1984 Field Testing of the Experimental Prototype of the Dual Roll Splitter

by

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

SUMMARY

The Roll Splitter is an experimental prototype equipped with two consecutive pairs of rollers--smooth uppers, bars of teeth on lowers. It combines dewatering, splintering and crushing functions, and can process bolts of up to 16 cm (6 in.) in diameter. The tests were conducted on three woody species (yellow poplar, red maple and loblolly pine) and aimed at quantifying the dewatering ability of the Roll Splitter, its energy requirements and the drying rate of the crushed material.

Mechanical dewatering (percent moisture loss-dry basis) averaged 9.9% for yellow poplar, 9.0% for loblolly pine and 5.3% for red maple, with values ranging from 1% to 21%.

After five days of air drying with sun exposure, the residues of yellow poplar, loblolly pine and red maple underwent a reduction of moisture content of 90.5%, 89.5% and 50.5% respectively. Dewatering and drying appeared to be most effective with high initial moisture content material.

Cycle comminution energy (definition p. 26) amounted to 622 MJ/ODT for the yellow poplar, 630 MJ/ODT for the loblolly pine and 732 MJ/ODT for the red maple. In the same order, machine comminution energy was 115, 139 and 187 MJ/ODT and machine dewatering energy was 1.1, 2.0 and 4.0 MJ/Kg. water. In contrast to a former version equipped with a single pair of rollers, machine comminution energy doubled and machine dewatering energy remained the same.

Roller speeds affected mechanical dewatering and quality of splinters, particularly in the case of yellow poplar. Still, with the same species, dewatering capacities are significantly increased with two pairs of rollers as opposed to a single pair. With medium and high density species, for instance red maple, high crushing forces do not necessarily improve roll-crushing quality. Although the high resilience of crushed material might impede drying, it could facilitate subsequent baling and compaction operations.

INTRODUCTION

With woody material, it is estimated that the energy needed to create a unit of surface perpendicular to the grain is roughly 100 times that the energy needed to cleave if parallel to the grain. The concept of roll splitting wood is based primarily on this assumption, and offers an alternative to other comminution techniques, like chipping and hammer milling, for the transformation of woody biomass. It was identified by FERIC as being an area of potential improvement through research and development. Two versions of a roll splitter have been built and tested by the firm K.C. Jones and Associates (Ottawa), and both are well documented in ENFOR reports. The present report is concerned with the evaluation of a third version of the roll splitter.

The original versions of the roll splitter had only one pair of rollers. The third prototype utilizes two pairs of rollers in series, with bars of teeth on lower rollers, and smooth upper rollers. It can split and crush wood, and at the same time squeeze out water, an important consideration in preparing woody biomass for transportation and conversion to energy.

A joint project was set up between FERIC and TVA (Tennessee Valley Authority) to field test the roll splitting concept. The evaluation took place in Norris, Tennessee, during the period of spring/summer '84. Bolts 1.7 m (5.7 feet) long and 7-15 cm (3-6 in.) in diameter, from three woody species, yellow poplar (Liriodendron tulipifera), red maple (Acer rubrum) and loblolly pine (Pinus taeda), were processed to measure the dewatering ability of the roll splitter, its energy requirements and the air-drying potential of the crushed material. The experimental design accounted for compatibility with research data available from tests of the former prototype versions.

Preliminary tests in winter with frozen wood showed that dual pairs of rollers in series have a greater action than the cumulative effect of passing a bolt twice through a single pair of rollers. The 1984 summer tests were set to verify whether the roll splitter would perform similarly using unfrozen wood, and to assess the mechanical design of the new version. Specific objectives were then formulated:

To assess the performance of the roll-splitter by

1. quantifying
   - the dewatering ability of the roll splitter;
   - the energy requirements of the roll splitter;
   - the air-drying potential of the resulting residues.

2. evaluating
   - the effect of roller speeds and crushing force on fiberization and mechanical dewatering;
   - the mechanical design.

Since the roll-crushing concept is in its very early stage of development, the evaluation aimed at getting a better understanding of some aspects of the roll-crushing action in identifying critical factors, in view of further developments.

DESCRIPTION OF PROTOTYPE ROLL SPLITTER

A. MECHANICAL DESIGN

General characteristics:

weight:	8200 kg
length:	496 cm
width:	198 cm
height:	305 cm
tongue weight:	1000 kg:
	7 cm ball hitch

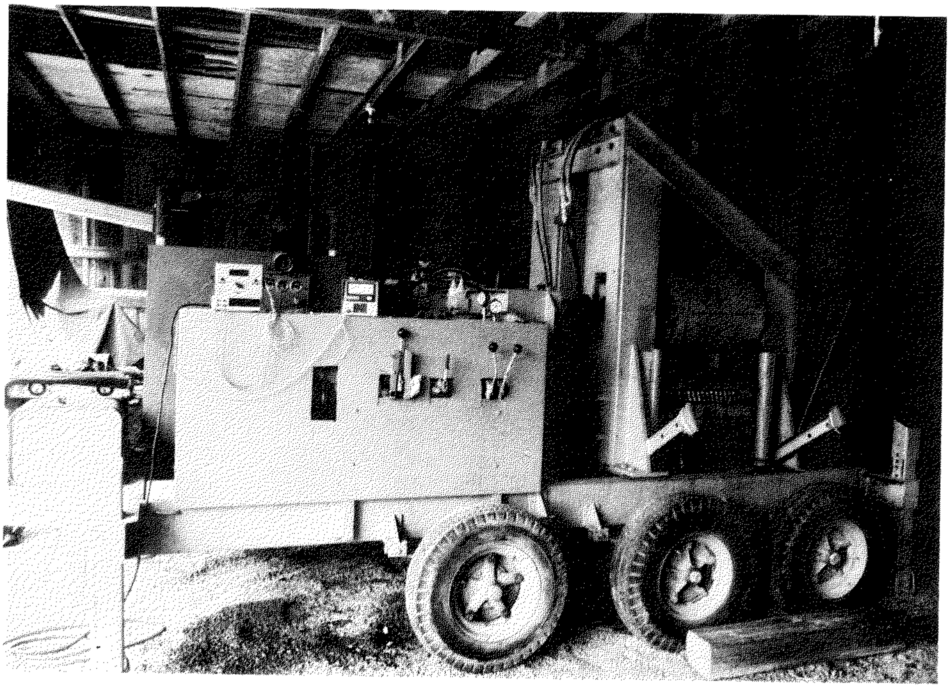
Power: Ford V8 - 7 litres (429 CID) - gasoline

recommended operating speed:	3000 rpm
delivered power:	130 kW or 175 HP
maximum operating speed:	3600 rpm

Mobility: Although the roll splitter as it is designed and built, is not suitable for testing in the field (refer to section D-iii for discussion on the matter), it can be towed by a mid-sized agricultural tractor on very good ground bearing conditions.

Rollers: The lower rollers were surfaced with 8 bars of teeth, spaced equally about their circumference, as illustrated in Figures 2 and 3. The bars of teeth resembled a saw tooth pattern and were flame cut from 5 cm thick steel plate. The teeth were 6 cm high, spaced 5 cm point-to-point on each bar. For self-cleansing of woody material, the bars of teeth were welded 17 cm apart. The upper rollers were covered with tread plates, providing a minimum of grip, and also making them smooth enough for good spreading of the crushed material.

Figure 1. Roll Splitter.



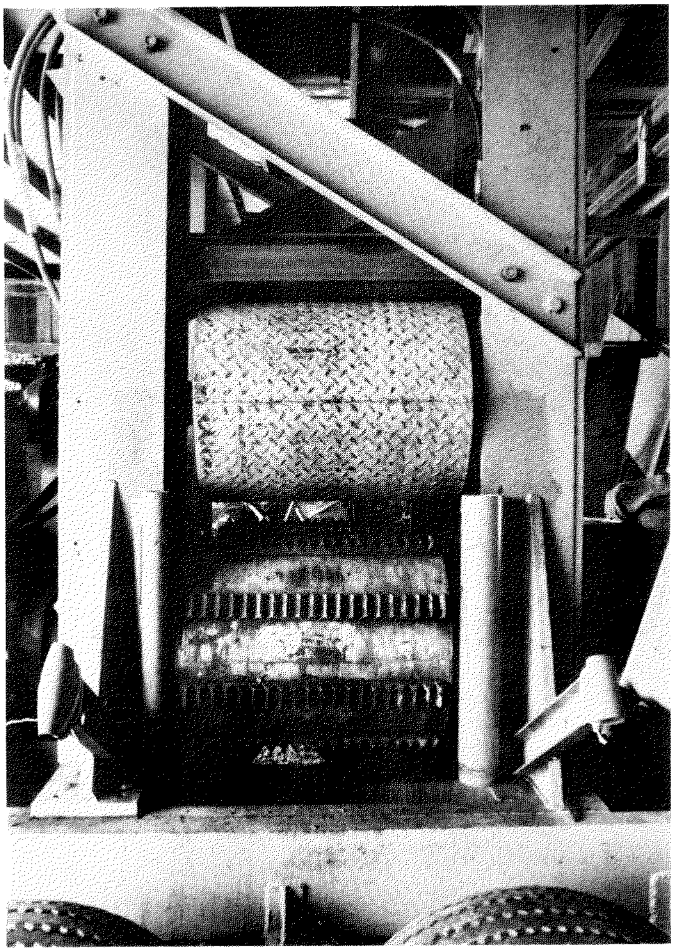


Figure 2.
Close View of the
Crushing Rollers.

Crushing-roller cylinders: Quantity: 4 Shaft bore diam.: 10.1 cm (4 inches). Generate a downward force on rollers to squeeze.

Layout: The basic layout and construction of the Roll Splitter allows easy access to pumps, motors, controls and other mechanical components. Pipe was welded to the front channels on either side of the infeed rollers, to act as a guard against material entering the space between the rollers and channels. A shielding panel was also added to protect the operator from hydraulic burns and abrasions in case of a hydraulic hose rupture.

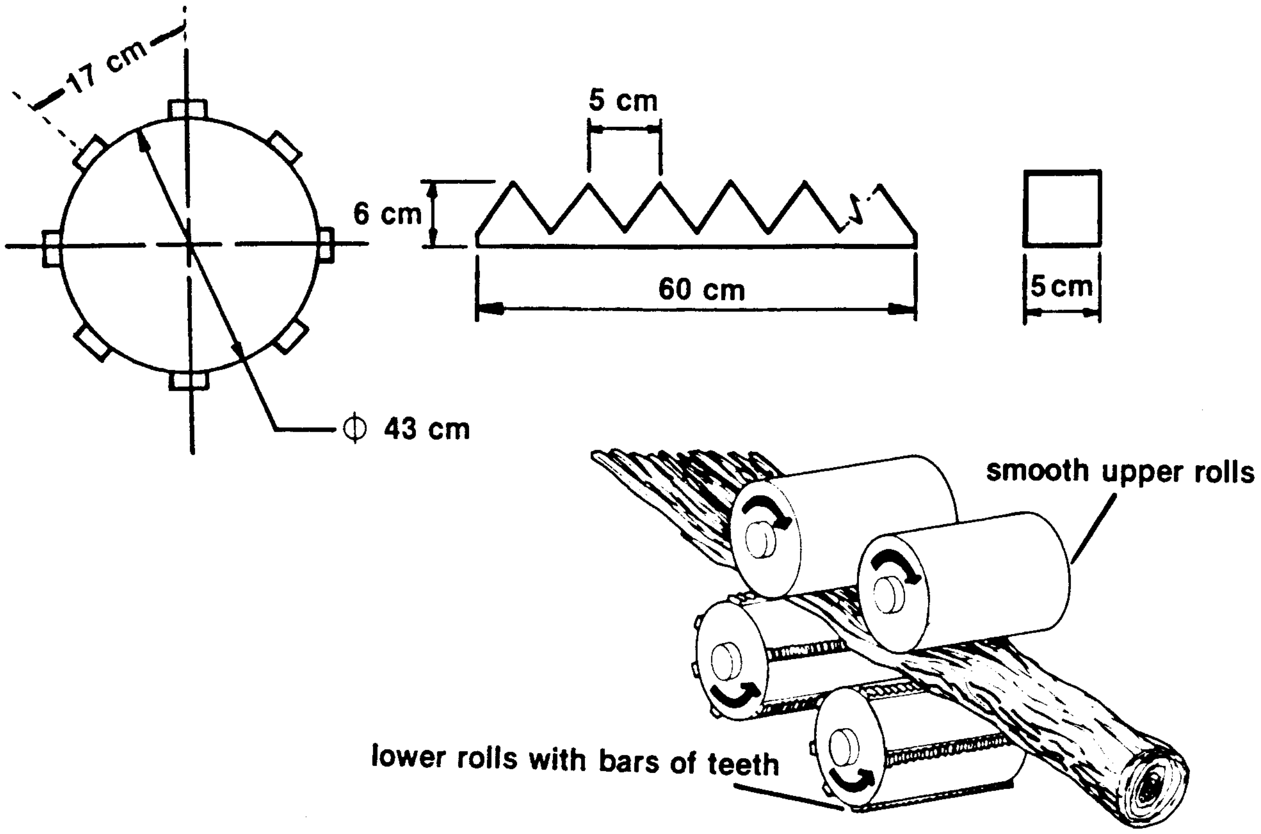


Figure 3. Tooth configuration of the lower rolls.

B. HYDRAULIC SYSTEM: OPERATING PRINCIPLES

The basic hydraulic system is simple, and a schematic is presented in Fig. 4. A Funk dual pump drive mounted to the engine flywheel assembly drives three hydraulic pumps operating the roll splitter. Two pumps are large variable displacement models (2.01 L/s or 32 gpm) mounted directly to the Funk drive. The third is a small fixed displacement pump (0.2 L/s or 3 gpm) mounted on one of the two large pumps.

One variable displacement pump drives the four hydraulic cylinders (10.1 cm - 4 in. bore by 20.3 cm - 8 in. stroke) and is equipped with a pressure compensator device that maintains constant pressure on the cylinders. That pump is mounted in tandem with the small pump, responsible for driving the hydraulic motors for the upper rollers. Hydraulic motors for the lower rollers are powered by the second variable displacement pump, featuring a load sensing control which maintains constant volume flow. The combined flow of the three pumps is 4.2 L/s at 20 685 kPa (3000 psi) continuous. The hydraulic reservoir capacity is 160 litres.

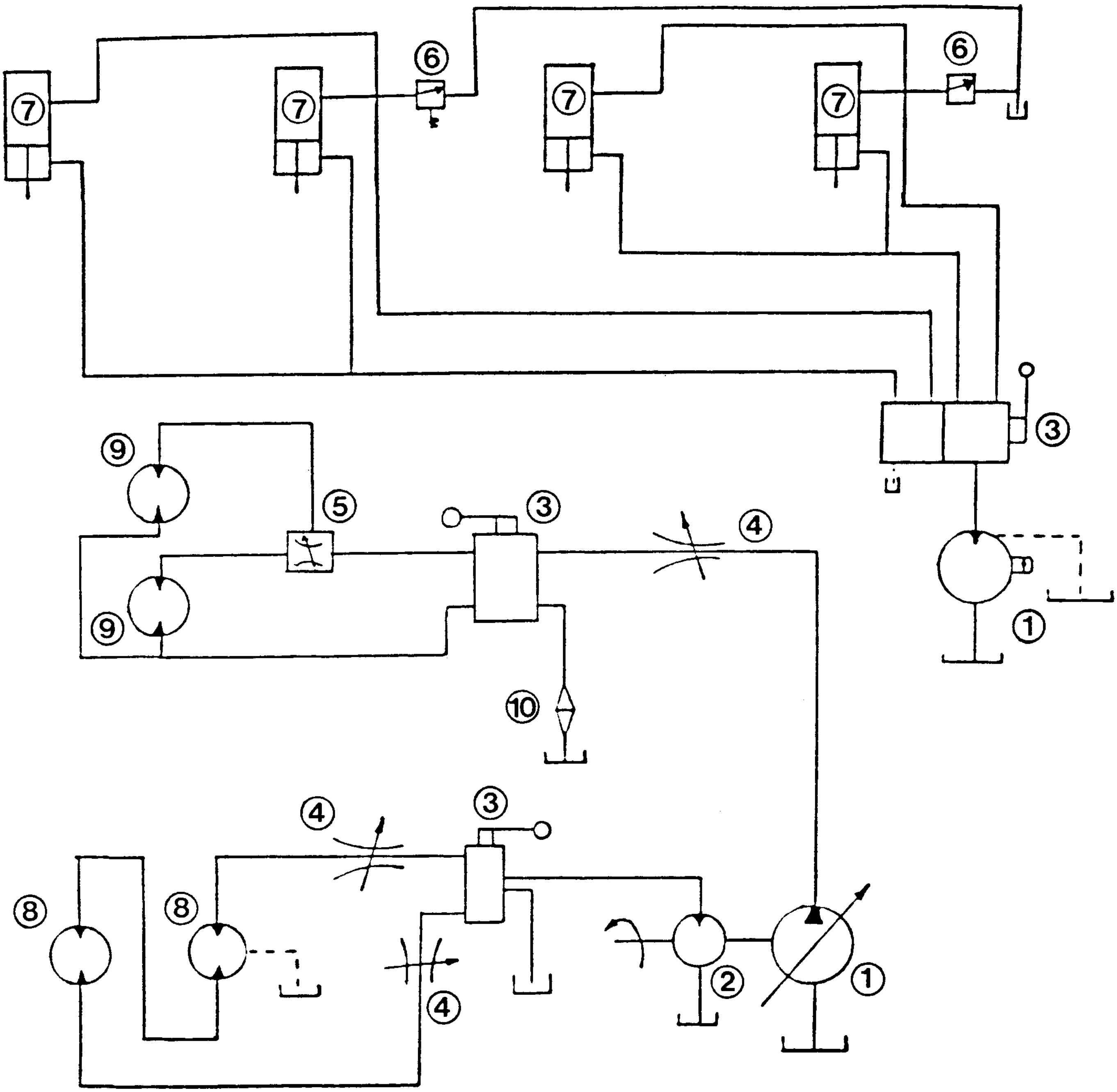


Figure 4. Hydraulic Schematic.

1. Pump, 2.0 L/s (32 gpm)
2. Pump, 0.2 L/s (3 gpm)
3. 4 way valve (single or dual spools)
4. Flow control
5. Flow divider
6. Relief valve
7. Hydraulic cylinder
8. Motor, upper roller drive
9. Motor, lower roller drive
10. Filter

Upper Rollers Drive

The upper rolls are directly driven at the same speed by identical motors connected in series. A four-way valve allows the flow to be reversed. One-way flow restriction valves in the motors supply and return lines make the roll speed variable from 0-80 rpm.

Lower Rollers Drive

Each motor driving the lower rolls is supplied by one leg of a complete variable ratio flow divider (0-100%) as shown in Figure 4. In this manner, the roll surface speed ratio between the front and rear rolls is infinitely adjustable. A four-way valve upstream from this divider makes both rolls simultaneously reversible. Preceding the 4-way valve, a flow control valve permits a variable flow of oil delivered over a complete range while maintaining full pressure. The reduction gear boxes provided a ratio of 45:1 for the front roller and a ratio of 37.4:1 for the rear roller.

TEST PROCEDURES

Test procedures varied slightly from one test to another. Provided below is a short description of each procedure. It is intended to show testing methods utilized, and in some cases those which proved unreliable, for guidance in future tests.

Cutting wood: Bolts purposely cut for tests, were collected in the morning and usually crushed in the afternoon. They were taken from residual trees left in a clearcut site. Trees were marked with a measuring stick, sectioned every 1.8 m and then loaded on a pick-up truck. Red maple was knottier and had a more irregular tree form than the other two species, particularly in the upper stem sections. Bolts having either an accentuated bend, numerous knots, an irregular taper form, or a rotten core, were kept solely for demonstration or visual observations, and were not included in tests.

Initial data: At the testing site, bolts were numbered, remeasured and marked precisely at 1.7 m from one-end. The excess length was trimmed in two cuts, so that a sample disk at least 3 cm thick was taken. This disk was sealed at once in a plastic bag, for determination of moisture content via the oven-dry method. Samples were oven-dried at 104^{o}C until stabilization of weight.

Crushing: An average of 20 to 25 bolts were processed on every shift (8 hours). Although two persons can manage to do all the work, a three-man crew is much more efficient; one working at the controls, one feeding the rollers and one collecting the residues for after-crushing weighing. Feeding was done manually. The operator would lower the upper roller only when the first end of the bolt was well over the top of the bottom roller. Consequently, the first 10-15 cm section of the bolt was not very well crushed and after processing it would act like the neck of a broom in retaining all the slivers. If the gap between the infeed rollers was set smaller than the diameter of the bolt, the bolt would often not be engaged by the rollers, hence causing delays, inaccurate switch-ons of the monitoring instruments and increasing the hazard of the operation. Concentration and attention are required from the operator to manipulate controls and recording instruments. It is preferable that the operator be the same person throughout the testing period.

Fuel consumption: The fuel consumption was measured with a Pierburg Plu Type 106 flowmeter. Consumption data were expressed in cubic centimeters with an accuracy range of 2 to 5%. Specific gravity of the fuel was also recorded to determine the mass of fuel consumed. A hydrometer for standard (60^{o}F) specific gravity and a thermometer were used for that purpose.

A timer was fixed on the indicator instrument so that a single switch would activate simultaneously the flowmeter and the timer.

Dewatering: From early tests, it was found that the most reliable method to estimate the loss of water throughout the crushing process was simply to weigh each bolt before and after crushing. In theory, the difference represents the loss of water but, in practice, we can only get a near estimate of it.

Plastic sheets were placed under the rollers and at their exit to ensure that all fragments were collected. After the crushing of each bolt, the rollers were cleaned of small loose particles, and a general check-up of the different parts (frame, channels...) was carried out to be sure no sizeable pieces were forgotten.

Obviously, it was nearly impossible to gather all the tiny pieces that stuck to wet metal parts. The plastic sheet underneath the rollers was removed and the free water from crushing allowed to drip off. The resulting fragments were added to the crushed bolt for weighing. A small portion of the extracted water was weighed with the residues, but the added water should compensate for any loss of woody fibers.

Another method to measure the mechanical dewatering was tried, but proved unreliable. It consisted of taking a cross-section sample from the crushed material. In several cases, this procedure produced the unexpected result of an increase in moisture content whereas some water had obviously been squeezed out. This pointed out the likelihood that water was transferred within the wood structure, making the moisture content very irregular in the crushed material.

Air drying: Evaluation of the drying potential of the crushed material was somewhat limited by the existing facilities. It soon became evident that the manipulation of several bolts at one time was cumbersone and could not guarantee reliable data, even though evaluating the drying of a mass of residues would have been more realistic. Consequently, drying was assessed on an individual bolt basis. Each bolt (plus the fragments) was laid on a plastic sheet (1 x 1.5 m) and left on the gravelled ground when under cover, and on a wood pallet when sun-exposed.

Pallets were used to eliminate the effects of run-off and puddles created during heavy showers. Bolts were laid out side by side, fairly close to each other, with the plastic folded under. For most tests, bolts were weighed each day for a week and on the 10th day after being crushed. Weight of plastic sheets were also recorded in order to determine net weight of residues.

Quality of roll-crushed material was rather difficult to define, since quality could refer to criteria of different aspects of the roll-crushed material, such as degree of fiberization, size and flexibility of comminuted material, moisture loss, etc. In this report, quality of splinters, of crushed material or of roll-crushing, will refer to the degree of fiberization of the wood bolts, or in other words, to how well wood bolts were comminuted into splinters, slivers, fibers or any technical term describing long particles.

However, quantifying the quality of crushed material through a simple, rapid and reliable method was not feasible. When it appeared necessary to document the effects of factors such as roller speeds and crushing forces on the quality of crushed material, the air-drying rate of the material was recorded. It was then hypothesized that better crushed material would also dry out more rapidly in the same drying conditions.

RESULTS AND DISCUSSION

Test results were grouped into four sections, in accordance to specified objectives of the evaluation:

A. Mechanical Dewatering
B. Air Drying Potential
C. Energy Requirements
D. Mechanical Considerations

Some of the testing may not be considered overly scientific because of limitations in sample sizes. Despite the limited amount of data, the results coincide with our observations.

For sake of clarity, details of statistical tests were omitted. One-way analyses of variance were carried out for treatment comparisons at the 5% level, with results being either significant or non-significant (very significant if at the 1% level). As for most scattered plots, a polynomial regression routine was performed. Regression curves were plotted in the sole cases where a high correlation factor existed.

A. MECHANICAL DEWATERING

For each species, dewatering results for bolts processed under similar hydraulic settings have been grouped and are presented, as well as a description of test samples, in Table 1. Both the roller speeds and pressures were adjustable, a desirable feature when using various tree species. The hydraulic settings in this experiment were as follows:

Yellow Poplar:
- roller speeds - outfeed rollers running slower than the infeed rollers
- crushing pressure - low to medium (4825-6205 kPa or 700-900 psi)

Red Maple:
- roller speeds - outfeed rollers running slightly faster than the infeed rollers
- crushing pressure - medium-high (6895-8275 kPa or 1000-1200 psi)

Loblolly Pine:
- roller speeds - outfeed rollers running slightly faster than the infeed rollers
- crushing pressure - medium (5515-6895 kPa or 800-1000 psi)

Table 1 presents a summary of dewatering results and a description of the test samples. The similarity of results between yellow poplar and loblolly pine is apparent. Both species have a low relative density, a high moisture content and high dewatering values. On the other hand, the red maple shows less impressive dewatering figures as it has a higher density and a lower moisture content. For spot observations, high density-species like oak were also processed but almost no splitting and dewatering resulted.

The wide range between minimum and maximum values in moisture content reduction (Table 1) implies that the effectiveness of the Roll Splitter in removing water is affected by several factors. Those listed in the following review were considered important and influential in the experimental framework.

Tree Species

Although the number of species that were crushed either for observation or for collection of data was very limited, it appeared that each species had a different dewatering pattern. Loblolly pine lost most of the extracted water at the crushing point whereas red maple water was primarily pressed out the end of the bolt. Yellow poplar exhibited a more balanced distribution of water loss between these two points. Relative density and grain structure (pores distribution) of the species may have played an important role in the dewatering process. Figures 5 and 6 show the mechanical dewatering of a loblolly pine bolt as the end of the bolt is being crushed by the infeed rollers.

Initial Moisture Content

Reduction in moisture content by crushing is greater for bolts with high initial moisture content. This is especially true for yellow poplar (Fig. 7). A similar conclusion is less obvious for red maple or loblolly pine, since the range of percent moisture loss is greater for these two species.

Size of Bolt

Effective crushing and dewatering are achieved simultaneously only up to a certain diameter which varies with species. Although it depends firstly on machine capacity or ability to crush, relative density is a factor limiting maximum diameter. For instance, a low density species such as yellow poplar has a higher upper limit of diameters which can be processed than that of red maple.

Table 1. Summary of dewatering results and description of test samples.

		Yellow Poplar	Red Maple	Loblolly Pine
Diameter (cm)	$\tilde{x}$*	10.3	9.2	10.8
	s.d.	1.8	1.6	2.2
	min.	6.9	6.1	6.1
	max.	15.5	12.9	16.4
Basic relative density	$\tilde{x}$	0.362	0.512	0.379
	s.d.	0.025	0.039	0.070
	min.	0.325	0.416	0.267
	max.	0.421	0.614	0.450
Green moisture content (%) (dry basis)	$\tilde{x}$	121.9	76.7	144.6
	s.d.	11.0	9.7	25.4
	min.	99.5	54.9	99.5
	max.	146.7	117.0	202.0
Moisture content change(%)	$\tilde{x}$	9.9	5.3	9.0
	s.d.	4.3	1.7	4.0
	min.	0.1	1.6	2.6
	max.	18.0	9.3	20.9
Green weight (kg)	$\tilde{x}$	11.931	10.750	14.872
	s.d.	4.418	3.885	5.533
	min.	4.363	4.545	4.681
	max.	24.815	19.543	30.315
Weight change (kg)	$\tilde{x}$	0.569	0.326	0.552
	s.d.	0.304	0.153	0.308
	min.	0.022	0.068	0.308
	max.	1.136	0.727	1.681
Number of samples		70	76	83

* $\tilde{x}$ = mean
s.d. = standard deviation

When considering dewatering alone, Figure 8 shows that more water is likely to be lost with larger diameters until the crushing capacity of equipment is approached. Figure 9 points out the range of diameters where the highest proportion of water loss occurred. That range falls approximately between 9 and 13 cm.

Beyond the 13 cm diameter point for yellow poplar, the relative amount of water liberated diminishes as the equipment lacks sufficient mechanical power to crush the bolt to the same degree as those in the middle range of diameters. Few bolts over 13 cm in diameter were processed because machine limits were perceived early in the tests. At less than 9 cm in diameter, the amount of water liberated also decreases because of the open configuration of toothed bars and the minimum gap opening possible between the upper and lower rollers. This created a continuous high and low pattern of the crushing forces that was amplified with smaller bolts. The relationships between mechanical dewatering and diameter, as demonstrated by yellow poplar, also apply to loblolly pine and red maple, though not so markedly.

Degree of Knottiness

Knottiness is a very important factor. Knots are very difficult to crush and are mostly only cracked in the process. Groups of knots are even more of a problem. Dewatering is definitely not as good with knotty bolts. When stalling occurred, the operator had no choice but to lift either upper roller, or both. Moreover, quality of crushing suffers and fuel consumption notably increases. Red maple proved to be much knottier in our tests than the other two species, for it had a smaller proportion of its boles clear of knots. Even though we do not have figures supporting the fact, this may very well be one of the reasons red maple shows low dewatering results.

Ability of the Operator

All operations with the Roll Splitter prototype are manually done. The machine operator required good reflexes to control both sets of rollers, the switch activating the timer and the fuel consumption recorder. Because attention, concentration and practical experience were required, the operator remained the same throughout the whole testing period.

The Crushing Force and the Roller Speeds

These two parameters have direct influences on the dewatering, and are discussed in detail in Section D.

With such a variety of factors inherent in our tests, it is difficult to draw specific conclusions about any single factor. It also partly explains why results may vary to some extent from one test to another.

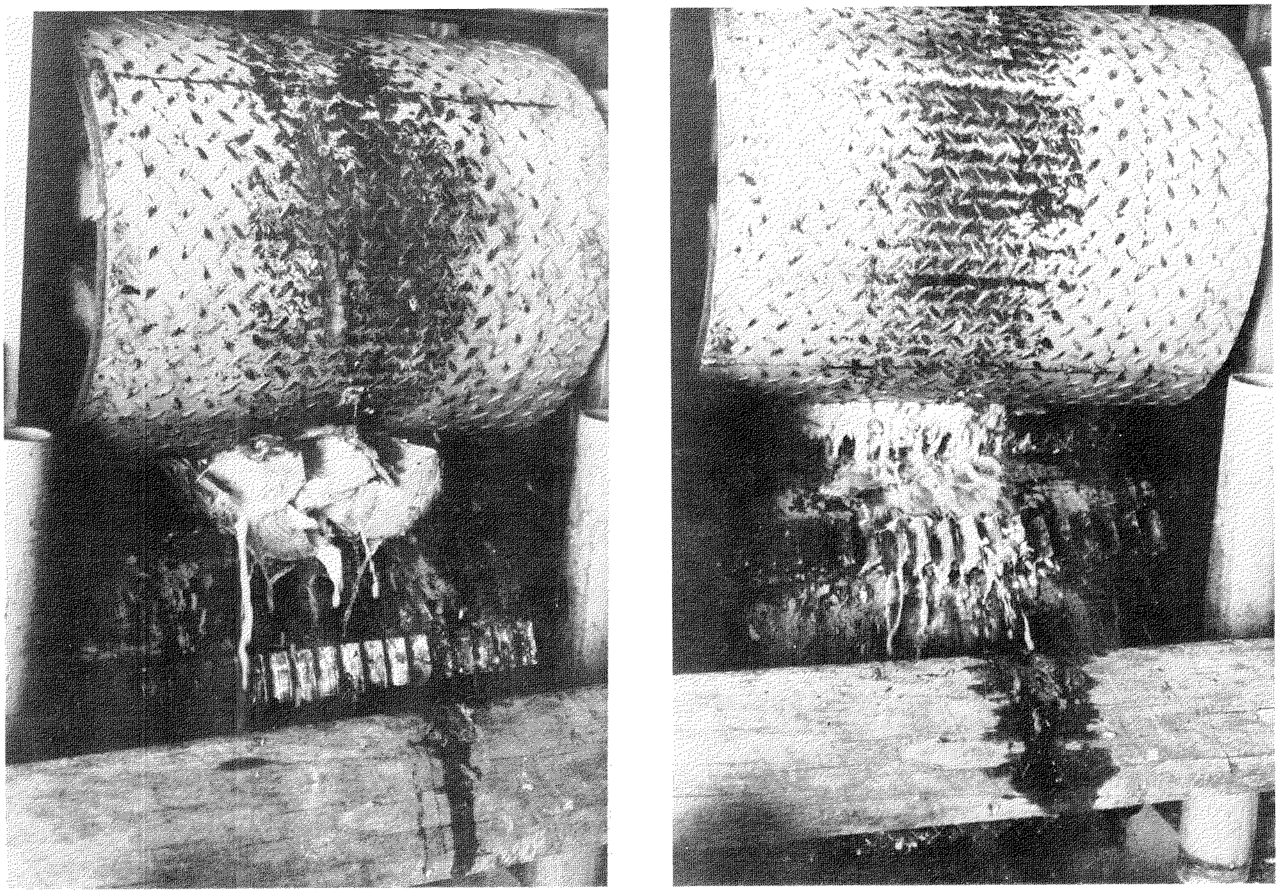


Figure 5 and 6. Dewatering action from loblolly pine.

Table 2 shows dewatering results for different versions of the Roll Splitter. A brief analysis would indicate that the addition of a second pair of rollers has improved the dewatering. Considering the associated increase in initial moisture content, and the fact that the methods used to estimate the dewatering differ in each case, it is presumptuous to cast any conclusion. Therefore a series of bolts was processed using only the input rollers with the output rollers remaining idle, followed by a series of bolts processed with both pairs of rollers. This test was done on yellow poplar and red maple. Figures 10 to 13 illustrate bolts after crushing and the test results are summarized in Table 3. In the case of yellow poplar, the evident difference in the quality of roll crushing between single and dual pairs of rollers appears clearly in the pictures, and is reinforced by Figure 14 which shows the evolution of the moisture content of crushed material following air-drying.

There is an increase of over 50% in the change of moisture content of yellow poplar bolts with the addition of a second pair of rollers. Surprisingly with red maple, the two sets of data do not differ statistically, either in the dewatering or in the quality of crushing when measured through the air-drying rate. This may be an important indication that the concept of dual roll-crushing has limitations dependant on size and species to be processed.

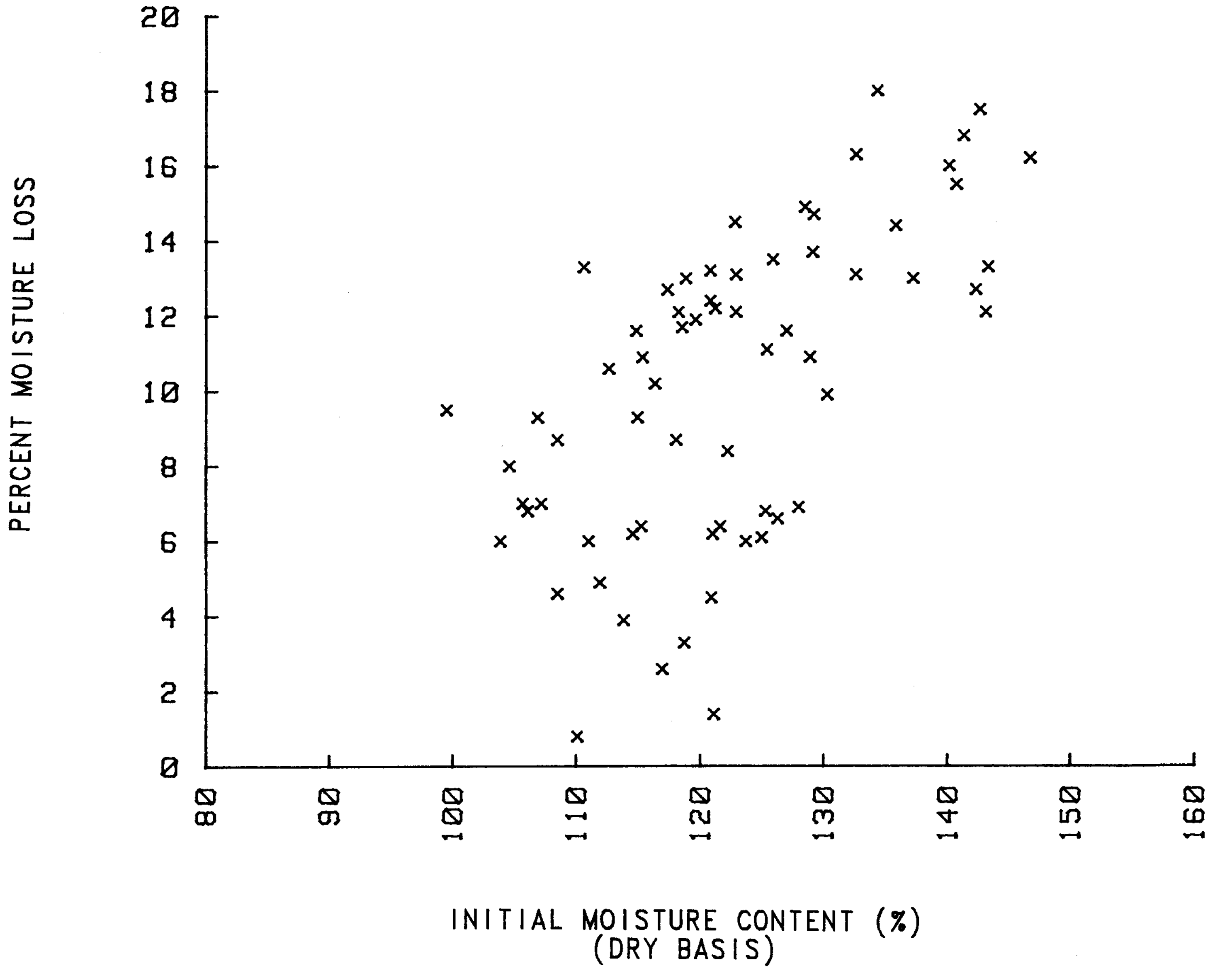


Figure 7. Percent moisture loss from roll-crushing vs initial moisture content (%). Dry basis -- yellow poplar.

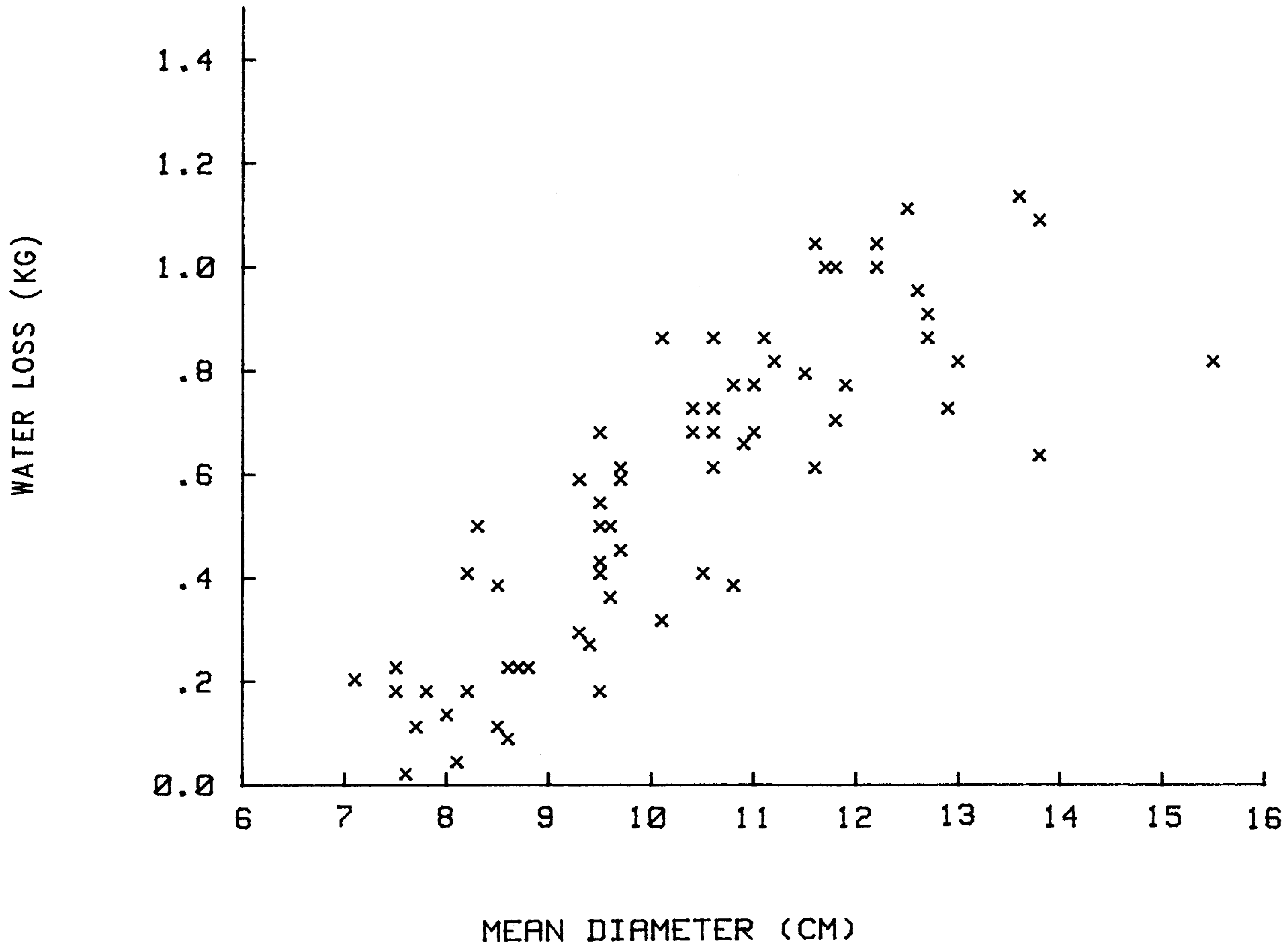


Figure 8. Loss of water from roll-crushing vs mean diameter (cm) - yellow poplar.

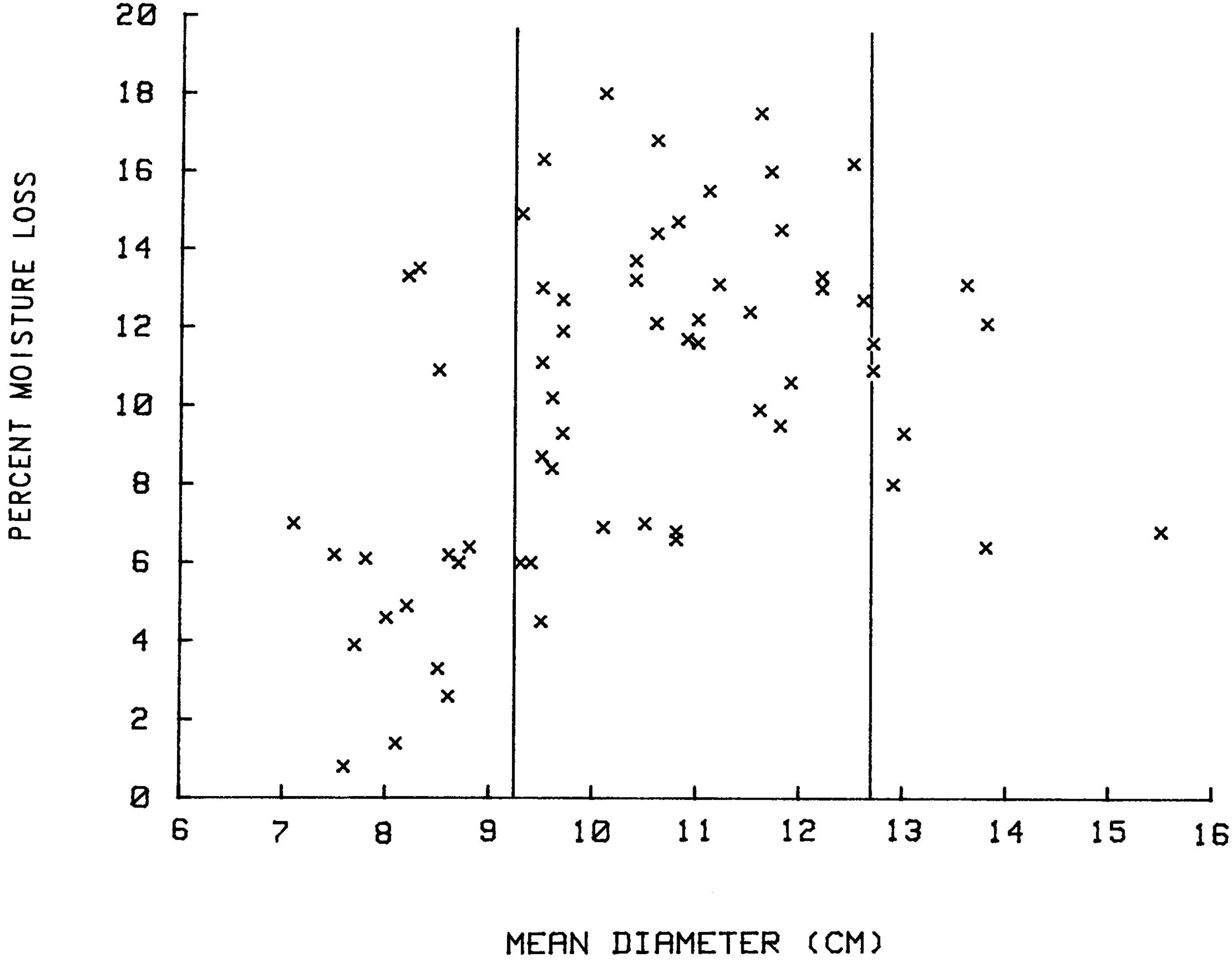


Figure 9. Percent moisture loss from roll-crushing vs mean diameter (cm) -- yellow poplar.

Table 2. Comparison of dewatering results between different versions of the Roll Splitter.

	Aspen/Yellow Poplar		Red Maple	
	Initial moisture content (%)	Change of moisture content (%)	Initial moisture content (%)	Change of moisture content (%)
Roll Splitter (TVA's modified) One pair of rollers	100	6.3	70	3.6
Roll Splitter One pair of rollers (Axe - like teeth)	Results not available - (winter tests)			
Roll Splitter Dual pairs of rollers	122	9.9	77	5.3

Table 3. Mechanical dewatering––Single pair vs. Dual pairs of rollers.

Species	# Pairs of Rollers	Number of Bolts	Mean Diameter (cm)	Mean Green Moisture Content (%)	Percent Moisture Loss	Statistics	
Yellow Poplar	1 2	7 9	10.2 9.1	96.2 98.0	4.1 6.9	F ratio F prob.	10.122 0.007
Red Maple	1 2	8 8	9.0 9.0	84.4 84.1	4.5 4.4	F ratio F prob.	0.036 0.852

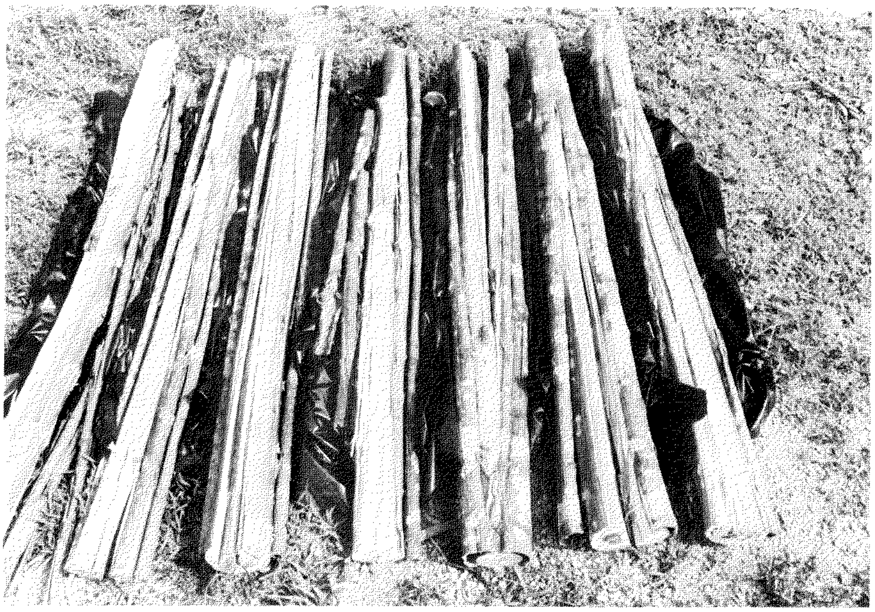


Figure 10. Yellow poplar bolts crushed with a single pair of rollers.

Figure 11. Yellow poplar bolts crushed with two pairs of rollers.

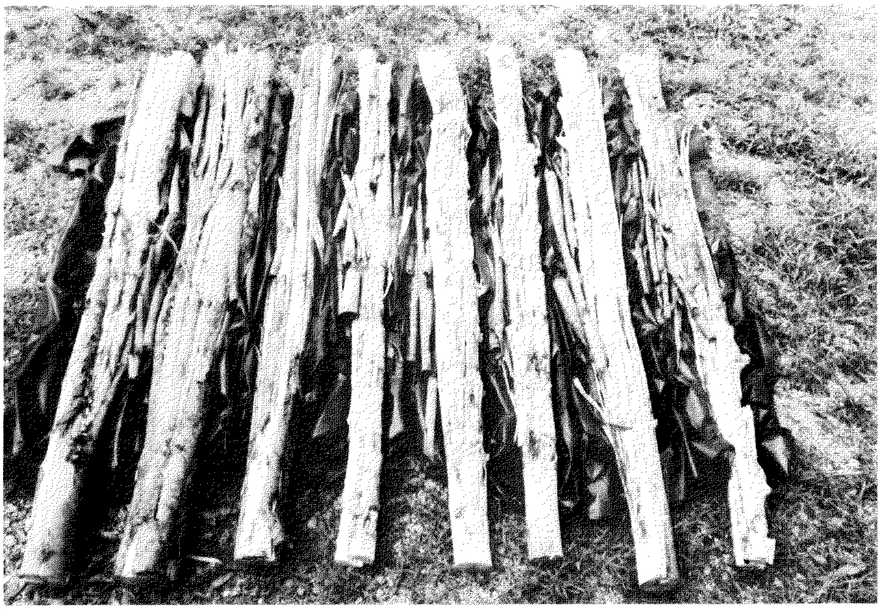


Figure 12. Red maple bolts crushed with a single pair of rollers.

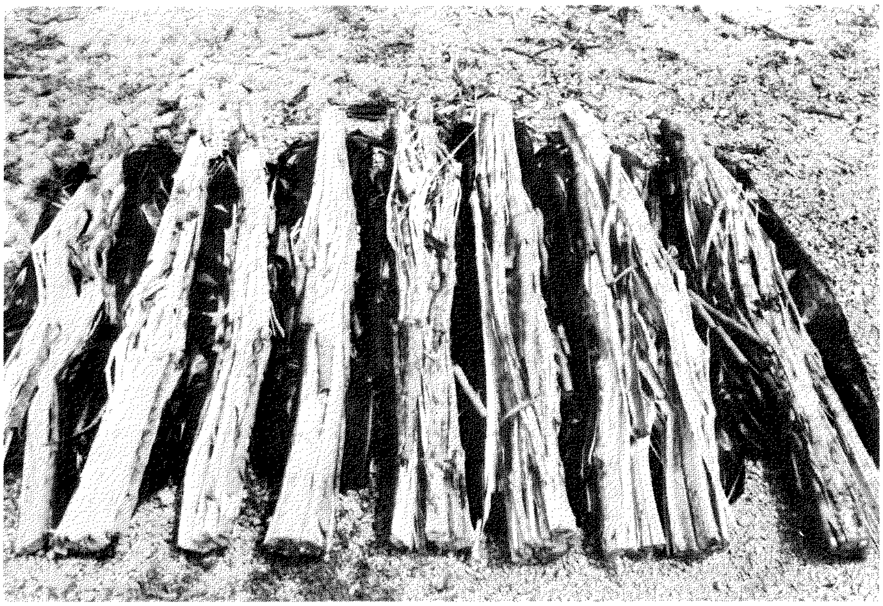


Figure 13. Red maple bolts crushed with two pairs of rollers.

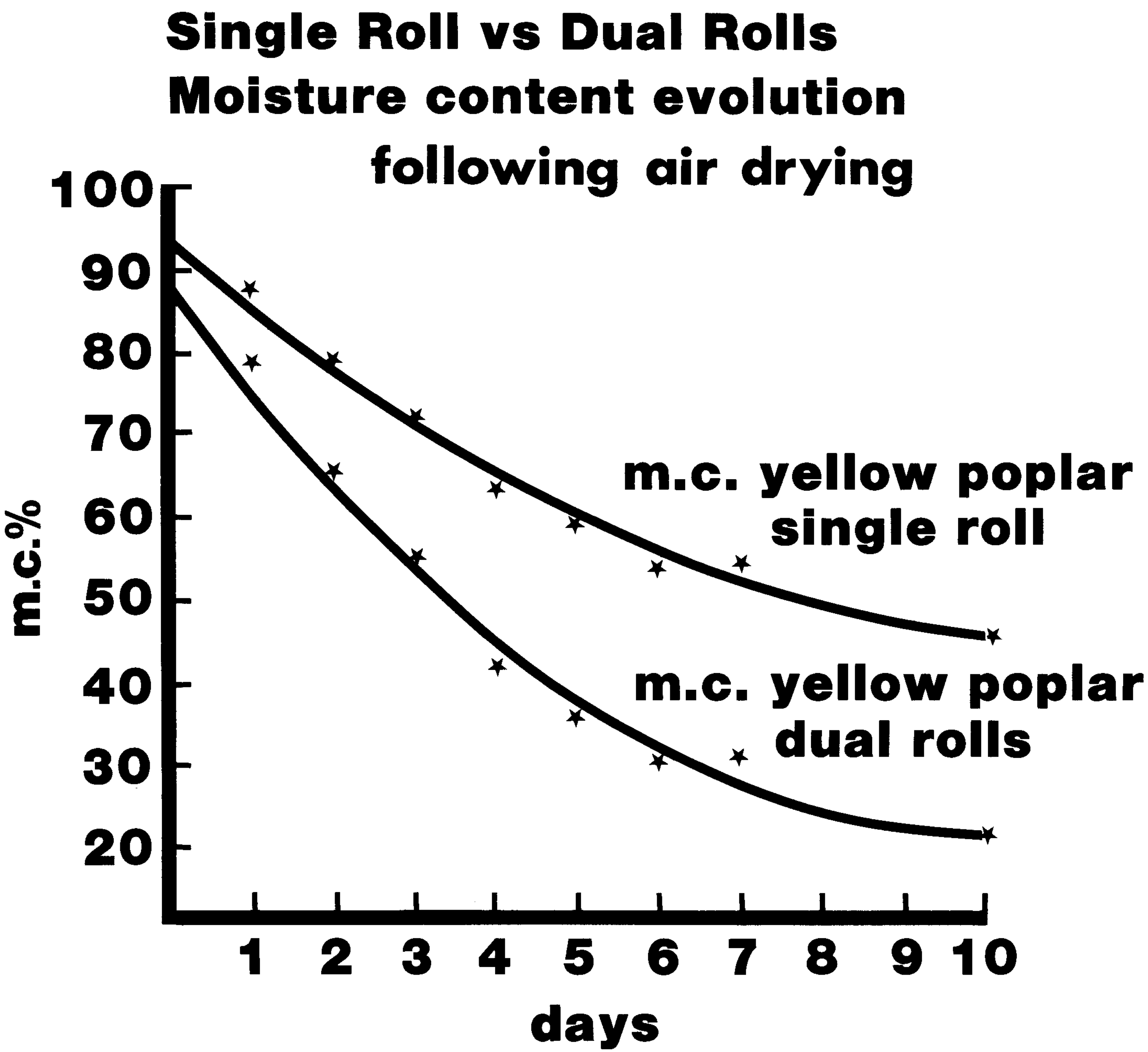


Figure 14. Single Roll vs Dual Rolls Moisture content evolution following air-drying.

B. AIR DRYING POTENTIAL OF CRUSHED MATERIAL

Transportation and conversion into energy of comminuted woody material are two important stages in the use of biomass for energy. The drying of comminuted material is therefore doubly beneficial. Not only does the reduction in moisture content lower transportation costs, but it also significantly raises the calorific value of the material. Moreover, in the event of further comminution, several techniques (e.g. hammer milling) require less energy with drier materials (below f.s.p.).

In order to assess the drying potential of roll-crushed material, an attempt was made to define a simple and accurate method to measure either weight or moisture content. The manipulation of a mass of crushed bolts being impractical in the existing conditions and moisture content sampling being too unreliable, it was decided to appraise the rate of drying by weighing bolts individually.

One specific test consisted of crushing 8 bolts of each of the three species under constant mechanical parameters (roller speeds, crushing forces). The crushed bolts were then laid out on pallets for air drying in the sun, along with two uncrushed bolts of each species as controls. The maximum daily temperature for the ten-day period averaged 29.4^{o}C (84.9^{o}F) and relative humidity at noon averaged 68%. It rained on the 8th, 9th and 10th days. Figures 15 and 16 show the evolution of the total weight and moisture content for the 8 bolts of each species during the period. Total weights of bolts acting as controls are plotted in Figure 17. The following observations can be inferred from these figures.

i) The initial moisture content seemed to be a predominant factor in the potential loss of water through air-drying. After five days (see Table 4), bolts had lost most of the water they were going to lose; and after 7 days, weight and moisture content tended to stabilize. These results clearly show that roll-crushed material can lose moisture at a high rate.

ii) The high values of the 10th day point out that while the crushed bolts can dry out quickly, they can also absorb moisture rapidly during wet weather.

iii) Water loss with controls is negligible compared to the drastic evaporation with crushed material.

In a similar test, in which after two days of ideal drying conditions we had to stop collecting data because of heavy showers, results summarized in Table 5 show an ever higher drying rate.

Table 4. Reduction of water after 5 days—-air drying with sun exposure.

	Total mass of water evaporated for the 8 bolts, in kg	Water loss per bolt (kg)	Water loss (kg) per oven-dried ton of material	Reduction of moisture content underwent (%)
Yellow poplar	41.97	5.20	905	90.5
Loblolly pine	41.54	5.19	855	85.5
Red maple	21.61	2.70	505	50.5

Table 5. Change of moisture content and equivalent loss of water per bolt—-air drying with sun exposure.

	DAY (1)	DAY (2)	
Yellow poplar	38.4%	23.6%	change of moisture content - average per bolt
Red maple	19.4%	11.1%	
Yellow poplar	1.99 kg	1.29 kg	equivalent loss of water - average per bolt
Red maple	1.20 kg	0.76 kg	

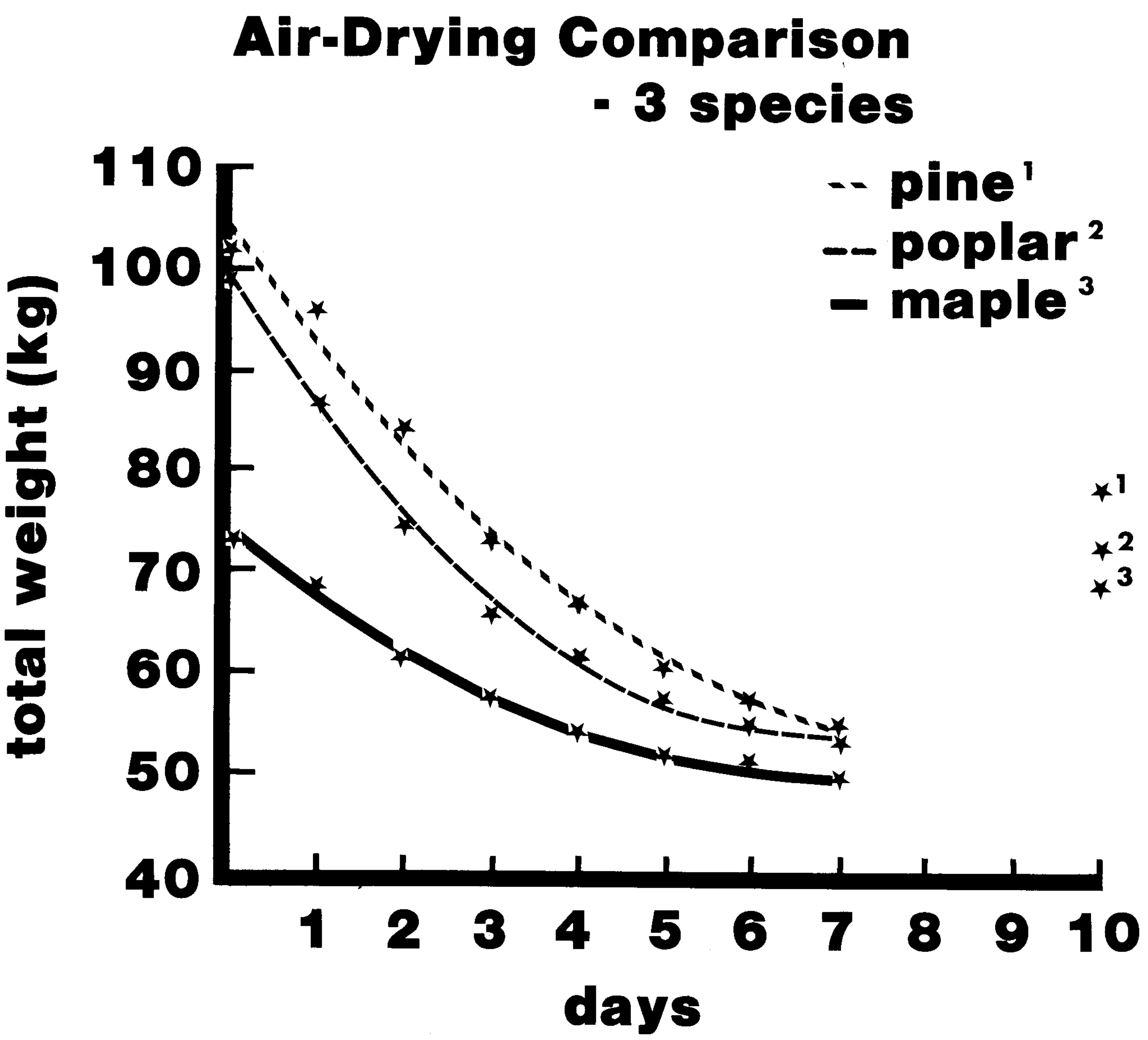


Figure 15. Comparison of air-drying rate for three species of roll-crushed material--total weight.

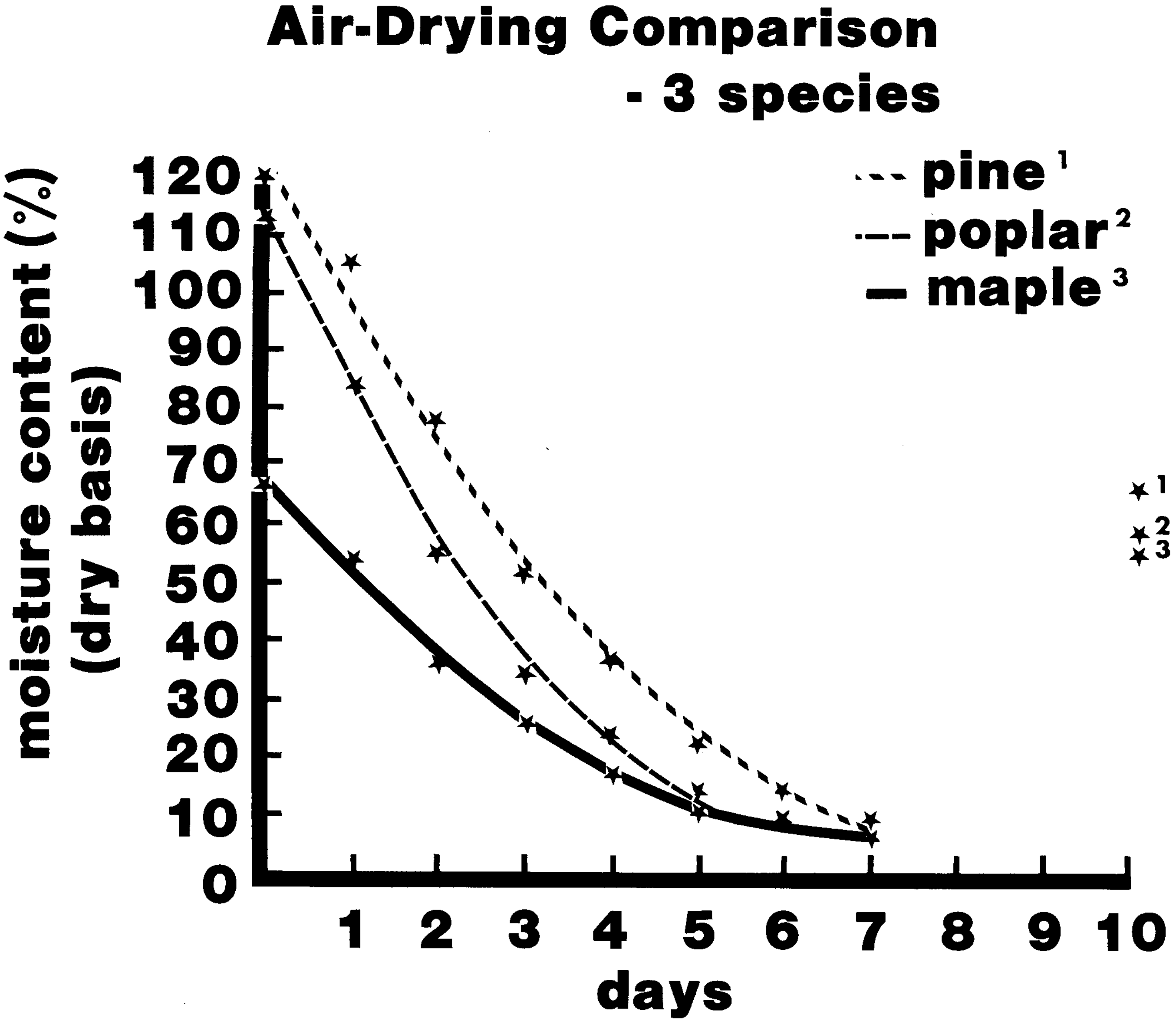


Figure 16. Comparison of air-drying rates for three species of roll-crushed material--moisture content.

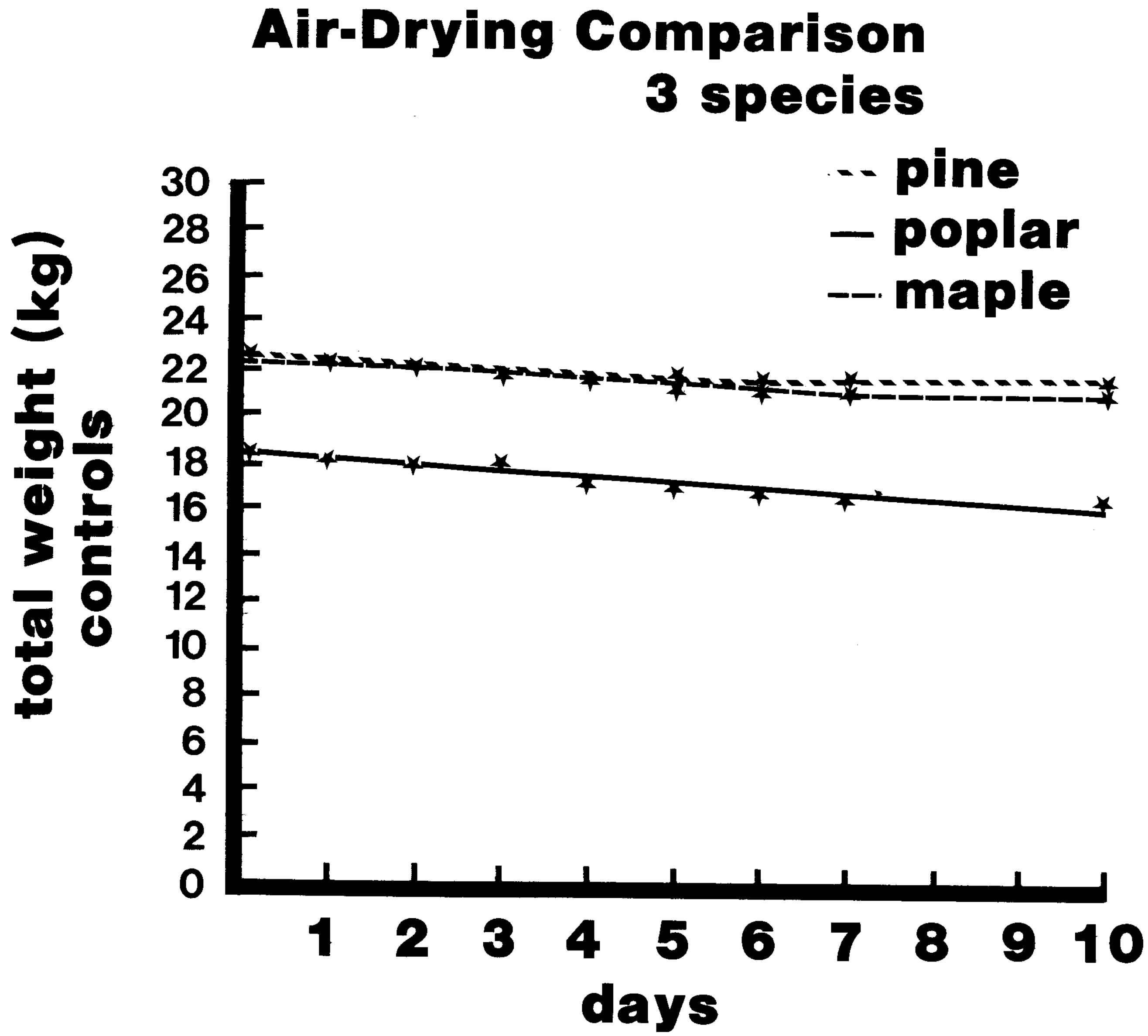


Figure 17. Comparison of air-drying rates for controls of three species--total weight.

C. ENERGY REQUIREMENTS

1. Comminution Energy

As roll-crushing is one step in the processing of biomass material for energy production it is important to estimate the input of energy in the transformation, at this point. In order to compare the energy requirements of the different models of the roll splitter or even of different comminution techniques, we selected the approach used by K.C. Jones [4] in his evaluations.

The energy requirements of roll splitting are described in terms of Machine and Cycle energy requirements as first proposed by Gasslander, Mattson and Sunberg.

Machine comminution energy (MCE) refers to the energy consumed by the working tools. It is equal to the total measured energy consumption less the no-load energy consumption rate times the processing time. It is expressed in terms of Magajoules per Oven Dry tonne (MJ/ODt) of material processed:

$$E_M = (E_{TOTAL} - E_{NO\ LOAD} \times T)/Wd$$

where:

E_M = Machine energy

E_{TOTAL} = Total measured energy consumption

$E_{NO-LOAD}$ = Energy consumption rate at no-load

T = Total time to process

Wd = Dry weight processed

The Machine energy level is the most reasonable one at which to make comparisons between different processes. Beyond this level, material handling aspects and no-load energy consumption rates particular to prime mover types and individual machine designs come into play. In most cases these elements account for a higher percentage of energy consumption than do the working tools themselves.

Cycle comminution energy (CCE) refers to the total measured energy consumed during processing and includes the no-load energy consumption of the machine. It too is expressed in terms of MJ/ODt.

The energy consumed as a function of the roll splitter's dewatering ability is also expressed at the Machine and Cycle energy levels; but more properly in relation to the weight of liquid extracted, MJ/kg of water.

Table 6 summarized test results on energy requirements for three species. These results should be looked upon with some reserve. Although the accuracy of overall instrumentation cannot be stated exactly, it is believed to be within 10% of the actual values. However, the range of values well illustrates the level of energy requirements. CME values averaged 115 MJ/ODt for yellow poplar, 139 MJ/ODt for loblolly pine and 187 MJ/ODt for red maple. This last species produced the highest CME average, but as it presents neither the largest mean diameter nor the largest mean crushing time among the three species, its higher density and knottiness may account for this result.

Table 6. Summary of test results--energy requirements.

		Yellow Poplar	Red Maple	Loblolly Pine
Diameter (cm)	$\tilde{x}$	10.9	9.4	12.1
	s.d.	1.8	1.9	2.1
	min.	8.3	6.9	8.0
	max.	15.5	13.0	16.4
Comminution cycle energy (MJ/ODt)	$\tilde{x}$	622	732	630
	s.d.	171	223	169
	min.	330	413	408
	max.	1043	1300	1060
Comminution machine energy (MJ/ODt)	$\tilde{x}$	115	187	139
	s.d.	26	52	41
	min.	63	105	70
	max.	157	283	261
Dewatering cycle energy (MJ/kg H_2O)	$\tilde{x}$	6.1	15.5	9.0
	s.d.	4.0	5.1	4.8
	min.	3.4	7.7	3.5
	max.	20.2	26.2	20.9
Dewatering machine energy (MJ/kg H_2O)	$\tilde{x}$	1.1	4.0	2.0
	s.d.	0.7	1.3	1.1
	min.	0.6	2.0	0.5
	max.	3.4	6.3	5.9
Crushing time (s)	$\tilde{x}$	13.69	14.18	16.30
	s.d.	1.73	2.45	2.72
	min.	10.69	10.55	11.13
	max.	18.75	21.41	22.46
Number of samples		32	32	32

Table 7 compares the energy requirements of different versions of the roll splitter. Because the first version's energy requirements were derived from an electric motor drive system whereas the others were from gas engines, prime mover energy conversion efficiencies must be taken into account when contrasting comminution energy figures. We have assumed 30% and 85% energy conversion efficiencies for electric and gasoline engines respectively. In interpreting these results, one must be careful to keep in mind that the construction of the dual roll splitter lacked optimization in design, for various reasons. The ratios MCE/CCE implies that a lesser proportion of energy available is used for comminution itself with the dual roll splitter. The MCE for the third version is roughly twice that of the first one, which is not very surprising since the dual roll splitter has evolved in a little more sophisticated hydraulic machine than the other two, with double the number of rollers, etc.

Table 7. Energy requirements for different versions of the Roll Splitter.

	Cycle comminution energy (MJ/ODt)		Machine comminution energy (MJ/ODt)		Ratio MCE/CCE
	Aspen/ Yellow Poplar	Red Maple	Aspen/ Yellow Poplar	Red Maple	Red Maple
Roll Splitter (TVA's modified)	33	46	23	32	1:1.4
Roll Splitter* (axe-like teeth)	52	43**	not available		
Roll Splitter* (dual rollers)	219	258	40	66	1:3.9

* adjusted with electric and gas efficiency ratios
** White Birch

In Table 8, MCE for dual roll splitting is compared to pulp chipping and hogging MCE values. Dual roll splitting MCE requirements are approximately 8 times those of pulp chipping. This ratio is considerable since dual roll splitting cannot be regarded at this stage, as a final comminution process. However, Table 9 demonstrates that the amount of energy (CCE) input in roll splitting is still a small fraction (3-5%) of the recoverable heating value of dry wood.

Table 8. Machine comminution energy (MJ/ODt) for different comminution techniques from K.C. Jones [4] and Papworth [7].

	oak	hemlock	loblolly pine	maple	Aspen/ yellow poplar
Pulp chipping	20	16		22.6	16.9
Hogging-hammermilling	240	100			
Dual roll splitting			49	65	40

Figures 18 to 21 supplement Table 6 for interpretation of the energy consumption by species. Mean diameters and the mean green weights of bolts among the three species are different, and consequently, their CCE and MCE values follow similar variations.

In Figure 18, even though we cannot sort any specific trend to a single species, there is a predominant overall trend, by which we can state that bolts under 12 cm in diameter are likely to require proportionally more comminution energy. Differentiation among the three species appears more clearly in Figure 19 where dry weight of bolt replaces diameter on the horizontal axis. Therein, the CCE values of yellow poplar are consistently lower than those of red maple, whereas CCE values of loblolly pine overlap the fields of points of the other two species.

Figures 20 and 21 on machine comminution energy reinforce the differences between yellow poplar and red maple. It is worth noting that the distribution of points of yellow poplar describe a more specific pattern than the other two species. Bolts from 11 to 14 cm of diameter appear to be in a critical range (Figure 20).

Table 9. Energy consumption and heating value of red maple and loblolly pine.

Species	Moisture content of wood (dry basis)	Heating value (MJ/ODt)	Recoverable heat dry (MJ/ODt)	Recoverable heat wet (MJ/ODt)	Efficiency % dry	Efficiency % wet	Cycle comminution energy (MJ/ODt)	Cycle comminution energy/ recoverable heat - dry
Loblolly pine	100	19 960	16 780	13 970	84	70	630	3.75%
Red maple	85	18 540	15 390	13 340	83	72	732	4.75%

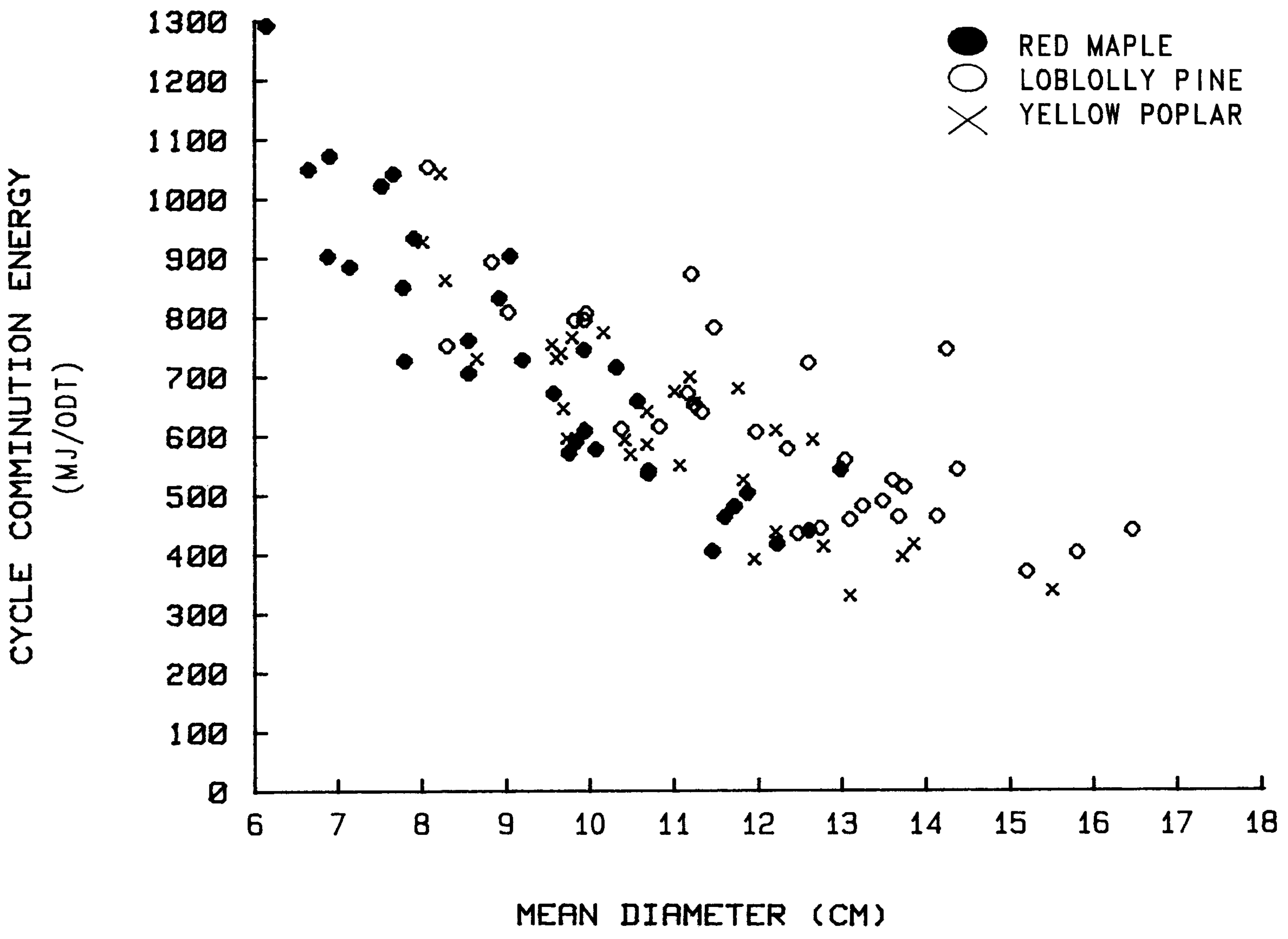


Figure 18. Cycle comminution energy (MJ/ODt) vs mean diameter of bolt (cm).

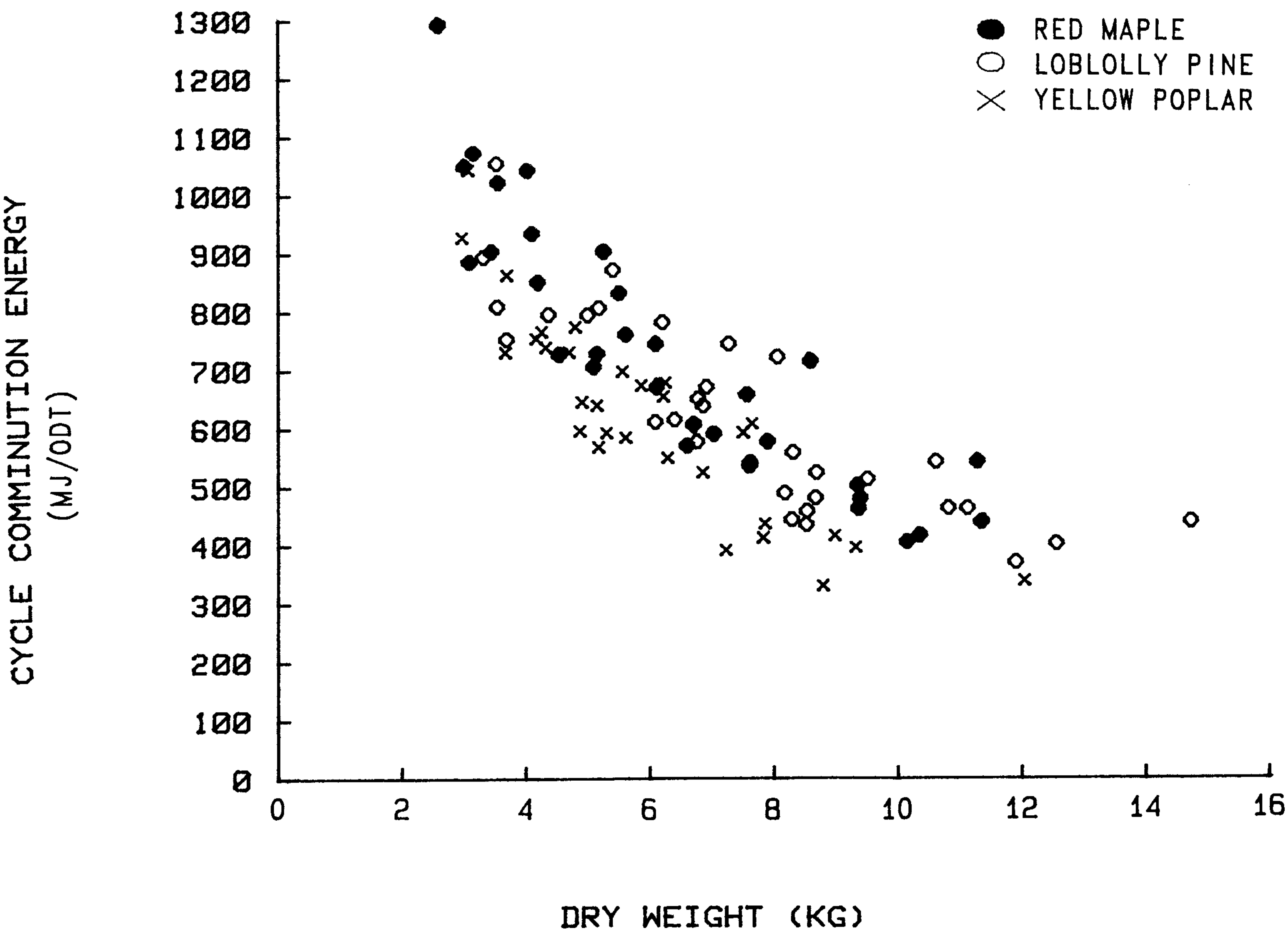


Figure 19. Cycle comminution energy (MJ/ODt) vs dry weight of bolt (kg).

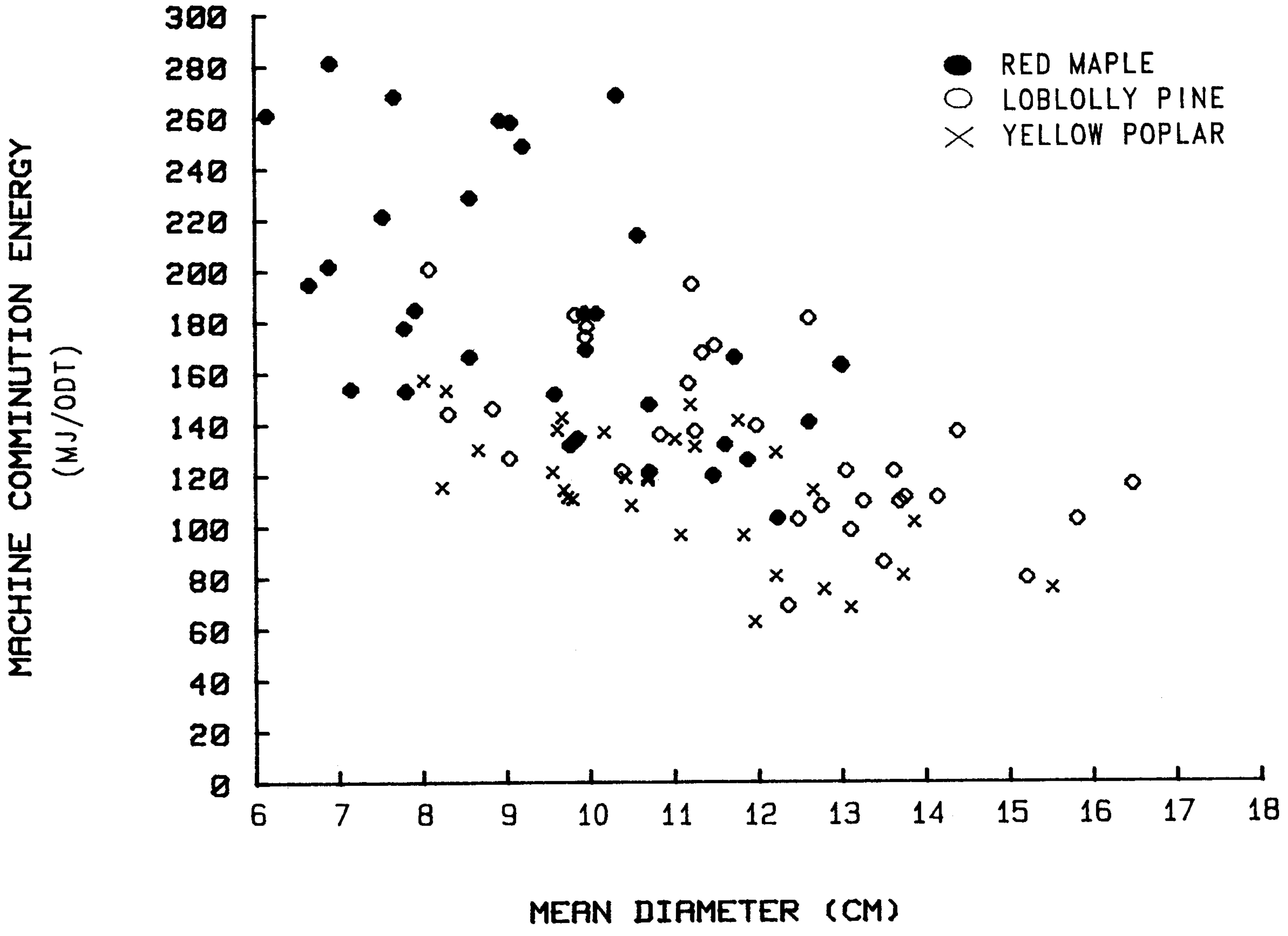


Figure 20. Machine comminution energy (MJ/ODt) vs mean diameter of bolt (cm).

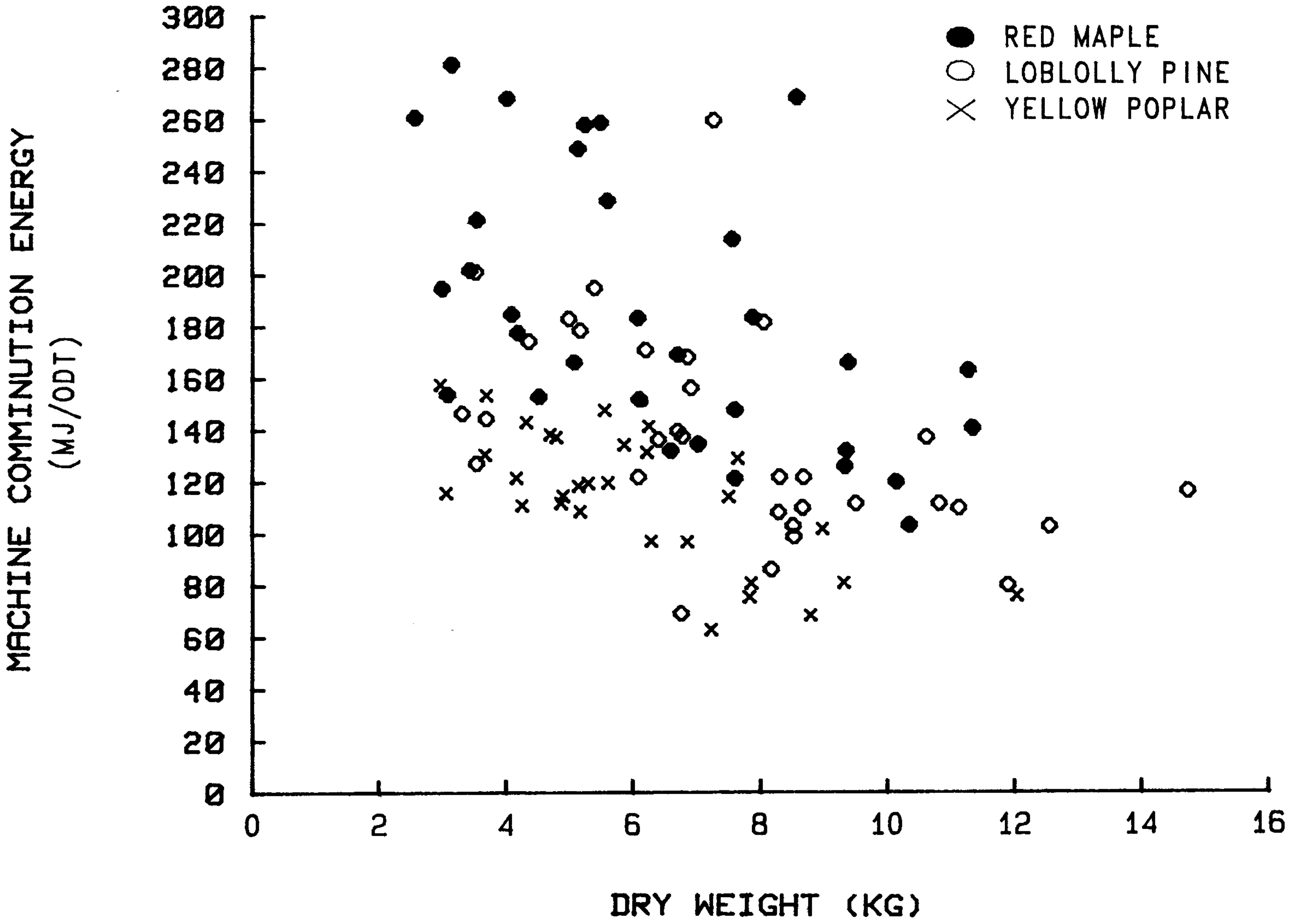


Figure 21. Machine comminution energy (MJ/ODt) vs dry weight of bolt (kg).

2. Dewatering Energy

Scatter plots of dewatering cycle energy (DCE) and dewatering machine energy (DME) on diameter and dry weight are illustrated in Figures 22 to 25. As with the comminution energy, yellow poplar shows the lowest values among all, red maple the highest and loblolly pine in between.

In Figure 22, diameters smaller than 10 cm produced higher corresponding DCE values. However, the same range of diameters was also the least effective in dewatering when expressed in change of moisture content (see Figure 9). Therefore, the less water extracted in the crushing process, the higher was the proportion of dewatering energy per unit of extracted water.

Table 10 contrasts dewatering energy between different versions of the roll-splitter. MDE of dual roll splitter compares favorably to MDE of first prototype. MDE of red maple is nearly four times that of yellow poplar, and twice that of loblolly pine. The evaporation of water requires roughly 2.25 MJ/kg of H_2O by standard thermal requirements. Dewatering yellow poplar with the dual roll splitter demands half that energy, while dewatering red maple consumes twice that energy. Figure 26 indicates how samples of each species compare with the enthalpy to evaporate water from 20°C to 100°C. Red maple values, although covering a narrow range of initial moisture content, are higher than the enthalpy level, whereas yellow poplar values are consistently lower. Loblolly pine, throughout its very wide range of moisture content, has most of its points under the enthalpy bar. This shows that it is only with red maple that mechanical dewatering proved less energy efficient than thermal drying.

Table 10. Dewatering energy for different versions of the Roll Splitter.

	Cycle dewatering cycle (MJ/kg H_2O)		Machine dewatering energy (MJ/kg H_2O)		
	Aspen/ yellow poplar	Red maple	Aspen/ yellow poplar	Red maple	Loblolly pine
Roll splitter (TVA modified)	0.71	2.20	0.5	1.5	-
Roll splitter (axe-like teeth)	- - - - - - - -		winter tests		- - - - - - - -
Roll splitter (dual rollers)	6.1	15.5	1.1	4.0	2.0
adjusted with electric and gas efficiency ratios	2.2*	5.5	0.4	1.4	0.7

* 6.1 x 0.30 ÷ 0.85 = 2.2

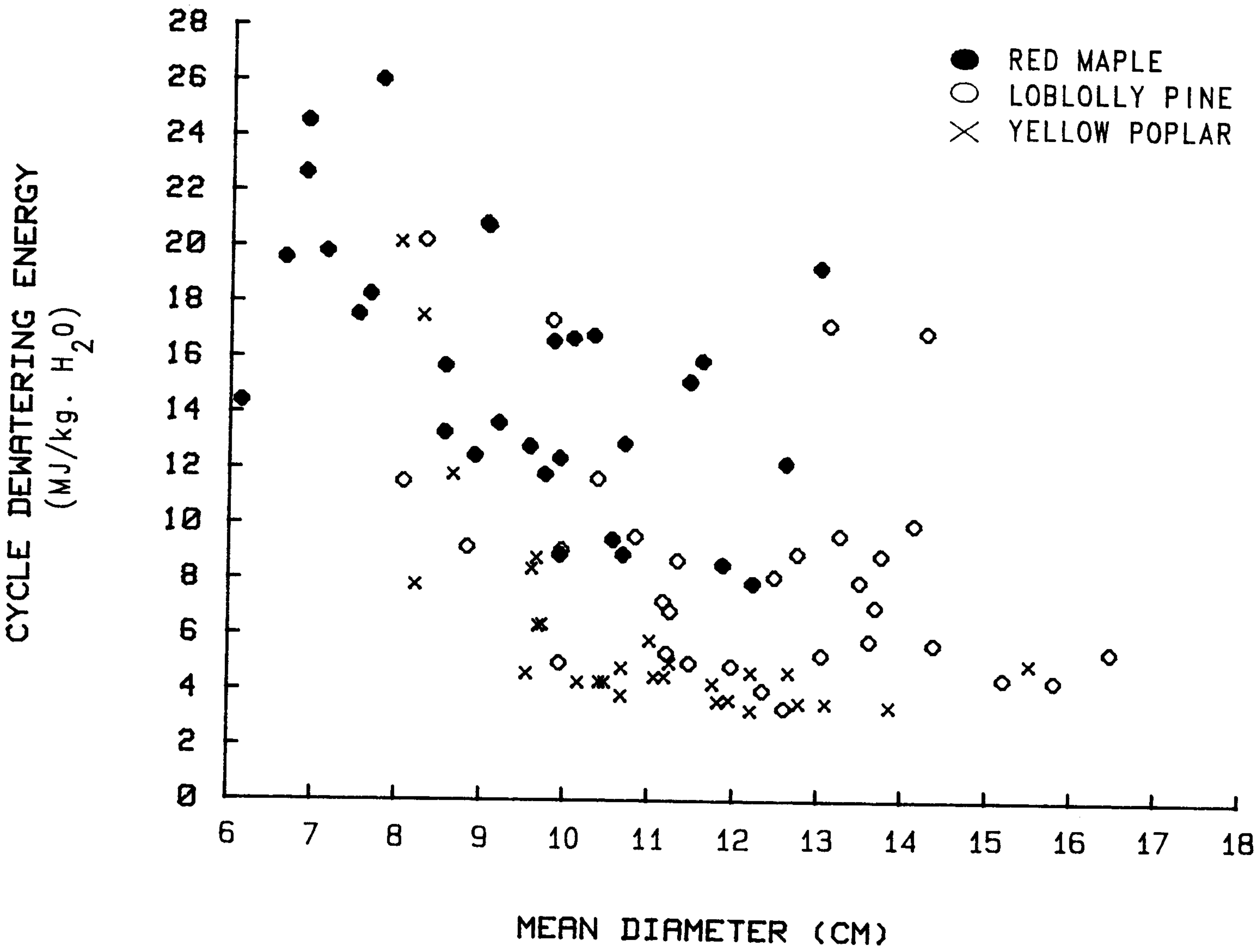


Figure 22. Cycle dewatering energy (MJ/kg H_2O) vs mean diameter of bolt (cm).

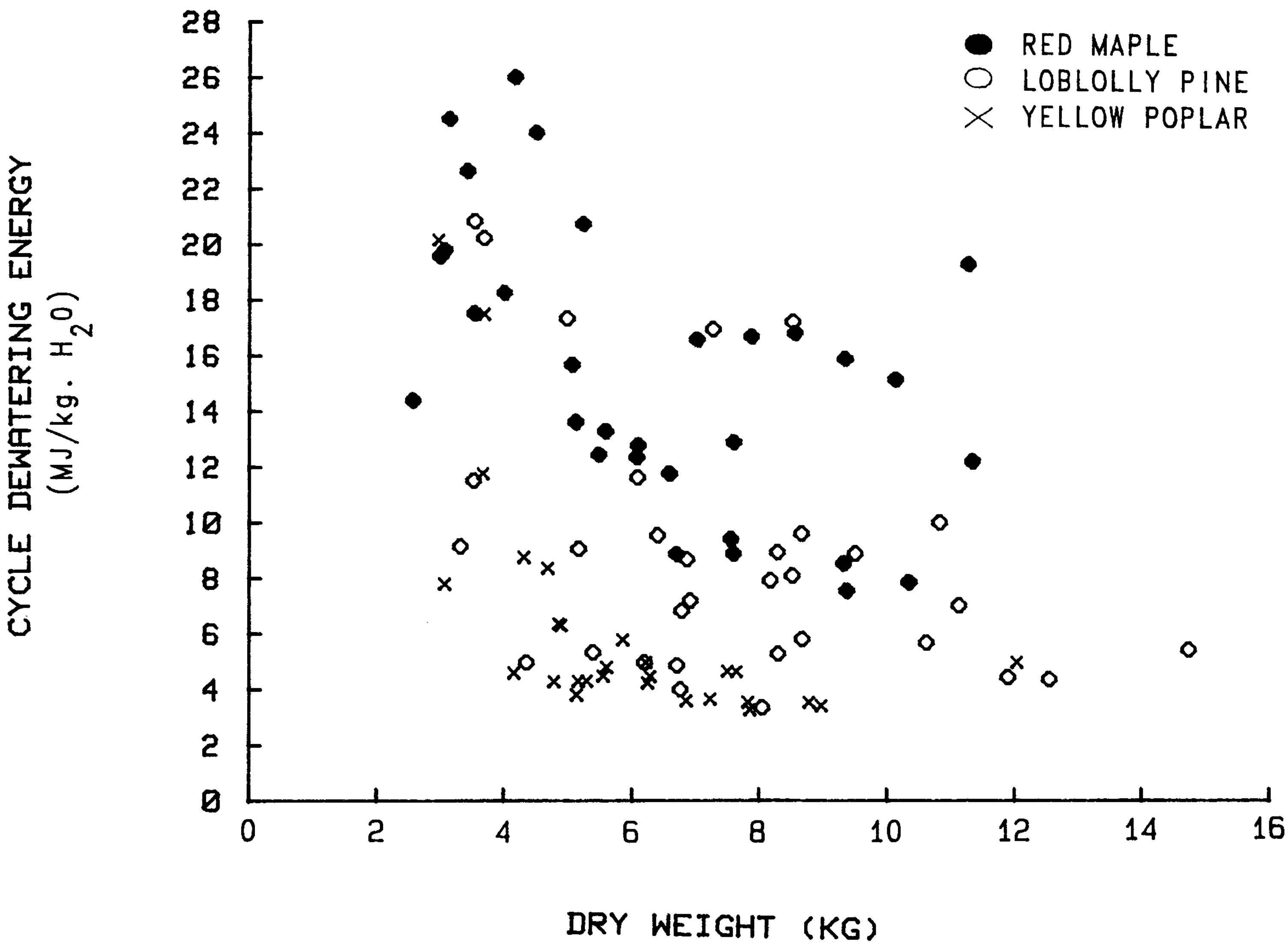


Figure 23. Cycle dewatering energy (MJ/kg H_2O) vs dry weight of bolt (kg).

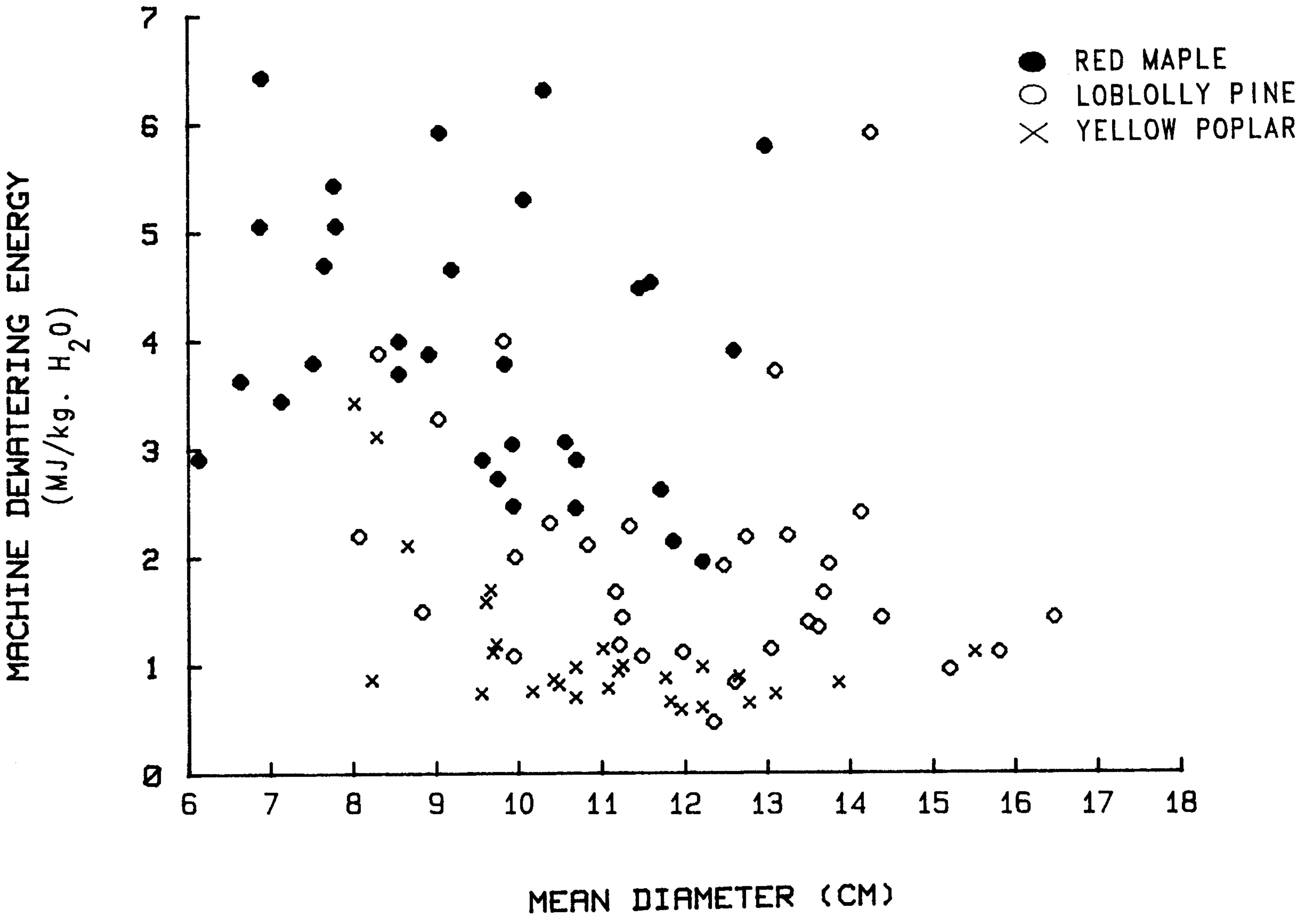


Figure 24. Machine dewatering energy (MJ/kg H_2O) vs mean diameter of bolt (cm).

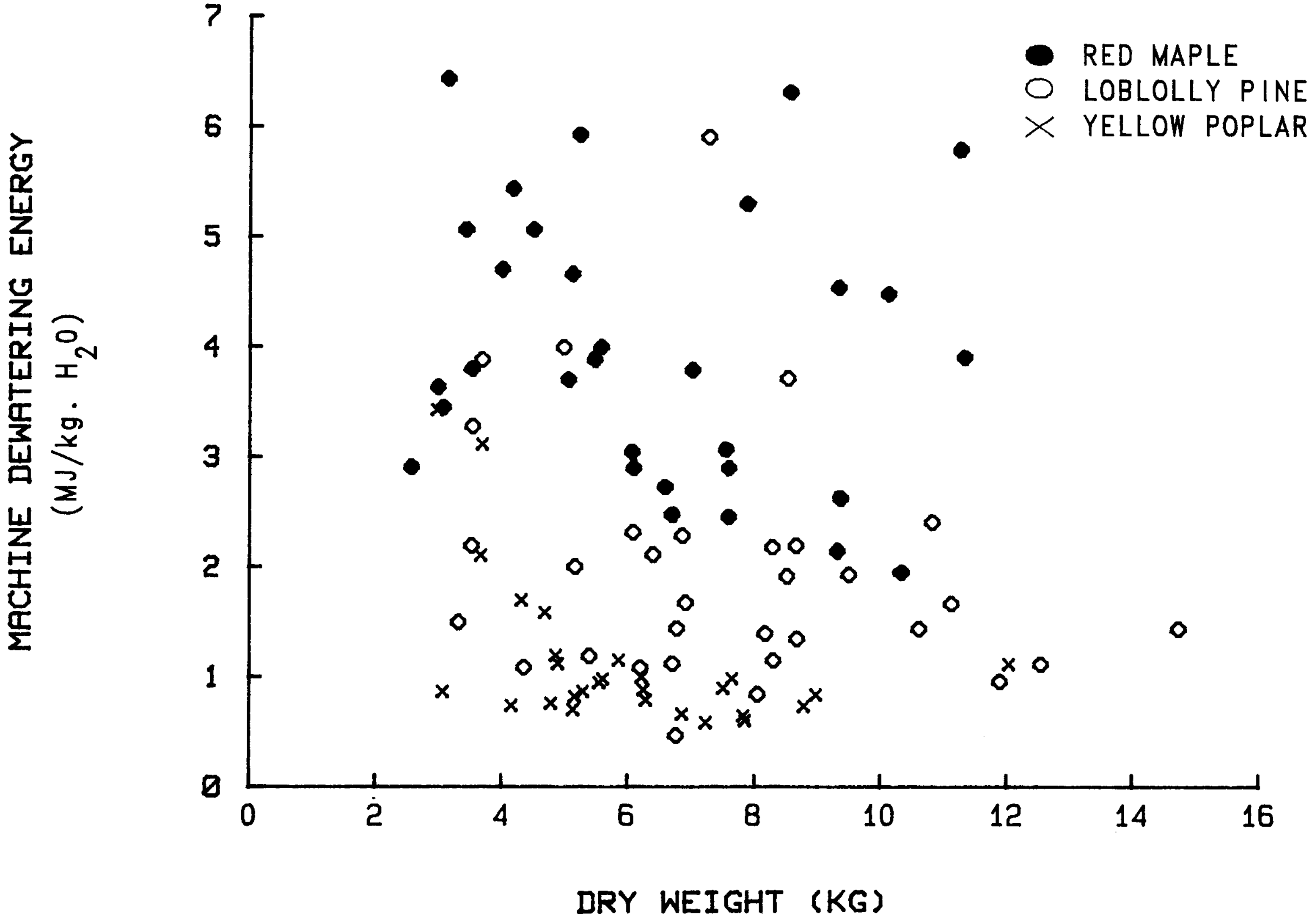


Figure 25. Machine dewatering energy (MJ/kg H_2O) vs dry weight of bolt (kg).

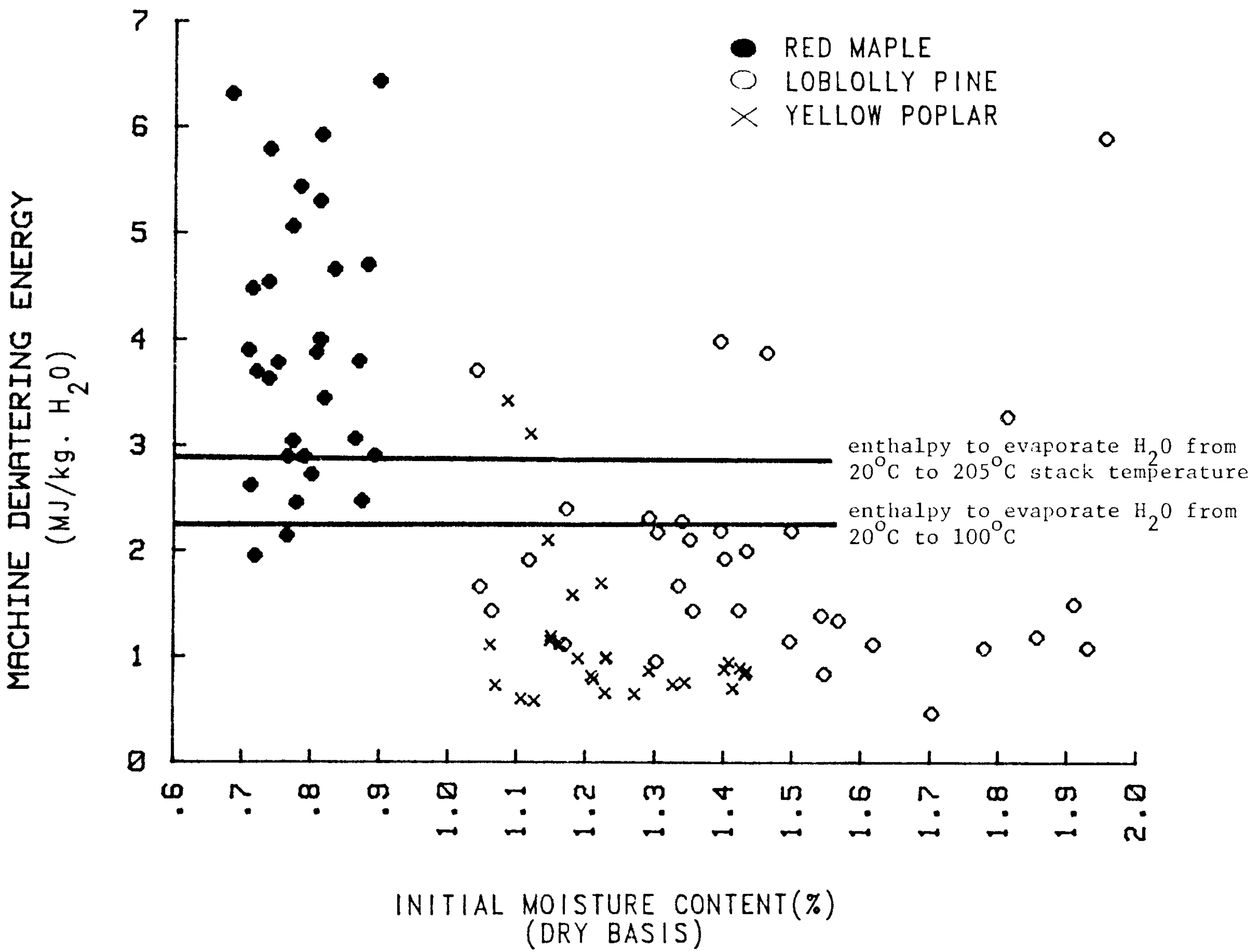


Figure 26. Machine dewatering energy (MJ/kg H_2O) vs initial moisture content (% dry basis).

D. MECHANICAL CONSIDERATIONS

1. Roller Speeds

Roller speeds had a significant influence on both the dewatering and splitting actions. It was found early in the evaluation that roller speed had considerable effect on bolts of yellow poplar, but much less on those of red maple and loblolly pine. A flow divider in the hydraulic circuit made possible different combinations of speeds with input and output rollers. The following cases were tested to exemplify the gradual effect.

$V_1 > V_2$

$V_1 = V_2$

$V_1 < V_2$

where: V_1 = speed of infeed rollers

V_2 = speed of outfeed rollers

Results of two independant tests on the yellow poplar are shown in Table 11, and lead to the following remarks.

Table 11. Effect of roller speeds on the mechanical dewatering.

	V_1 (m/min)	V_2 (m/min)	Reduction of moisture content (%) - dewatering	Crushing time
i)	17.6	10.6	7.9	14.05
ii)	15.3	15.3	10.0	15.62
iii)	14.6	18.9	10.1	16.17
iv)	20.7	15.3	7.9	8.95
v)	11.6	7.9	13.2	21.74
vi)	15.3	23.2	18.3	14.26
vii)	8.8	12.5	17.4	24.84

- When the outfeed rollers are running slower than the infeed ones, there is a significant reduction in the dewatering as well as in the crushing time, in comparison with the case of equal speeds or the case of higher speed on rear rollers (i, ii & iii).

- In the sole case of higher speed on infeed rollers, with hydraulic flow cut approximately in half (both roller speeds are proportionally reduced), dewatering was significantly increased. However, in reducing roller speeds, stalling occurs more frequently and crushing time is considerably increased. For this reason, full flow capacity on hydraulic motor drives was maintained for every other test in the evaluation.

In the case of the yellow poplar, when the outfeed rollers are running slower than the infeed ones, splinters were bent between the rollers and produced a much more flexible product than with other speed combinations. The effect is accentuated when the gap between the outfeed rollers is kept to a minimum for a brief moment as the bolt reaches them (see Figure 29). Yet, the transversal breaking of the fibers is limited to the center portion of the bolt.

Results were different for the red maple and loblolly pine. Roller speeds did not have very much effect on the degree of fiberization. If the infeed rollers was set at a higher speed, the bolt would often simply jam when it got to the outfeed rollers. Consequently, the best set of speeds appeared to have the second pair of rollers running slightly faster, since this also increased the dewatering capacity slightly. Mechanical dewatering of red maple and loblolly pine varied in the same way as yellow poplar, though to a lesser extent.

Most of the crushed material produced in these tests was not readily suitable for baling. The resilience of summer wood (unfrozen) prevented clear splintering and defiberizing. This contrasts to the excellent results achieved at some demonstrations held during winter '84, where bolts processed showed a high degree of splintering.

Observations in several roller speed tests indicate that gradients among different sets of roller speeds exist for such parameters as mechanical dewatering, energy consumption, defibration, etc. These gradients, clearly more apparent with yellow poplar, are illustrated in Figure 27 and 28. The ">" sign means superior and the "<" sign means inferior.

V1 > V2	V1 = V2	V1 < V2
−	dewatering	+
+	air-drying - compaction	−
−	crushing time	+
+	attention-concentration/operator	−

V1 = speed of the infeed rollers

V2 = speed of the outfeed rollers

Figure 27. Roller speeds effects on roll-crushing.

Figure 28. Effect of roller speeds on degree of fiberization. From left to right:

Ø (cm):	7.5	7.0	9.3	9.3	12.6
V_1/V_2 :	$V_1 > V_2$	$V_1 = V_2$	V_1*> V_2	V_1*< V_2	$V_1 < V_2$

* Compare these two bolts for they have the same diameter, but were crushed with different speed settings.

Figure 29. Typical transversal breaking of fibers on a bolt of yellow poplar ($V_1 > V_2$ + minimum gap between outfeed rollers V_2).

CRUSHING PRESSURE

The maximum useful force that can be applied by the top roller cylinders is a function of the torque limit of the roll drive system. If the crushing force applied by the top roller cylinders is too great, the hydraulic motors turning the lower rollers will simply stall. The precise relationship of torque limit to crushing force is a complex mix of parameters; species, relative density, grain orientation of material processed, tooth pattern and shape, etc.

Stalling occurs more frequently with denser species since they require more pressure for the same quality of crushing. Large knots often caused stalling. The sudden resistance to crushing by knots could not be overcome by the rollers. As a consequence, one or both upper rollers had to be lifted, resulting in irregular dewatering and crushing quality. As a result crushing time and energy consumption were substantially increased, with productivity decreasing.

Loblolly pine with brittle, dry knots was the least affected in terms of end product by inadvertent stoppage of the rollers. Yellow poplar was not only slightly more subject to those stoppages; high pressures even had a tendency to chunk the smaller bolts into pieces, reducing mechanical dewatering. Stalling was encountered mainly with red maple. As with the latter species high crushing pressure led to long crushing time, a compromise was reached between sufficient crushing force (6900-7600 kPa or 1000-1100 psi) and minimum crushing time.

Table 12 illustrates the paradoxal relationship between pressure and quality of roll-crushed material from red maple. The reduction of moisture content during the first days following crushing was significantly less with bolts crushed with high pressures. Although the opposite results were anticipated, stalling and subsequent roller adjustments to free the bolts account for these results. Smaller crushing cylinders or a pressure reducing valve on the cylinders would help minimize the negative effects of stalling. No significant difference in the dewatering capacity was noted, perhaps because of the limited sampling. Although the sample size is rather small to carry out an analysis of variance, this test was performed in order to document our observations.

Table 12. Effect of crushing force on dewatering and quality of crushing--average per bolt--red maple.

Pressure	#	Crushing time (s)	Percent moisture loss (dry basis) through roll-splitting action only	Percent moisture loss (dry basis) through first air-drying day after roll-splitting	Percent moisture loss (dry basis) solely through second air-drying day	Percent moisture loss (dry basis) solely through third air-drying day
P_1 (800-1000 psi)	5	13.25	5.3	12.2	9.2	4.5
P_2 (1100-1200 psi)	5	14.32	5.8	10.2	8.7	5.1
P_3 (1400-1500 psi)	5	15.36	5.7	8.1	7.3	3.7
Analysis of variance		significant	not significant	very significant	significant	very significant

DEVELOPMENT

The Roll Splitter is well suited as a test-bench unit to study the concept of crushing wood along the longitudinal axis. Because it is a prototype, a number of points on its mechanical design lacked optimization or presented weaknesses, and must be given consideration for further developments:

- weight distribution along the wheel axle (in view of roll-over risks);
- position of gas tank to engine and exhaust;
- provisions for electrical and in-line connections for instrumentation;
- frictional heating caused by undersized hoses and connections, by-passing circuit with full operative pressure, undersized hydraulic oil reservoir...;
- cooling system, particularly in warm weather conditions;
- simple mechanical set-up of the rollers, drive components, etc. for rapid changes of components;
- safety items such as warning and procedure signs, ear protection, identification of controls, etc.

Early in the evaluation it became apparent that hydraulic oil overheating was significantly decreasing the efficiency of the roll splitter. Ambient temperatures over 32°C were frequent. A difference in quality of crushing was observed when two bolts of the same size were crushed at some time interval, as the machine tended to lose crushing capabilities and to stall more easily. It was often observed how unusually good the crushing was for the first 2 or 3 bolts at the beginning of a test when the hydraulic system was relatively cool and the progressive loss of crushing capacity. A water-cooling coil was therefore added to the oil reservoir to provide cooling. This addition considerably stabilized the performance of the roll splitter.

Modifications in roller design would certainly induce different results in dewatering and degree of splintering, whether with single or a dual roll splitter. This is the key aspect in the further development of the concept of longitudinal splitting and crushing. However, future developments in roller design will have to take into account both the infeed material and the desired product. Species (softwood or hardwood), size (range of diameters), relative density and nature of material (bolts, whole trees...) are paramount factors in selecting the number of rollers and the appropriate roller design. For diameters less than 8 cm, rollers of this prototype proved to be not very energy efficient and had low dewatering capacity.

CONCLUSIONS

The evaluation of the dual roll splitter has demonstrated promising results even though some are not as satisfactory as we first anticipated. The quality of roll-crushing differs radically whether the infeed material is frozen or unfrozen wood. The fiberization process with unfrozen wood is quite inferior than with frozen wood. The brittleness of frozen wood as opposed to the strong resilience of unfrozen wood would explain the difference. However, mechanical dewatering and subsequent drying of the crushed material can only be performed with unfrozen wood.

Mechanical dewatering showed optimum results in the approximate range of 9 to 13 cm. Present roller design is not very effective for diameters less than 9 cm, whereas the machine itself lacked power for diameters superior to 13 cm.

Several factors such as initial moisture content, diameter, species..., affect the mechanical dewatering. Results contrasting dewatering with one and two pairs of rollers have shown a significant influence in the sole case of yellow poplar. Though there has been no repetition of the test, the fact that no significant difference in dewatering was found for the red maple indicate that the roller design is not altogether optimized. Quality of crushing is better when two pairs of rollers are used, but machine comminution energy has increased two fold while machine dewatering energy remained noticeably the same in comparison to the first prototype version which had only a single pair.

Roll crushed material dries out at high rates considering the degree of fiberization achieved. If the latter could be improved, it is probable that drying rates would also increase. According to our tests, weight and moisture content of crushed material stabilized after seven days of air drying. Regardless of the initial levels of weight and moisture content for the three species, stabilization occurred at the same level. A period of five days appears to be the optimal period for the material to reduce its moisture content to a low level. The potential for drying crushed material whether artificially or naturally is present, and offers obvious advantages for further comminution, transportation or energy conversion operations.

Roller speeds also affect dewatering and quality of crushing. The best set of roller speeds, with or without a differential between input and output rollers, is peculiar to each species. Better results were achieved with the yellow poplar when rear rollers were running slower than the front ones, whereas with the red maple and loblolly pine, front rollers running slower were preferable. The main disadvantage when the rear rollers are running slower is that processing is hardly possible on an automatic basis, at this stage. There is also the fact that only low density species can be processed with such a differential of roller speeds. Therefore, if one set of roller speeds had to be selected for all species, as on a productive unit, equal speed on both pairs of rollers or one with the front rollers running a bit slower than one rear roller would be recommended as long as the quality of crushing is sufficient for rapid drying.

Roller design is a key area in which further development should take place. Better fiberization of unfrozen wood should be favoured over better mechanical dewatering if subsequent drying is considered, since the reduction of moisture content through mechanical dewatering is a small fraction of the total reduction of moisture content through air drying. The size and form of the infeed material should be taken into account when considering the number and size of rollers. Sophistication in machine design increases both costs and CCE/MCE ratio. Material with diameters less than 8 cm may not need two pairs of rollers for roll crushing process. Different roller configuration should be experimented with the present Roll Splitter to determine the best combination and configuration of rollers for different categories of materials.

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CONVERSION TABLE

1 cm (centimetre)	0.39 inch
1 m (metre)	3.28 feet
1 L (litre)	0.22 Imperial gallon 0.26 American gallon
1 kg (kilogram)	2.20 pounds
1 kPa (kilopascal)	0.145 pounds per square inch (psi)
1 kW (kilowatt)	1.34 horse-power
1 MJ (megajoule)	9.484×10^{2} BTU 7.374×10^{5} foot-pounds 2.778×10^{-1} kW-hour 3.725×10^{-1} hp-hour
1 kg of gasoline	42,335 BTU 44.6 MJ