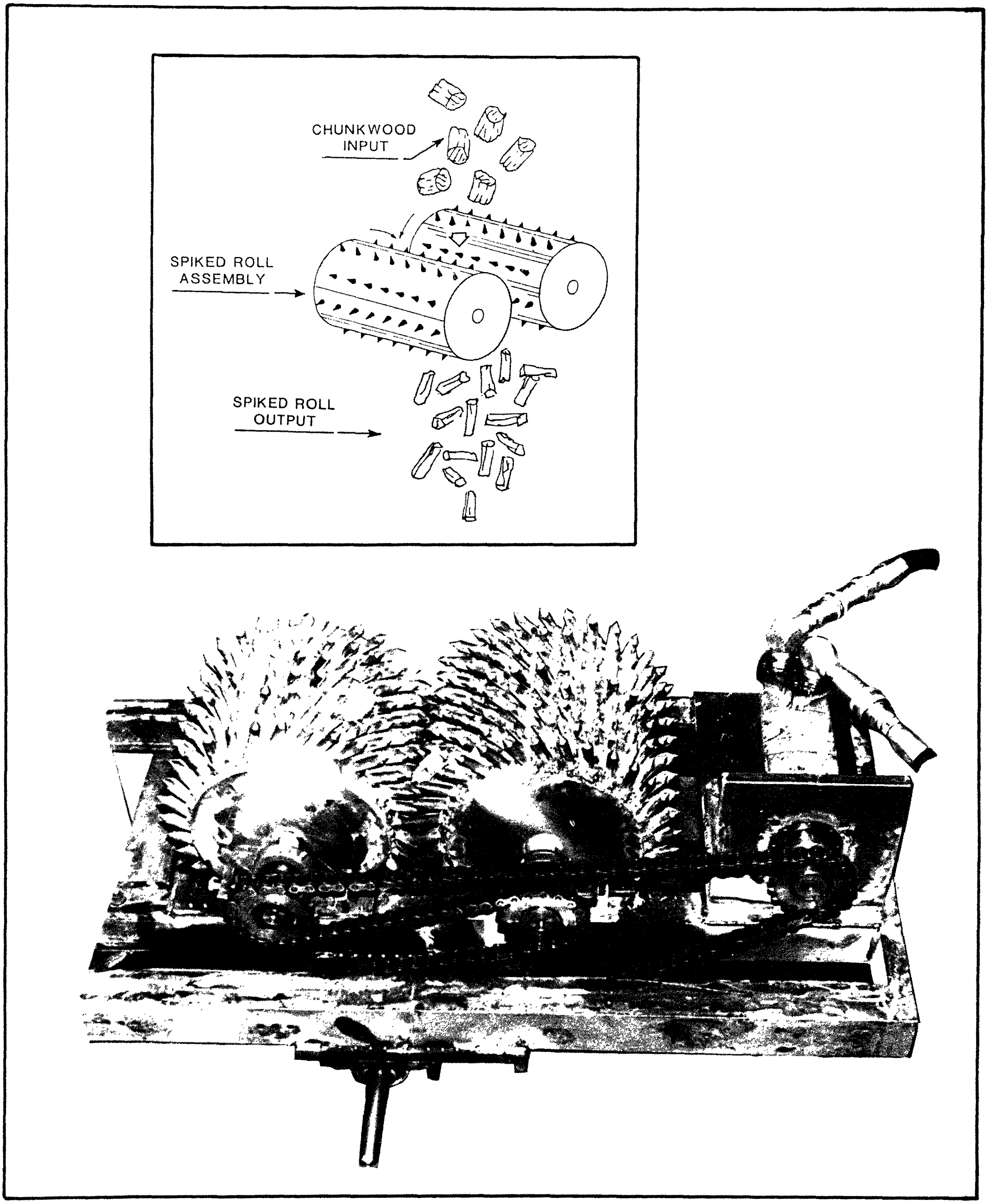

Figure 8.—*Photo and schematic of spiked roll assembly.*

Test Procedure

To simulate the commercial version, all chunkwood samples were processed through the spiked roll assembly three separate times at decreasing roll spacings. As in the hammermill tests, five logs of each species were randomly selected and chunked, and 25 percent of the sample removed for the control. The remaining 75 percent was weighed and fed through the spiked roll assembly. The test sample was initially processed at the widest roll spacing of 1-inch tip separation and reclassified. The resulting material was then processed using a setting in which the spikes were even and finally processed at the closest spacing, which was a 2-inch intermesh. This procedure was followed for each test log.

Analysis

Analysis of variance was run on the spiked roll assembly data to determine if there was a difference in the percent of large chunks (OVERSIZE) due to treatment (each pass was considered a separate treatment) or species. Although a species difference was indicated, only the treatment differences were of consequence from a practical standpoint, so the species were combined for additional analysis (table 5). Post hoc T-tests on the mean values showed that, after each stage of treatment, the output from the spiked roll assembly contained a significantly (99-percent level) smaller percent in OVERSIZE. The percent of chunks (by weight) in OVERSIZE for untreated, stage 1, stage 2, and stage 3 were 72, 62, 40, and 7 percent, respectively, while the fines segment increased from 3.4 percent of input to just 6.9 percent of input. The output also became more homogeneous as chunks passed through the three consecutive stages, as the curves of the Weibull probability function clearly indicate (fig. 9, table 6).

Table 5.—*Analysis of variance for spiked roll assembly tests*[1]

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatment (T)[2]	3	24,316.9	8,105.6	264.2
Species (S)	1	561.8	561.8	18.3
Interaction T x S	3	78.4	26.1	0.8
Error	32	981.8	30.7	
Total	39	25,938.8		

[1] Dependent variable was OVERSIZE.
[2] Four treatments—untreated, stage 1, stage 2, stage 3.

Table 6.—*Effect of the spiked roll assembly on particle size distribution*

	Input weight	Moisture content	Percentage of chunks (by weight) failing to pass the following screen openings: Fines	+0.2[1]	+1.0[1]	+2.0[1] (OVERSIZE)	+2.5[1] (OVERSIZE)
	Pounds	*Percent*		*Inches*			
Input							
Mean	24.7	39	3.4	6.8	17.8	14.4	57.2
Std. dev.[2]	0.3		2.2	3.3	4.6	3.3	11.7
Stage analysis							
Stage one (1-inch tip separation)							
Mean	74.7	39	4.0	8.2	25.4	23.3	39.0
Std. dev.	0.5		1.2	2.9	3.7	4.1	8.1
Stage two (1-inch spike intermesh)							
Mean	74.5	37	4.9	11.1	43.0	26.2	14.7
Std. dev.	0.5		1.3	2.7	2.8	2.9	4.2
Stage three (2-inch spike intermesh)							
Mean	74.3	39	6.9	24.0	60.9	6.5	0.9
Std. dev.	0.5		1.2	3.2	3.1	1.6	0.5

[1] Size of screen opening.
[2] Standard deviation.

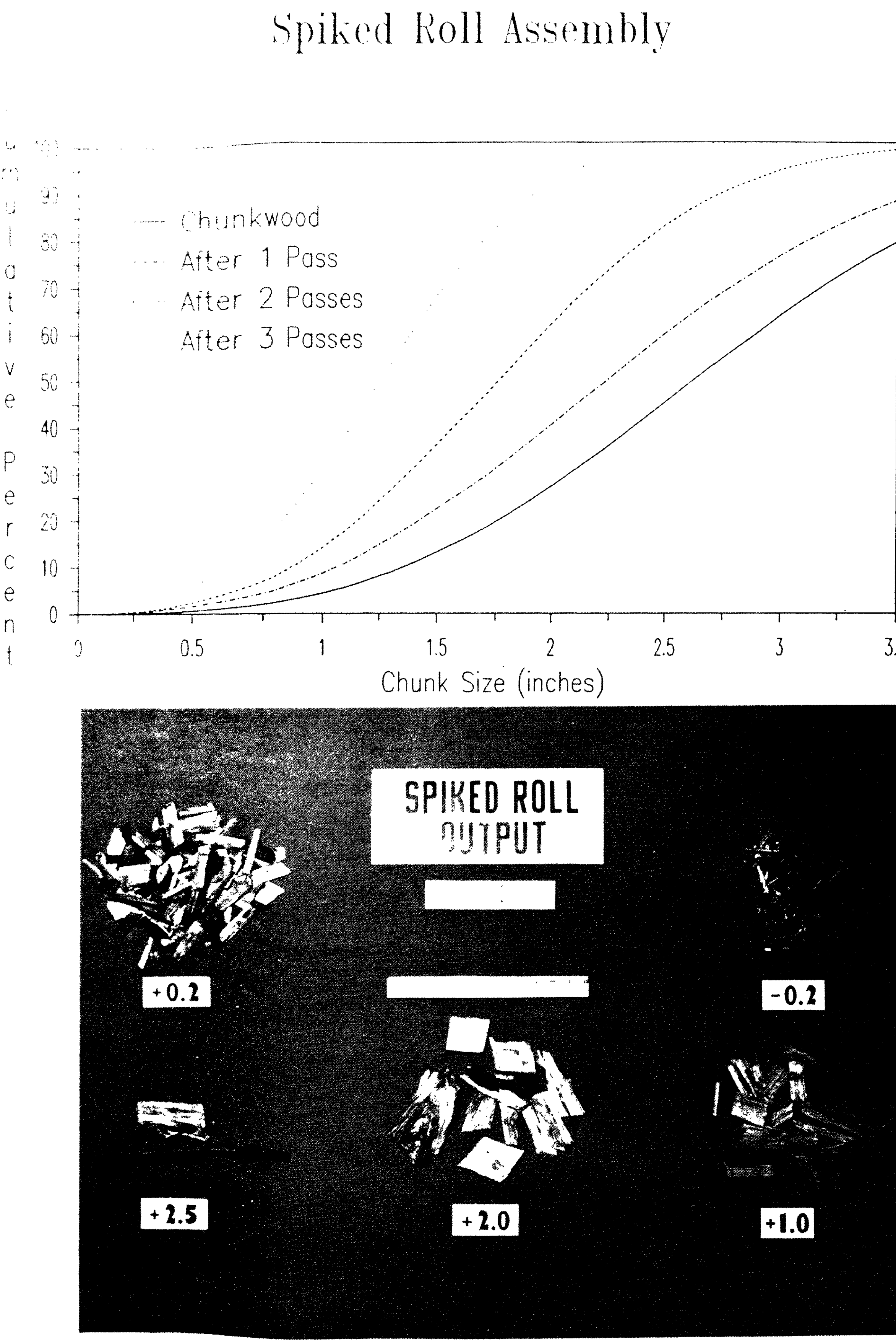

Figure 9.—*Weibull curves for spiked roll assembly.*

EXPERIMENTAL ROLL CRUSHER

Researchers with the Forest Engineering Research Institute of Canada (FERIC) have developed a machine (fig. 10) to crush logs. We thought that chunking crushed logs might produce material that fits the description of "fingerlings" (Gardner *et al.* 1978).

The machine features two sets of opposing 18-inch-diameter crushing rollers fitted with ridged sleeves to prevent roll slip. Hydraulic cylinders exert a maximum downward force of 12,570 pounds upon each of the upper rollers. The motors for the rollers and the cylinders are hydraulically powered by a pump driven by a 427-cubic-inch displacement gasoline engine. The log (or tree) is placed between the first set of rollers and drawn in so that it is initially crushed by the first set of rollers. The partially crushed log is then drawn into the second roll set for the final crush. The severity of crushing of the first and second roll pairs is hydraulically adjustable.

Test Procedure

The control samples for the roll crusher tests were obtained by chunking similar logs of the same species and obtaining representative chunks. Ten logs of each species were then crushed and hand fed to the chunker in random sequence. From each crushed log, samples of about 25 pounds of chunks were collected and classified using the rotary square-hole screen classifier; they were analyzed as in the previous test procedures.

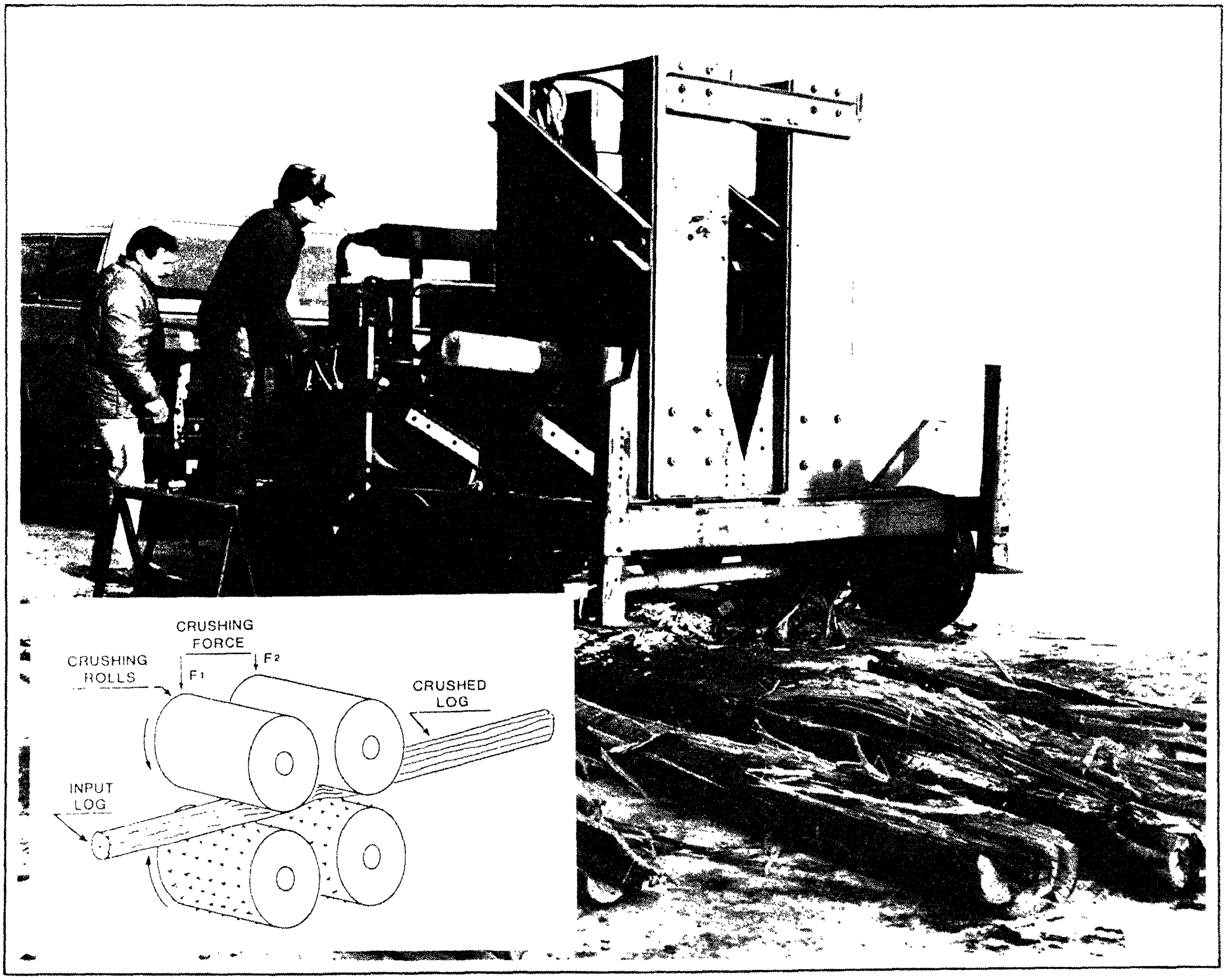

Figure 10.—*Photo and schematic of roll crusher.*

Analysis

Two-way ANOVA of the chunks from the roll-crushed material indicated a significant difference between treated and untreated logs at the 99-percent confidence level. No significant difference was found between species (table 7). The chunks in the control samples from the roll crusher tests were larger than those in the other control samples (hammermill, spiked roll, and 3/8-inch blade tests) (fig. 11). For unknown reasons, the control samples for the roll crusher averaged 90 percent OVERSIZE (standard deviation = 4.2), whereas the control samples from the other machines had an average of only 65 percent with a standard deviation of 11.7. Some possible causes are a change in cutter disc speed, a difference in wood condition (age, moisture, partially frozen, etc.), or a difference in chunker operation (table 8).

Table 7.—*Analysis of variance before and after roll crushing*[1]

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatment (T)	1	25,996.5	25,996.5	284.1
Species (S)	1	23.0	23.6	0.3
Interaction T x S	1	0.8	0.8	0.01
Error	27	2,470.7	91.5	
Total	30	28,491.1		

[1] Dependent variable was OVERSIZE.

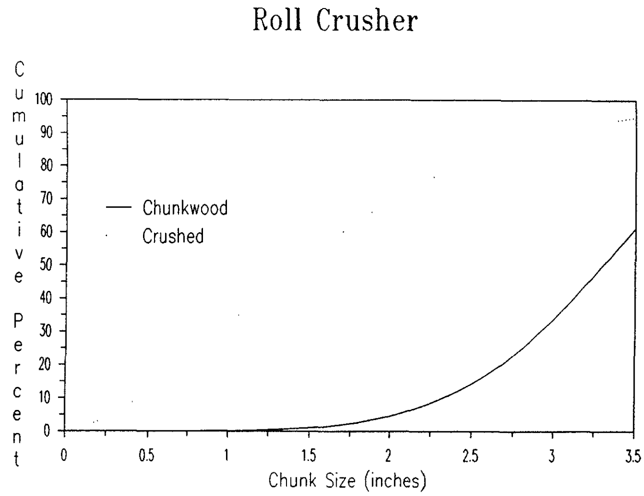

Figure 11.—*Weibull curves for roll crusher data.*

COMPARISON OF REDUCTION METHODS

All the reduction methods successfully broke down large chunks into smaller, more homogeneous particles (fig. 12). Three passes through the spiked roll assembly produced output very similar to the material that was hammermilled. About 80 percent of the material stayed on the 0.2- and 1-inch screens after these two treatments. The hammermill created more fines (11 percent) than the spiked roll assembly (7 percent) or the roll crusher (6 percent), due to the harsher treatment of the chunks (fig. 13). Although the roll-crushing treatment reduced the average particle size significantly, it was not as effective as the other two treatments nor were the resulting particles

Table 8.—*Effects of chunking crushed logs on particle size distribution*

	Input weight	Moisture content	Fines	+0.2[1]	+1.0[1]	+2.0[1] (OVERSIZE)	+3.0[1] (OVERSIZE)
			Percentage of chunks (by weight) failing to pass the following screen openings				
	Pounds	*Percent*		*Inches*	*Inches*	*Inches*	*Inches*
Chunks from uncrushed logs							
Mean	67.0	37	1.6	1.7	6.7	22.3	67.8
Std. dev.[2]	27.8		0.5	0.6	3.3	9.1	12.4
Chunks from crushed logs							
Mean	26.5	37	5.9	26.1	37.9	20.0	8.1
Std. dev.	3.5		2.2	6.3	4.8	4.9	8.4

[1] Size of screen opening.
[2] Standard deviation.

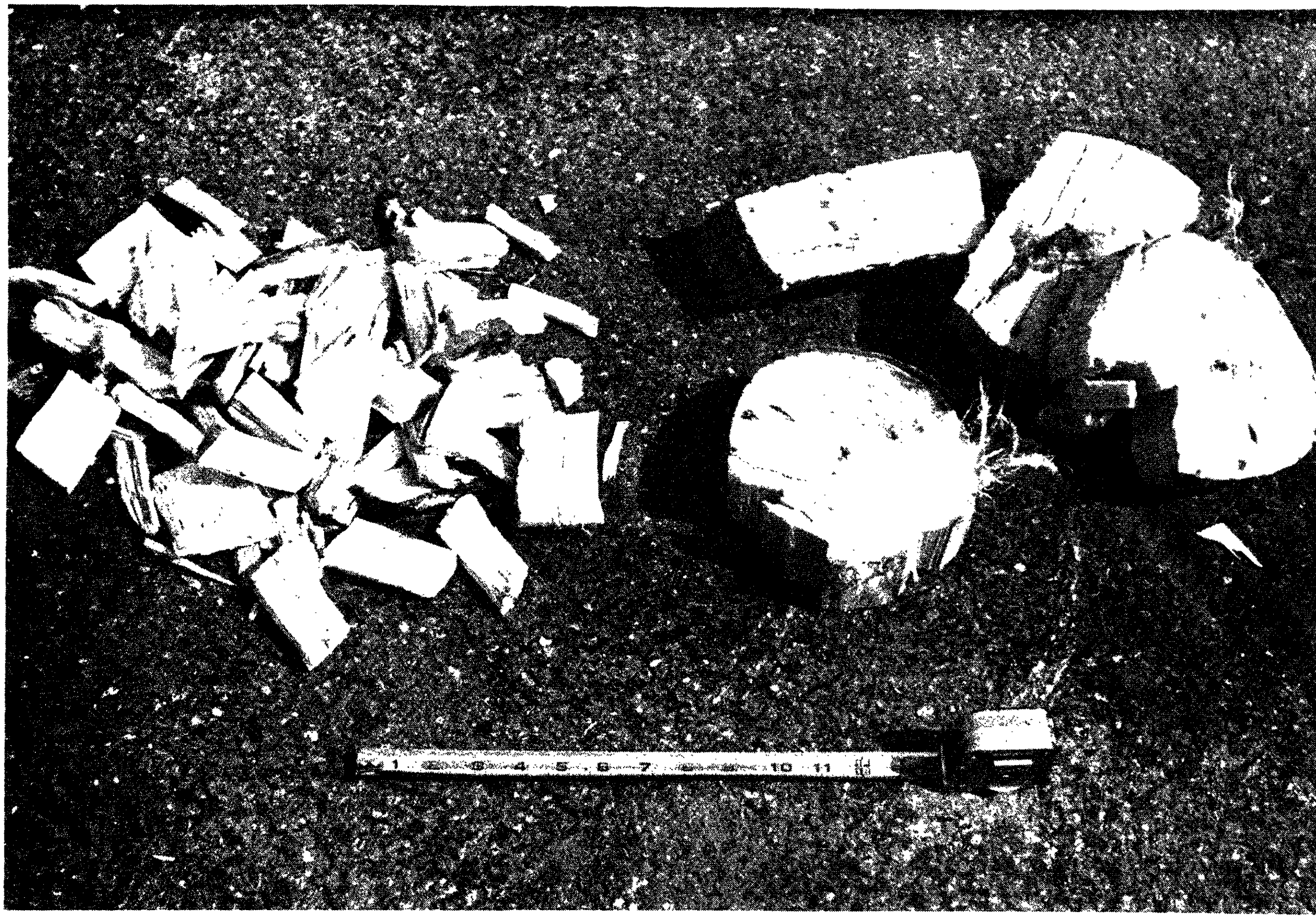

Figure 12.—*Comparison of chunkwood and reduced chunkwood.*

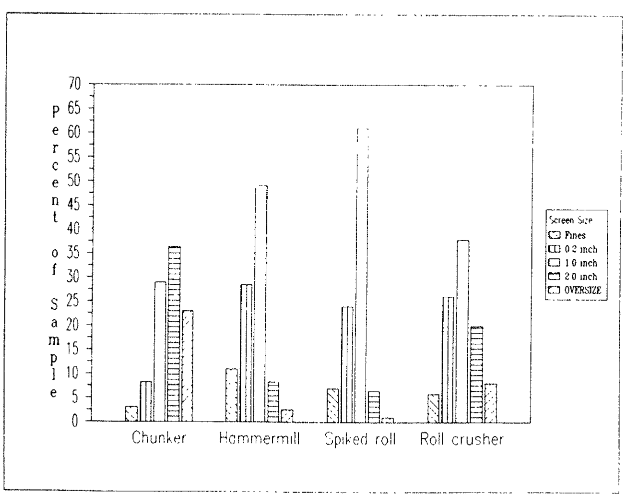

Figure 13.—*Comparison of chunkwood particle size distribution for reduction machinery.*

as homogeneous. Twenty-eight percent of the chunks (by weight) were still in the OVERSIZE category after chunking the crushed material, as opposed to about 10 percent after the hammermill or spiked roll treatments. This could be due, in part, to the same factors that produced larger chunks in the roll crusher control sample. In addition, the crushed logs did not chunk cleanly, and the resulting stringy pieces caused them to stay on the larger screens.

CONCLUSIONS

Chunker blade thickness has an impact on chunk size. A secondary factor is the cutting edge geometry; the double-bevel configuration produces smaller chunks than the single-bevel edge. The 1/4-inch single- and double-bevel blades produced 20 and 30 percent of the chunks under 2 inches, respectively. The 3/8-inch-thick blades produced 40 percent within that range. The 3/8-inch-thick ramp attachment to the 1/4-inch double-bevel blades (effectively making them 5/8 inch thick at the cutting edge) produced 50 percent of the chunks within the 2-inch target range.

The postchunking methods of reduction were effective in yielding a homogeneous output when compared with untreated chunks. Because the hammermill was a small unit, it could handle only 25 pounds in batch. The hammermill reduced the OVERSIZE segment of the output by about 83 percent. This type of hogging is presently used for fuel wood and could be applied on a commercial basis to size chunkwood. This process doubled the amount of fines, however, to 11 percent. The spiked roll assembly's through-put was much greater than that of the hammermill due to the continuous feed capability. It is envisioned that a commercial version of this machine would have successive stages, with each stage progressively reducing the larger particles. Our test machine had four possible settings, but in preliminary work we found that it performed well using only three. The setting where the opposing spike tips were even with each other did not appreciably improve particle reduction or machine performance so it was excluded from the test program. The reduced chunkwood output was quite homogeneous with a fines segment of only 7 percent. Because of the nature of this reducing method, the machine tends to reduce only the large pieces and does not increase fines content greatly. There were some problems breaking up the knotty pieces. The knotty pieces, which were the major constituent of the OVERSIZE component of the output (7.4 percent of input), would jam between the spikes, especially on the closest setting. The hammermill, however, would simply discharge these pieces without reduction.

Although the roll crusher effectively crushed the logs, it was difficult to control the degree of crushing necessary for this study. When logs were run through this machine, they shattered so completely that they literally fell apart, which made feeding the chunker extremely difficult and chunker performance on the shattered logs less than ideal. When we attempted to restrict the degree of crushing so that logs were well shattered but still retained some form, we had to continually adjust the rollers, making it impossible to maintain a constant crushing force, especially on smaller logs. The chunker blades would not cleanly sever the shattered logs, leaving long, splinter-like pieces in the chunker output. For this study, the roll crusher was a separate machine; the concept, however, could be incorporated into the chunker by replacing the feed rollers, which would possibly eliminate the log feed problem. A crushed log trapped between the rolls and positioned close to the chunker blades should restrain the wood enough for a clean cut. Although chunkwood reduction following roll crushing was not as complete as in the post-chunking approaches, it resulted in a 72 percent reduction in the OVERSIZE category.

Chunkwood offers an alternative to typical wood chips. The chunky shape offers new utilization opportunities and cost benefits over current methods of wood comminution. Reducing the particle size while maintaining the chunky shape and the longer fiber length could provide the flakeboard industry and other wood users such as the pulp and paper industries with a tailored wood particle. Particles larger than pulp chips may prove superior for certain combustors. Finally, chunkwood from low-value poletimber stands, timber stand improvements, or logging residues could greatly extend the timber resource and perhaps provide a market incentive for thinnings and timber stand management.

LITERATURE CITED

Arola, Rodger A.; Radcliffe, Robert C.; Sturos, Joseph B. 1988a. Characterizing chunkwood. In: Production, storage and utilization of wood fuels: Proceedings of IEA/BE conference task 3/activity 6 and 7; 1988 December 6-7; Uppsala, SE. Res. Note 133/1988. Garpenberg, SE: The Swedish University of Agricultural Sciences, Department of Operational Efficiency; 1: 49-67.

Arola, Rodger A.; Sturos, Joseph B.; Radcliffe, Robert C. 1988b. U.S. chunkwood machines. In: Production, storage and utilization of wood fuels: Proceedings of IEA/BE conference task 3/activity 6 and 7; 1988 December 6-7; Uppsala, SE. Res. Note 133/1988. Garpenberg, SE: The Swedish University of Agricultural Sciences, Department of Operational Efficiency; 1: 1-20.

Arola, Rodger A.; Winsauer, Sharon A.; Radcliffe, Robert C.; Smith, Martyn R. 1983. Chunkwood production: a new concept. Forest Products Journal. 33(7/8): 43-51.

Barnett, Paul E.; Sirois, Donald L.; Ashmore, Colin. 1986. Reduction of biomass moisture by crushing/splitting - a concept. In: Rockwood, Donald L., ed. Proceedings of the 1985 Southern forest biomass workshop; 1985 June 11-14; Gainesville, FL. Gainesville, FL: University of Florida, Institute of Food and Agricultural Sciences: 13-16.

Barwise, Robert D.; Arola, Rodger A.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1984. Involuted disc slicer. U.S. patent 4,431,039. February 14. 11 p. Int. Cl.[3] B27L 11/02. U.S. Cl. 144/176.

Gardner, Rulon B.; Schaffer, Erwin L.; Erickson, John R. 1978. Converting forest residue to structural flakeboard—the fingerling concept. Res. Pap. INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 31 p.

Haataja, Bruce A.; Adams, Roy D.; Arola, Rodger A. [1984]. Total tree chunkwood as raw material for flake products. In: Corcoran, Thomas J.; Gill, Douglas R., eds. Proceedings, 1984 COFE/IUFRO [Council on Forest Engineering/International Union of Forestry Research Organizations]; 1984 August 11-18; Orono, ME. SAF Publ. 84-13. Orono, ME: University of Maine: 157-163.

Technical Association of the Pulp and Paper Industry. 1967. TAPPI Standard T 18m-53. Specific gravity (density) and moisture content of pulpwood. TAPPI Press. 4 p.

APPENDIX

Coefficients derived from nonlinear regression analysis for the Weibull probability function: $E(Y) = 1 - \exp(-b_1 X^{b_2})$ for the curves presented in the listed figures.

Blade tests—red maple only (fig. 5).

Blade type	n	b_1	b_2	r^2
3/8-inch single-bevel	50	0.0986	2.4505	0.98
1/4-inch single-bevel	50	.0164	3.8870	.97
1/4-inch double-bevel	50	.0470	2.8878	.97
1/4-inch double-bevel w/ramp attachment	45	.1125	2.6810	.99

Hammermill—individual species (fig. 7).

Treatment	n	b_1	b_2	r^2
Untreated aspen	25	0.0530	2.7293	0.93
Hammermilled aspen	25	.4381	2.1469	.98
Untreated red maple	25	.1334	2.0794	.94
Hammermilled red maple	25	.5740	2.1221	.97

Spiked roll by stages—aspen and red maple combined (fig. 9).

Treatment	n	b_1	b_2	r^2
Untreated	50	0.0438	2.8535	0.95
Stage 1	50	.0903	2.5157	.97
Stage 2	50	.1512	2.6699	.99
Stage 3	50	.3708	2.7462	.99

Roll crusher—aspen and red maple combined (fig. 11).

Treatment	n	b_1	b_2	r^2
Untreated	50	0.0011	5.3986	0.97
Crushed	105	.3898	1.6094	.96

Comparison of reduced chunks from three machines—aspen and red maple combined (fig. 13).

Treatment	n	b_1	b_2	r^2
Hammermill	50	0.5030	2.1106	0.97
Spiked roll	50	.3708	2.7462	.99
Crushed	105	.3898	1.6094	.96

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it. As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager meet these challenges while protecting the environment is what research at North Central is all about.

NORTH CENTRAL FOREST EXPERIMENT STATION