Field tests to develop energy saving wood comminution techniques

by

K.C. Jones & Associates Ltd.

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FOREWORD

This report was prepared under the auspices of the ENFOR (Energy from the Forest) program of the Canadian Forestry Service. Under this program, research and development activities are conducted to increase the knowledge and improve the technology relating to the utilization of forest biomass as a source of energy.

The ENFOR program is part of a comprehensive national effort encompassing the development and utilization of all renewable sources of energy. It is aimed essentially at reducing Canada's current dependency on oil and other non-renewable sources of energy.

Under the terms of an agreement with the Government of Canada, the Forest Engineering Research Institute of Canada retained the services of K.C. Jones & Associates Ltd. to design and implement a project which led to the preparation of this report.

ABSTRACT

This report condenses the results of 4 separate field and laboratory tests carried out:

i) to measure the in-service productivity and energy consumption distribution of the Fling Solid Waste Demolisher (SWD) and a portable knife hog processing logging residues;

ii) to determine the energy required to splinter and dewater roundwood using a roll crusher; and

iii) to measure the solid volume factors achieved by baling harvesting residues previously processed by a roll crusher.

The complete report of each test is attached as an appendix.

Conclusions and recommendations are made regarding the most appropriate course to follow in developing energy-saving techniques for preparing fuel stocks from harvesting residues.

TABLE OF CONTENTS

	PAGE
1.0 INTRODUCTION AND STUDY CONCEPT	1
1.1 Study Concept	1
1.2 Objectives	1
1.3 Methodology	2
1.3.1 Energy Level Concept	
1.4 Format of Presentation	3
2.0 SURFACE AND PHYSICAL ENERGY REQUIREMENTS	4
3.0 MACHINE ENERGY REQUIREMENTS	7
4.0 CYCLE ENERGY REQUIREMENTS	13
5.0 OPERATIONAL ENERGY REQUIREMENTS	14
6.0 CONCLUSIONS	16
7.0 RECOMMENDATIONS	18
REFERENCES	19

APPENDIX A - STEAM GENERATOR TO BURN WHOLE BALES

APPENDIX B - EXTENDED BIOMASS HARVESTING PROJECT

APPENDIX C - REPORT: ENERGY REQUIREMENTS AND PRODUCTIVITY OF THE FLING SOLID WASTE DEMOLISHER

APPENDIX D - REPORT: ENERGY REQUIREMENTS AND PRODUCTIVITY OF A PORTABLE KNIFE HOG

APPENDIX E - REPORT: ENERGY REQUIREMENTS TO ROLL-SPLIT WOOD

APPENDIX F - REPORT: ROLL-SPLITTING AND BALING HARVESTING RESIDUES

LIST OF FIGURES

NO.		PAGE
1.	Energy Requirements: Physical, Machine, Cycle and Operational	2
2.	Surface Energy (particle size and shape)	5
3.	Surface Energy and Size Distribution	5
4.	Size Distribution Processed by the Fling SWD	6
5.	Comparison of Machine Energy Requirements	8
6.	Residue Jaw Crusher	9
7.	TVA Fiberizer	9
8.	Product of the TVA Fiberizer	10
9.	Roll Splitter	10
10.	Moisture Content Change vs: Initial Moisture Content	11
11.	Machine Dewatering Energy vs: Initial Moisture Content	11
12.	Splitting Rolls to Process 30 cm Diameter Material	12
13.	Compaction and Baling	13
14.	Cycle Energy Requirements vs: Productivity	14
15.	Morgardstuggen: Slash Chewer	16
16.	Low Energy Processing Centre	17

LIST OF TABLES

NO.		PAGE
(1)	Physical Energy Requirements of the Fling SWD	7
(2)	Productivity of Residue Chipping Operations	15

1.0 INTRODUCTION AND STUDY CONCEPT

This report examines the energy requirements for comminuting residues recovered from conventional logging operations. It is a summary of the result of 4 field test reports attached as appendices C through F. This ENFOR program has been conducted as part of a three-stage Extended Biomass Harvesting project managed by the Forest Engineering Research Institute of Canada (FERIC). The scope and general objectives of this project are described in Appendix "B".

1.1 Study Concept

The guiding concept behind this study has been that the comminution of wood into small elements has to date usually been done by and for the wood pulp manufacturing industry. Consequently the design of machines and the techniques for using them have been governed by the industry's traditional concept of scale and product quality. However, the utilization of biomass for energy does not require pulp chip specifications. In fact, the quality concepts applicable to traditional and energy conversion processes are somewhat in conflict when the topic of comminution is considered.

Pulp and dimension lumber industries have as their basic quality criteria the concept that fibre integrity must be preserved. Energy conversion processes, on the other hand, require only that comminution expose sufficient surface area to achieve a desired rate of drying and/or control of the energy conversion processes. This is best accomplished by the production of ragged and fractured particles, which are quite the opposite qualities of a pulp chip, which is intended to maximize digester capacity and minimize fibre damage.

We are not suggesting that chippers do not produce an acceptable fuel, only that alternatives exist, and that they should be considered in any general assessment of the energy required to recover, comminute and convert harvesting residues into useable energy.

1.2 Objectives

The principal objectives of this study were:

- to demonstrate equipment which will be the least energy demanding in reducing forest harvesting residues to a useable fuel; and

- to measure the energy requirements of prototype or unusual comminution equipment to acquire sufficient data to direct development of equipment and techniques particularly suited to the comminution of harvesting residues for fuel at a low energy cost.

This type of investigation is quite different from the broad-scope input-output energy analyses, which have in the past confirmed the net energy gains to be realized from collecting and converting harvesting residues to energy (Ash Knoblock and Peters (17)). Rather, this is an engineering study to quantify the data needed to identify problems and opportunities which exist for the development of equipment intended specifically to reduce the energy requirements of comminuting harvesting residues.

1.3 Methodology

Detailed comparisons of the energy requirements to prepare fuel or those of any other mechanized forestry operation, are not common. The only comprehensive study of forest harvesting and processing energy requirements identified by this author has been published by the Department of Operational Efficiency of the Swedish University of Agricultural Sciences, (Gasslander, Mattsson and Sundberg (2)). In this study we have adopted the terminology of the system used in that study to compare energy requirements of comminution. The system recognizes four levels of direct energy requirements for any process: Physical, Machine, Cycle and Operational. The definitions of these levels are as follows:

Physical: A theoretical measure, based on the surface area created, of the minimum energy required to produce a given size distribution of particles.

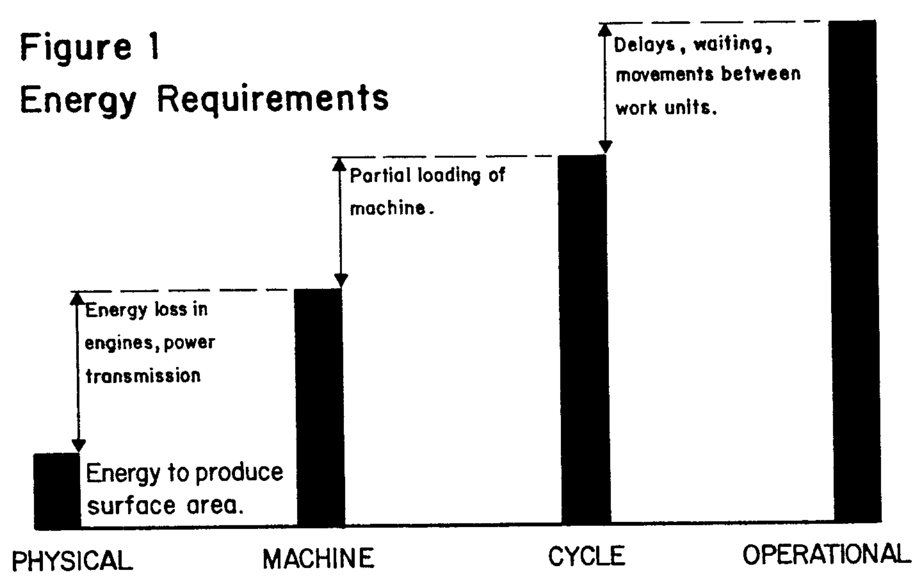
Machine: The energy consumed by a machine while performing useful work, in this case breaking material apart. This includes only the fuel consumed by the working tools. It does not include energy consumed as a base load, i.e., energy used under no-load conditions to drive transmissions and auxiliary equipment such as fans and oil pumps.

Cycle: All energy consumed by a machine while processing material, including the energy lost driving machine elements other than the comminution elements, i.e., fans and conveyor belts.

Operational: The total energy used during a normal operating period, e.g., one shift. This includes all energy lost during idling times, and while waiting to process material.

Figure 1 illustrates the relationship between these levels of energy requirements.

Figure 1
Energy Requirements



The Physical energy needed to produce a new surface area is a rather theoretical concept. However, it does supply a common base against which to compare the energy requirements of all types of equipment. It is the only level at which really useful work is accomplished. The differences between it and the succeeding levels are all losses. The Machine energy level is useful to the mechanical design engineer in determining peak power requirements of each equipment type based on surge loads. To the manager, however, differences between Machine, Cycle and Operational energy levels are of greater interest since they are the losses which can be reduced through modification to operating techniques.

In the study conducted by Gasslander et al (1), the levels of energy requirements were extended to include a fifth level, "System", which assigned indirect energy values to repair actions, spare parts, lubricants and Machine energy values. While this is a valid consideration, we have not included this level in our studies since the project's objective was to initiate development and prototyping of new equipment.

1.4 Format of Presentation

The results of this study have been published in two separate reports. This report combines the results of four field tests aimed at gathering data to develop more energy-efficient residue processing machines and techniques. The tests have been written as independent reports and presented as such in Appendices C, D, E and F:

- Appendix C - Energy Requirements and Productivity of the Fling Solid Waste Demolisher.
- Appendix D - Energy Requirements and Productivity of a Portable Knife-hog.
- Appendix E - Energy Requirements to Roll-split Wood.
- Appendix F - Baling Roll-split harvesting residues.

This executive summary condenses and compares the results of these tests.

In the second report published as part of this study, "A Review of Energy Requirements to Comminute Harvesting Residues", Jones (2). The results of numerous past laboratory tests to determine comminution energy requirements have been reviewed and compared. A small portion of that report has also been summarized in this report in order to preserve continuity of the overall study.

While this executive summary is based on data and conclusions found in each of the five reports it does not offer a precis of them. Instead, it presents its own conclusions which are a combined result of, not an abstract or summary of, the individual reports.

2.0 SURFACE AND PHYSICAL ENERGY

According to its original definition, Gasslander et al (1), the Physical energy requirement was based on the minimum theoretical energy needed to accomplish work - a force times the distance through which it acts. Obviously, this minimum energy requirement can never be achieved in practice. However, in the case of comminution, we can use the Physical Energy Requirement to compare the amount of useful work accomplished by a wide variety of processors, based on the change in size distribution and the different energy requirements to produce surface areas perpendicular and parallel to the grain.

Best estimates of the minimum energy requirements to produce surface areas perpendicular and parallel to the grain of black spruce (Picea mariana) are 1 and .01 Joule/cm^2 respectively, Jones (2). The precision of the two estimates is not of great significance, though the .01 Joule/cm^2 assigned to surfaces parallel to the grain has been determined by careful experimentation. What is significant is their ratio of roughly two orders of magnitude.

Using these figures, it is possible to develop a series of equations relating a minimum theoretical energy requirement, the Physical Energy Requirement, to produce various sizes and shapes of particles. The sum of the product of the projected surface areas perpendicular and parallel to the grain and their respective effective surface energies assign an energy value to a material based on its size and shape. This value is its surface energy. The difference between the surface energy value before and after comminution is the Physical energy level.

For example, assuming a specific gravity (SG) of .38 for black spruce, the following equations can be developed which express the energy represented by the surface areas of cubic and pulp chip shaped particles. Equations (1) and (2) are illustrated in Figure 2.

Cubic (L:R:T = 1:1:1)

$$\text{Surface Energy Requirement} = \frac{5.4}{x} \text{ MJ/ODt} \qquad (1)$$

Pulp Chips (L:R:T = 4:4:1)

$$\text{Surface Energy Requirement} = \frac{5.6}{x} \text{ MJ/ODt} \qquad (2)$$

Where x = particle length parallel to the grain.

Comparing equations (1) and (2), to split 1 cm cubic particles into four pieces requires only .2 MJ/ODt, a very small energy requirement considering the gain in surface area. By using equation (1) and the size distributions in Figure 3, the effect of producing even a small percentage of fines is shown. By including only 5% fines in the .25 cm class, one distribution represents 1.7 times the energy of the other despite the fact that under most systems, both would be classified as the same nominal size.

As a further example of the importance of considering the size distribution of particles, we have used data gathered from a test of the Fling Solid Waste

FIGURE 2

SURFACE ENERGY (Size and shape of particles)

The surface energy represented by the size and shape of a particle can be calculated as the product of it's projected surface areas and effective surface energies perpendicular and parallel to the grain.

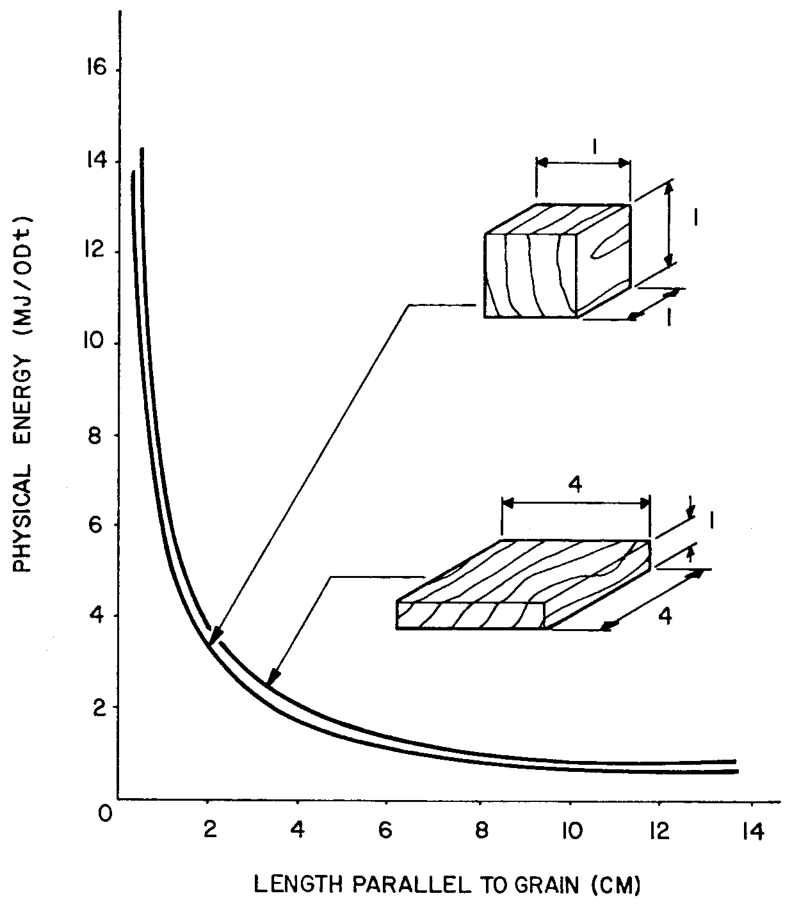
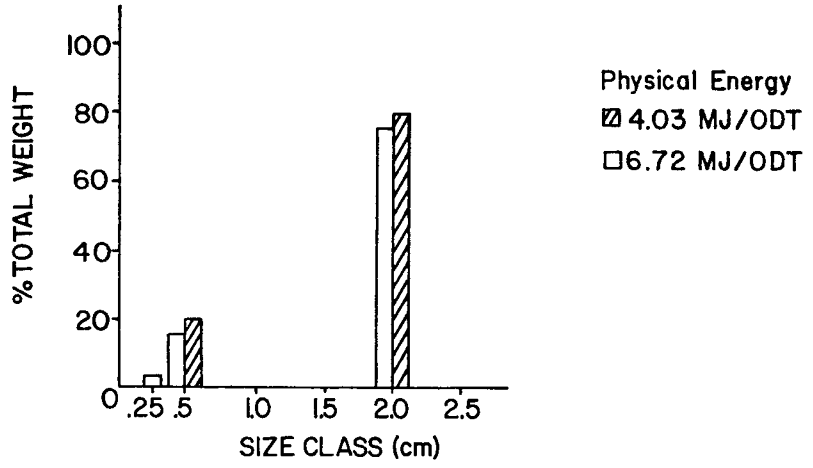


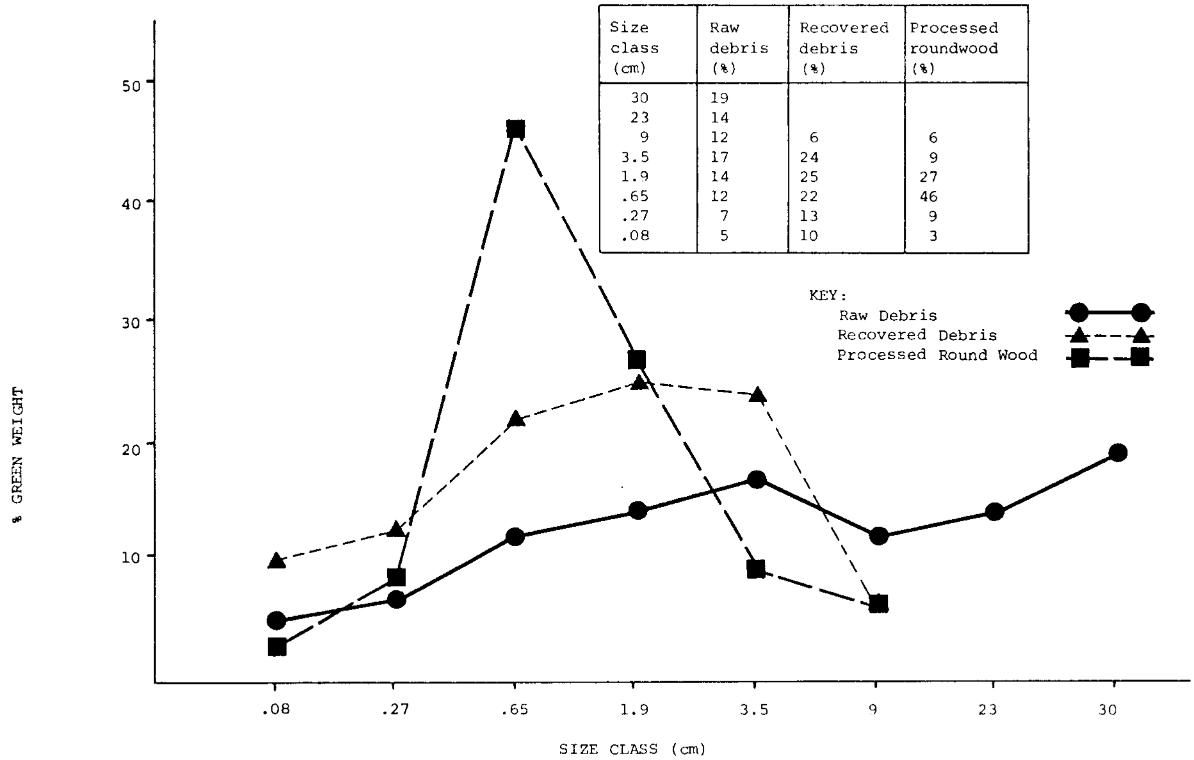
FIGURE 3

SURFACE ENERGY AND SIZE DISTRIBUTION

The inclusion of even a small amount of fines greatly increases the surface energy represented by the size distribution.



Demolisher (SWD), Appendix C, to compare Physical energy levels represented by different products from the same machine. Figure 3 illustrates the size distribution of sortyard debris before and after processing by the SWD. It also shows the distribution of particles produced by the SWD from roundwood bolts roughly 15 cm in diameter and 2 m in length. Table 1 compares the surface energy represented by these distributions, the Physical energy represented by the change in the size distributions and the measured Machine energy used to produce each product. It then expresses the relative efficiency of each process by dividing the Machine energy requirement by the Physical energy requirement. Equation (2) was used to calculate Physical Energy Requirements.



Size class (cm)	Raw debris (%)	Recovered debris (%)	Processed roundwood (%)
30	19		
23	14		
9	12	6	6
3.5	17	24	9
1.9	14	25	27
.65	12	22	46
.27	7	13	9
.08	5	10	3

FIGURE 4

SIZE DISTRIBUTION PROCESSED BY THE FLING S.W.D..

In this manner, we can see that while roughly four times as much energy was used to process roundwood bolts as to process debris (460 MJ/ODt:117 MJ/ODt), the energy efficiency of the useful work accomplished is only two and a half times as high (.019 to .049). In view of the sensitivity of this type of calculation to errors in measurement of fines, the efficiency of the two processors are not far apart. This is particularly true when one considers that while roundwood was being processed, the fines often tended to blow away and the sortyard debris contained a high percentage of grit in the smaller size classes. Both factors tend to bias the results in favour of the efficiency of debris processing.

TABLE 1

PHYSICAL ENERGY REQUIREMENTS OF THE FLING SWD

Material Processed	Surface Energy* (MJ/ODt)	Physical Energy (MJ/ODt)	Machine Energy** (MJ/ODt)	Energy Efficiency
Raw Debris	6.7	-	-	-
Processed Debris	12.4	5.7	117	.049
Roundwood	0.0	-	-	-
Processed Roundwood	8.9	8.9	460	.019

* Calculated using equation (2)
** Measured diesel energy consumption

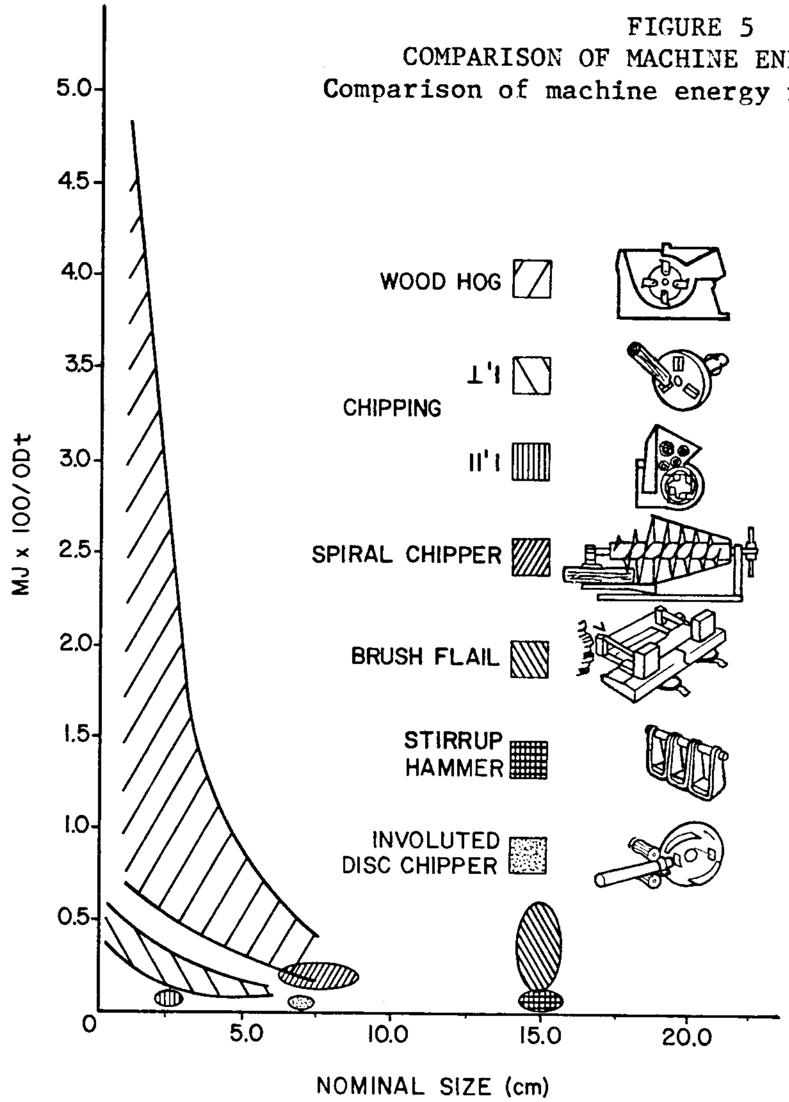
3.0 MACHINE ENERGY

Despite the desirability of recognizing the significant effect of shape and size distribution as pointed out in Section 2, most documented energy comparisons are based only on a nominal size classification of particles. In practice, this approach is a convenient and reasonable one. Comparisons based on a detailed examination of Physical Energy requirements are better reserved for comparative trials in closely parallel situations. As well in most cases, the nominal size refers to the maximum particle length parallel to the grain, which rather than thickness or width, is the determining factor in energy requirements.

A review of published literature based on this type of data, has provided the data illustrated in Figure 5, which compares the Machine Energy requirements of chipping and impact machines producing nominal size particles, Jones (2). The energy requirements from references used in developing Figure 5 were adjusted to a common electric motor basis, assuming 30% and 85% energy conversion efficiencies for internal combustion and electric engines respectively. Of note is the fact that the energy requirement of rugged impact equipment, producing nominal 15 cm size particles, is nearly equal to that of disc chippers producing 2.5 cm particles. However, these results are based on experiments in which the infeed material was 10 cm diameter bolts held rigidly in an infeed system. Applying the same impact mechanism to loose slash would result in considerably higher energy requirements.

In a general sense, the details of this reviw show that on a Machine Energy basis, harvesting residues should be comminuted when dried below the Fibre Saturation Point (FSP), particularily when impact machines such as hammermills, the Fling SWD and slash cutters are considered. Their energy requirements can be reduced by roughly half by such drying.

FIGURE 5
COMPARISON OF MACHINE ENERGIES
Comparison of machine energy requirements.



Not shown in Figure 5 are the energy requirements of crushers which are particularly suited to comminuting harvesting residues due to their relative immunity to damage by tramp material. As part of this project, laboratory tests were attempted using traditional jaw and roll crushers to process wood. These quickly demonstrated what was expected, namely that short stroke, high strength comminution mechanisms suited to processing brittle material are not capable of achieving significant size reduction when processing resilient and weak material such as wood. Their successful application requires major design and prototyping effort.

One successful application of crushing technology is a jaw crusher operating in Avesta, Sweden. It processes commercial, residential and harvesting residues into fuel for a 12 Megawatt central heating plant. The comminution action illustrated in Figure 6 is really a cross between a scissor action and jaw crusher, but nothing is known of its energy requirements, only that it is relatively immune to damage by tramp material. It would be well suited to billeting material fed into it in bundles. The versatility of the hopper infeed is an attractive feature, suited to the highly irregular shapes of harvesting residues.

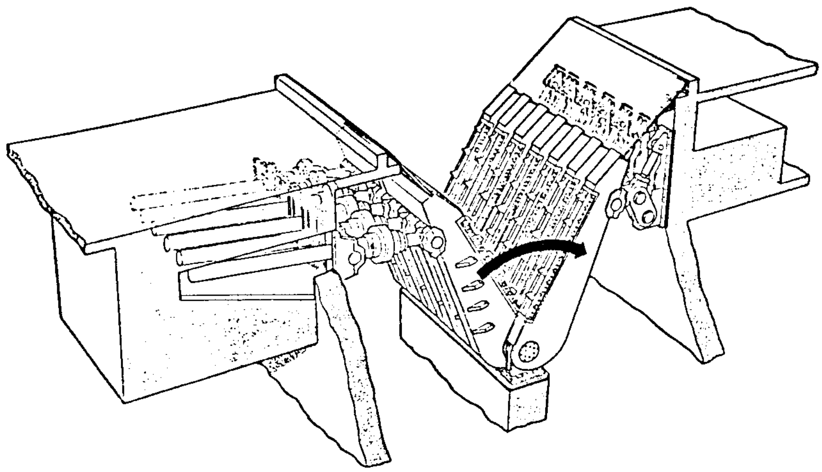


FIGURE 6
RESIDUE JAW CRUSHER.

While a suitable jaw crusher was not available for testing, we did have access to a prototype roll crusher (the TVA Fiberizer shown in Figure 7). It was designed and prototyped in the late 1960's to cleave and tear rough lumber apart, parallel to the grain, (Harvey (3)). Our initial tests demonstrated that its Machine Energy requirements to reduce roundwood bolts 9-18 cm in diameter to a loose mat of slivers, roughly 3 cm in cross-section and 1.7 metres in length, varied from 40 to 70 MJ/ODt. However, the process concentrated more on crushing wood than on cleaving it apart. The process also removed significant quantities of water at a Machine Energy cost of from .8 to 1.1 MJ/Kg of water removed.

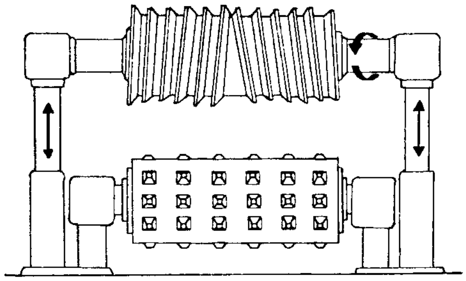


FIGURE 7
THE T.V.A. FIBERIZER
The t.v.a. Fiberizer uses opposing buttress threads to split, cleave and tear wood apart while applying a crushing force of roughly 42,000 Kg.

These comminution energy requirements placed the process somewhere between the Machine energy requirements of chipping material to 2.5 cm particles, 10-20 MJ/ODt, (Papworth and Erickson (4)) and hammermilling it to 2.5 cm particles 80-240 MJ/ODt, Gruendler (5). The dewatering energy requirements are less than half the thermal energy required to evaporate water in a boiler from 20°C-205°C, 2.8 MJ/Kg H_2O. The only reliable figures available to describe the dewatering energy requirements of other mechanical systems apply to the Stake Technology Co-axial Feeder, which in prototype tests required roughly .34 MJ/Kg of water removed (6). The product of the TVA process is shown in Figure 8.

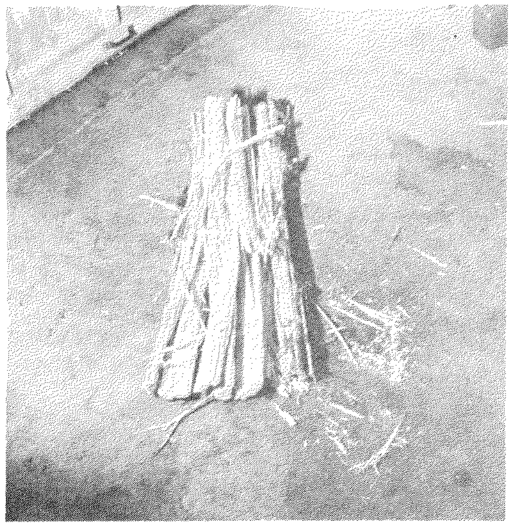


FIGURE 8
THE PRODUCT OF A T.V.A.
FIBERIZER OR ROLL SPLITTER
is a loose cohesive mass of
slivers roughly 3 cm in
cross section.

Following what was considered the initial success of the TVA tests, a new top roll was manufactured and installed on the TVA frame. It concentrated more on splitting wood than on crushing it, Appendix E. This roll had axe-like teeth as shown in Figure 9. The comminution action now became one of roll-splitting

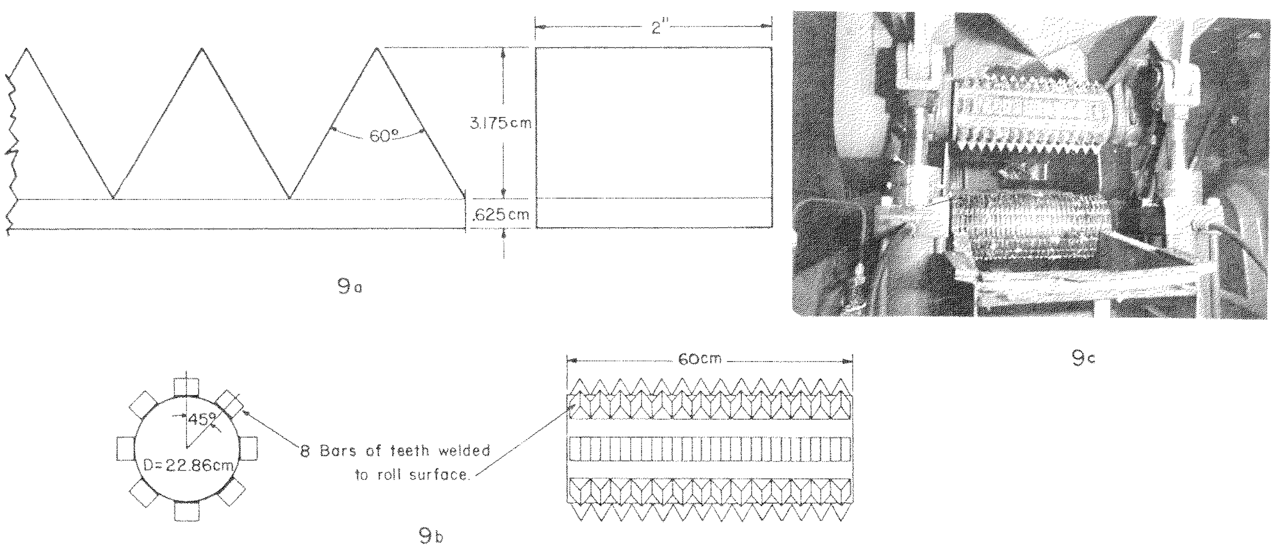


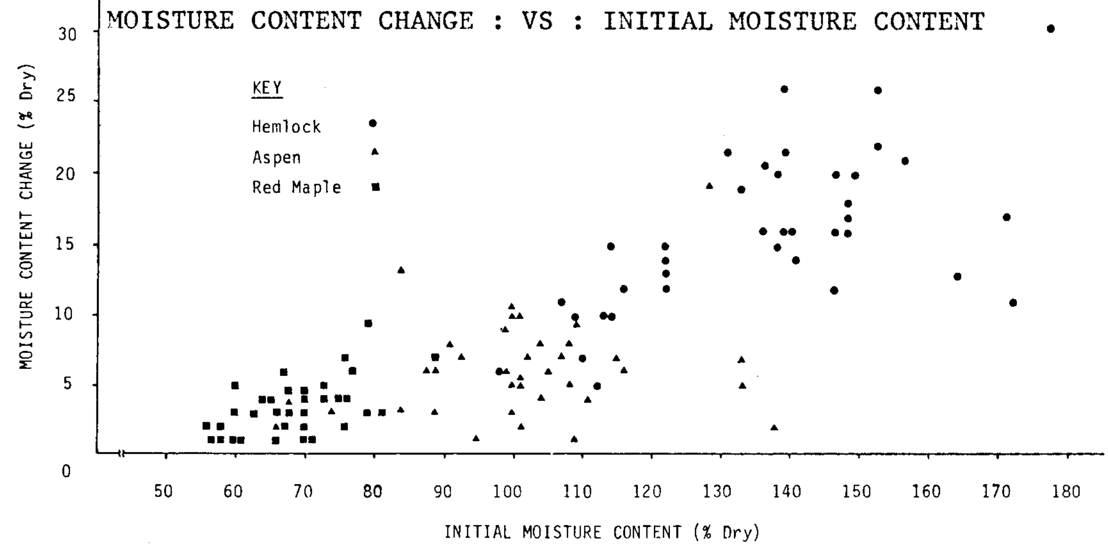
FIGURE 9
TOOTH PATTERN

Eight bars of axe like teeth were welded to the roll core. The teeth were flame cut from 5 cm steel plate. The axe points, 3.175 cm long with 60° angle included, were aligned circumferentially about the roll.

rather than crushing. The Machine Energy to produce a material similar to the TVA concept was reduced for all species tested. It ranged from 23-32 MJ/ODt, and the Machine dewatering energy efficiency was relatively unchanged, ranging from .2-1.5 MJ/ODt. What did change was the percentage drop in moisture content as a function of initial moisture content. It was less for roll-splitting. This decrease was understandable, since the Machine comminution energy decreased, with the Machine dewatering energy remaining unchanged. Figure 10 illustrates the moisture content change as a function of initial moisture content

FIGURE 10

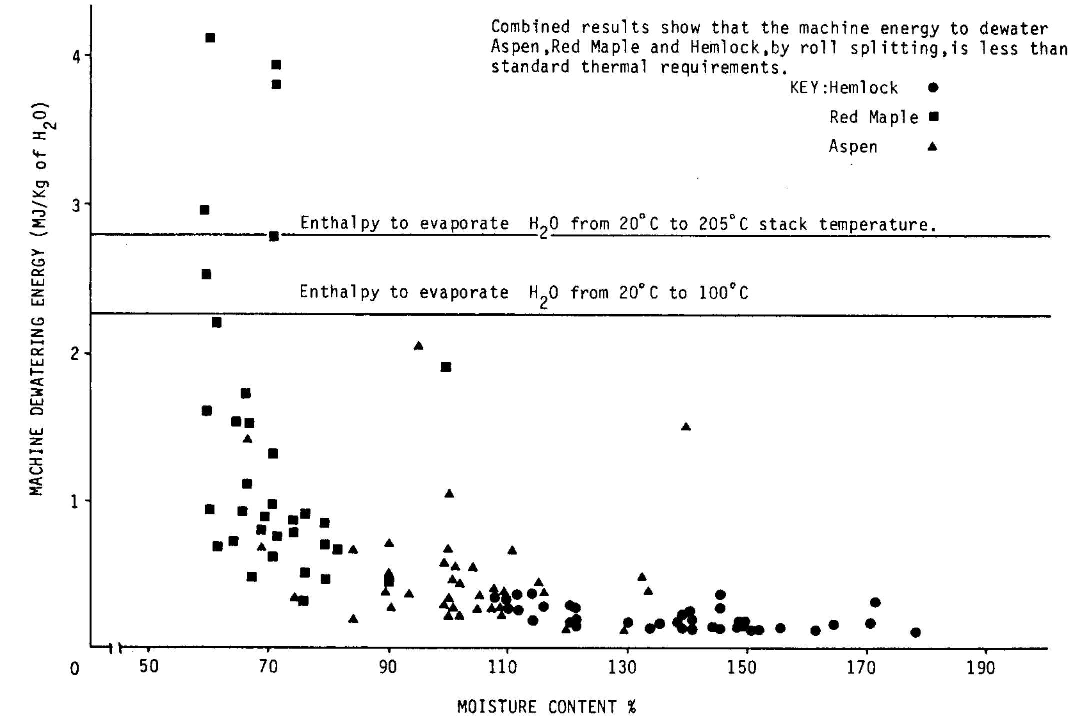
MOISTURE CONTENT CHANGE : VS : INITIAL MOISTURE CONTENT



resulting from roll-splitting. Of interest is the fact that water was being removed from wood at an initial moisture content of only 70%. Following this through to Figure 11 shows that this mechanical process was still less

FIGURE 11

MACHINE DEWATERING ENERGY : VS : INITIAL MOISTURE CONTENT



energy-intensive than a thermal drying operation, even at this low moisture content. Other devices undoubtedly remove water during comminution, however, none displays such clear evidence of drying as that shown in these tests.

The prototype machine used to test the roll-splitting concept was a 33.5 Kw model and was only able to process 9-12 cm bolts in a single pass. Larger pieces required two passes to produce 3 cm slivers. Future development work would best concentrate on producing a more powerful model with larger teeth capable of processing up to 30 cm diameter bolts in a single pass. Our experience indicates that a 100 Kw machine with maximum infeed speed of 30 m/min in combination with the rolls shown in Figure 12 would be sufficient. It is expected that this would considerably reduce Machine comminution energy requirements. To what extent this would sacrifice dewatering efficiency is impossible to tell.

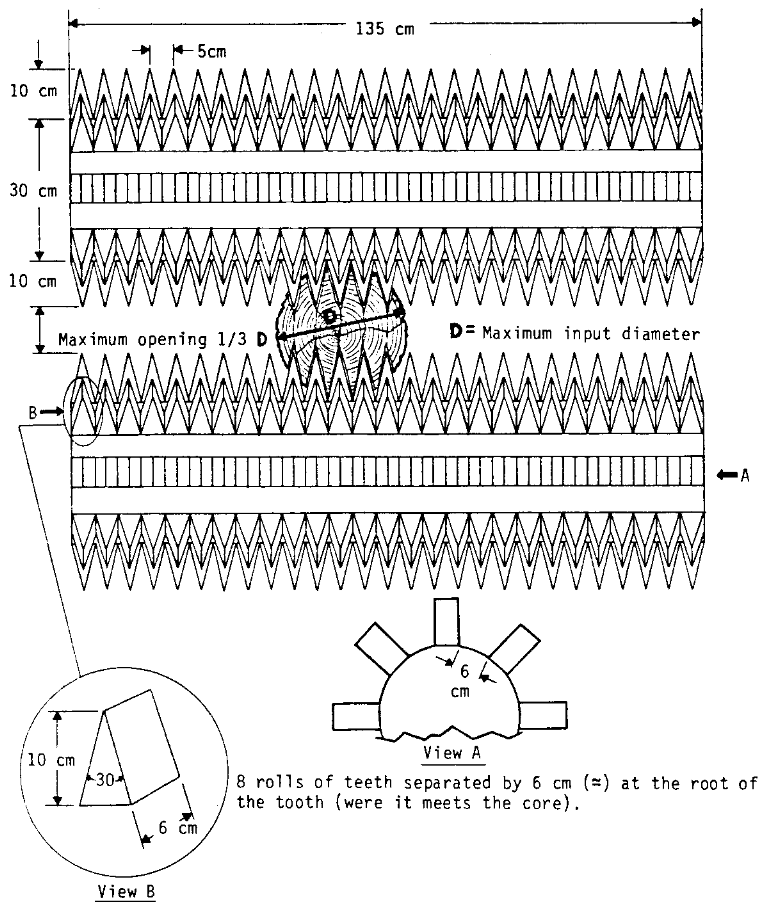


FIGURE 12
SPLITTING ROLL DIMENSIONS
To process 30 cm diameter logs into 3 cm slivers, in a single pass.

Baling tests were also included in our study program, Appendix F. The splintered wood produced in our roll-splitting tests, Appendix E, was baled using a prototype harvesting residue baler, (Walbridge and Stuart (7)). When using compaction pressure of 620 and 1000 Kpa (91 and 147 psi), bale solid volume factors ranged between 43% and 62% with an average of 53%. These solid volume factors can be compared to the 40% to 45% achieved with whole tree chips, and the 50% often achieved with chunkwood chips produced by involute disc or spiral-head chippers. We estimate that a minimum solid volume factor of 50% can be expected using only 350 Kpa (50 psi) and a proper production scale baling system.

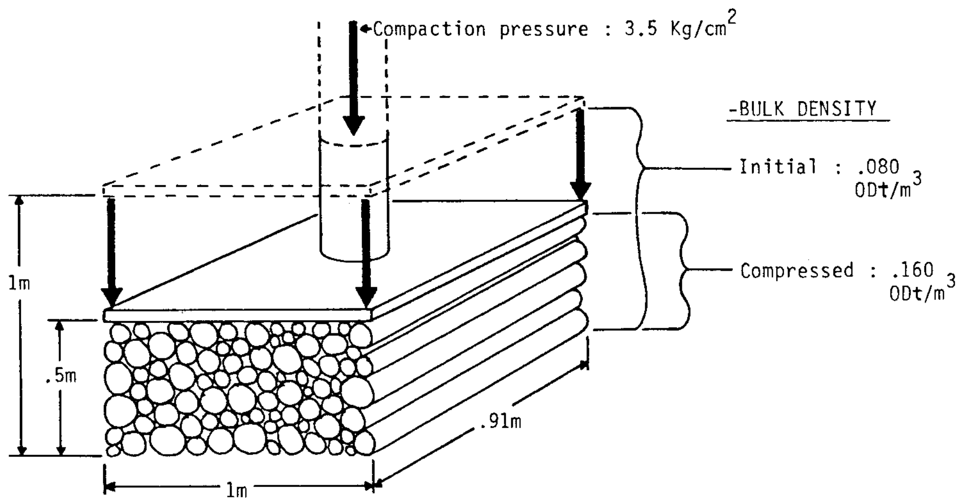


FIGURE 13
COMPACTION AND BALING

Based on the assumption that shearing and compacting Machine Energy requirements are additive, we calculate that 2.5 MJ/ODt are needed to form pine slash bales as illustrated in Figure 13. The only experiments known by the writer which measure compaction energy requirements, involved compaction of wood chips, Hassan (8). These studies estimated that Machine Energy to compact green pine chips (89% MC) varied from .73 MJ/ODt to 2.1 MJ/ODt. These figures are even lower than our calculated value for slash baling, though they do not include our shearing component, which was 1.4 MJ/ODt.

The comparisons of Machine energy requirements ignore the effects of materials handling systems and energy conversion differences of prime movers. At this level, as with the Physical Energy level, large particle processors have low energy requirements. Startlingly enough, crushing equipment, rolls, can be made to compete with the low energy requirements of chipping. Moreover, significant quantities of water can be removed during this process at a lower energy cost than through thermal drying. Whether this moisture removal is needed, or whether it in fact increases the net energy recovery of a conversion process depends upon the particular conversion application. With new conversion technologies, that make more efficient use of heat exchange devices, claiming a direct energy saving equivalent to the enthalpy of taking water from a liquid to a vapour state is no longer always valid.

4.0 CYCLE ENERGY REQUIREMENTS

The Cycle Energy requirements of a comminution process are the fixed operating cost associated with it. Consequently, once the machine type or model is chosen, the only way to minimize costs is to increase productivity during operative hours by loading the machine to its fullest capacity. Figure 14 illustrates the relationship of Cycle energy requirements to productivity. Individual machines obviously have a minimum Cycle Energy requirement, which is determined by the combination of maximum brake horsepower available for processing and the no-load energy consumption. A conservative estimate, based on engine power ratings and the measured no-load fuel consumption rates of machines tested in this project, would probably place the maximum proportion of fuel which can be consumed by the comminution mechanisms at 70% of the Cycle Energy requirement.

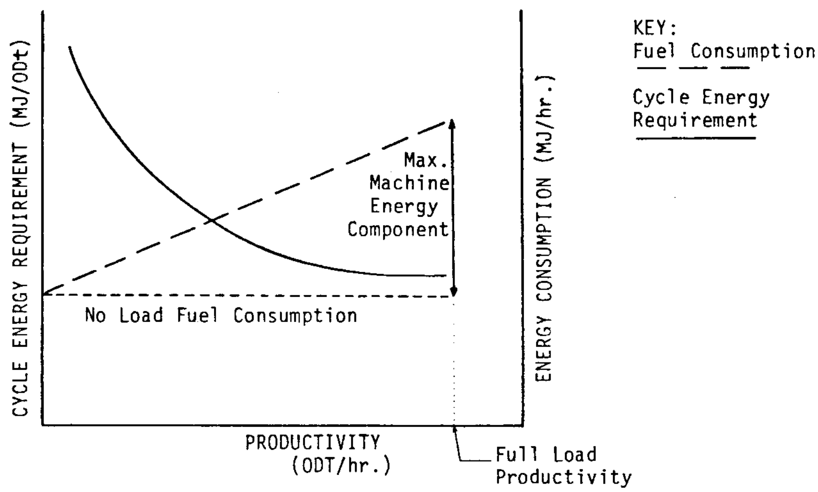


FIGURE 14
CYCLE ENERGY REQUIREMENTS: VS :PRODUCTIVITY

Whether this 70% limit varies significantly between mechanisms such as crushers, chippers, hammermills, etc., is doubtful. Of interest, in testing the roll splitting concept where the processor was under full load almost all the time, the Machine Energy requirement was 68% $\pm$ 1% of the Cycle Energy for all species tested, Appendix E. For the SWD and knife hog, it was calculated to be 75% and 70% respectively, Appendix C and D.

In the tests conducted under field conditions where harvesting residues were being processed, the Machine Energy proportion of the Cycle Energy requirement was always much lower than this assumed best of 70%. For the SWD it was 38%, while for the knife hog, it ranged from 6% to 9%. In an example calculated by Gasslander et al (1), where a large grapple-assisted chipper was processing slash at roadside, it was only 22%. Obviously the productivity of the machines is well below their technical limit due simply to the inability of the infeed system to get the material to the processor in sufficient quantities.

5.0 OPERATIONAL ENERGY REQUIREMENT

The losses associated with Operational Energy requirements are the variable energy costs of processing. They are incurred while the processor is running and waiting to be fed as the infeed system, manual or grapple, attempts to retrieve material or position it on or in some type of infeed device. In traditional pulp chipping operations this energy loss is relatively low, but in a second-pass residue recovery operation, the exceptional variably of the input material requires significantly more sorting and handling to position it properly in linear infeed systems, such as drag chains and infeed rolls. This is particularly true of "cold" logging systems operating from windrowed piles of tangled branches or trees. Table 2 shows the productivities of several residue chipping operations. In all cases the productivities (and therefore Cycle and Operational Energy requirements) are lowest for machines operating from cold piles, and productivity is even lower for random piles, Appendix D. Even in traditional pulp chipping operations the productivity of large grapple-assisted systems is significantly lower because of the tangle factor and frequent moves necessary to reach new material, (Folkema (18)).

TABLE 2

Productivity of Residue Chipping at Roadside

Literature Reference N°	Machine Description and Harvesting Situation	Productivity* ODt/productive working hour
	Knife hog (OLathe 816)	
Appendix D	- hand fed	
	- dry slash random piles	.37
	- green slash random piles	.79
	- 139 Kw engine	
(14)	Knife hog (manf. unknown)	
	- green saplings, hand piled	.87
	- 24 Kw engine	
(15)	Disc chipper (ABC 1000 M)	
	- green saplings, skidder piled	
	- hand fed from cold piles	1.84
	- grapple assisted	2.22
	- 56 Kw engine	
(16)	Disc chipper (Morbark 22)	8.30
	- large hardwood tops	
	- 0.6 green tonnes/top	
	- chipped "hot" at roadside	
	- 450 Kw engine	

* Calculated using green weight productivity, MC of processed material, and time spent chipping, infeeding or sorting.

6.0 CONCLUSIONS

The energy requirements for preparing fuel from harvesting residues can be most easily reduced by:

- developing an infeed mechanism able to accept any material fed to it in virtually any orientation;
- selecting a comminution mechanism that produces the surface area required for energy conversion by splitting wood parallel to the grain, rather than by cutting across it;
- producing a particle suitable for compacting and baling in order to increase uniformity and bulk density for transportation and secondary comminution or drying processes.

The requirement of the first conclusion can best be met with a large hopper infeed such as that employed by the Morgardstuggen (Slash Chewer), prototyped in Sweden and illustrated in Figure 15. Whole, small trees and logging slash are simply dumped into the hopper, and the chewing apparatus, two cylinders with intermeshing teeth rotating towards each other pull the residues in as they comminute it. The cylinders can be reversed to eliminate jams caused by tramp material. While this chewing device sensibly does not use blades requiring regular sharpening, this is considerably less important in saving energy than the hopper infeed concept.

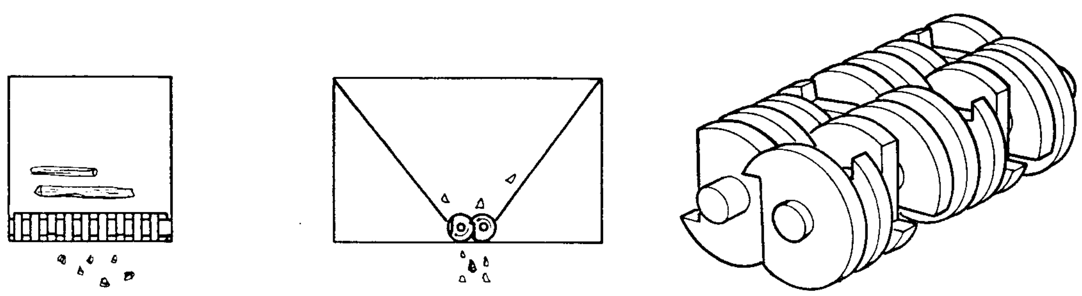


FIGURE 15
MORGARDSTUGGEN SLASH CHEWER

The larger hopper infeed and rugged chewing mechanism of the Morgardstuggen are ideally suited to processing slash and residues contaminated by stones.

Prototype manufactured by: Morgardstuggen A.B.
Box # 502
S-777 00 Smedjebaken
Sweden.

Canadian address: Mr. B. Soostmeyer, President
Centro-Morgardstuggen "Canada" Ltd.
220 Humberland Drive, Rexdale, Ont.
M9W 5Y4 Tel: 416-675-2662

Following development of an effective infeed device the next most important step in reducing energy requirements is selecting the comminution mechanism with the lowest Machine Energy requirement. In effect, choose the processor at the bottom of the hopper discussed in the previous paragraph. To reduce Machine Energy requirements the process demands a sharp cutting mechanism, either a chipper or shearing instrument. In view of the difficulty of maintaining blades, our recommendation is the Recufor concept developed in another portion of the Canada-Feric ENFOR agreement.

Taking the objective of reducing energy requirements of comminution to its fullest extent, the roll-splitting and Recufor concepts should be combined with a compaction and baling operation. A trailer-mounted processor such as the one illustrated in Figure 16 would be the most appropriate. A smaller version (or one more applicable to whole trees) would simply use a roll-splitter as an infeed and preprocessing device ahead of a compaction and bundling operation.

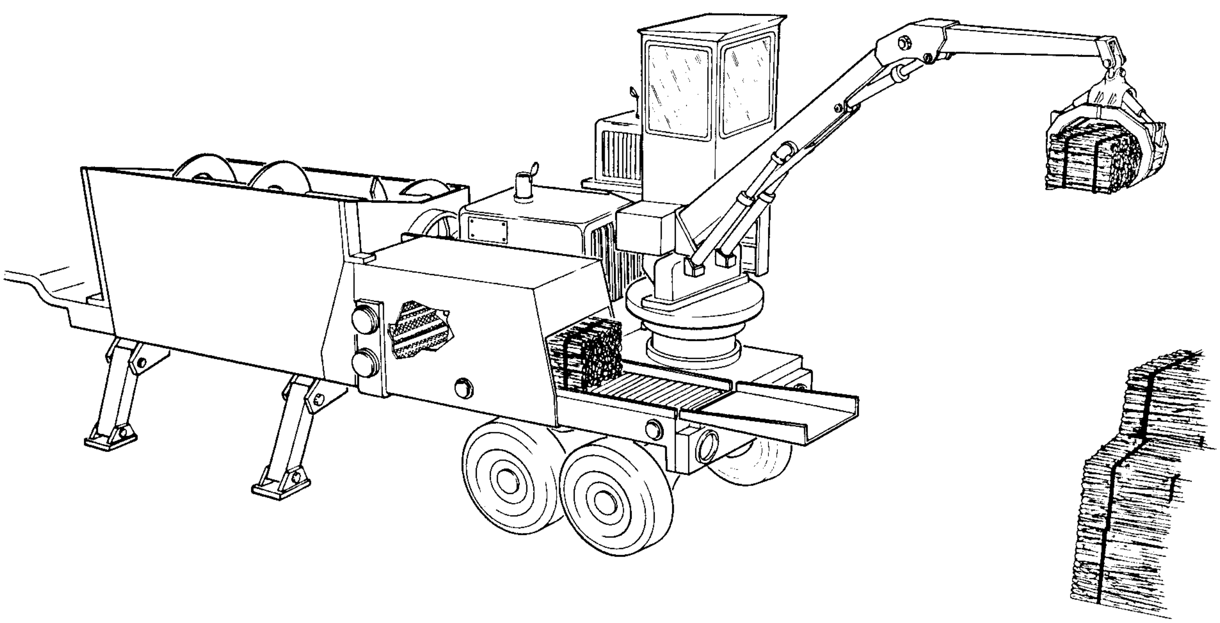


FIGURE 16

LOW ENERGY PROCESSING CENTRE

A RECUFOR is used to billet material which is then Roll Split into slivers and compacted into a bale for storage at roadside ; or compacted directly into a trailer.

7.0 RECOMMENDATIONS

The following three projects should be implemented:

1. A processor based on the concepts of hopper feeding, roll-splitting and compacting slash and rough residues into bales should be designed, constructed and tested. Data are available to determine required compaction forces, processor infeed requirements and general productivity and all the standard mechanical design criteria. We do not know what the most suitable banding material, preferably combustible, is and whether the bales can be made durable enough to withstand handling. Nor do we know the best size of bale to construct. We recommend a bale, roughly 1 m x 1 m, and slightly greater in length, perhaps 1.5 metres. The next best alternative is to keep the height equal to one-half the load height.

2. Once bales are produced, or in a parallel study using hand-built bales of varying sizes, shapes and compaction pressures,the problems and potentials of drying and biological degrade within bales should be examined. Fire hazard, drying rates and the effects on bale structure as they dry should be investigated.

3. A design program should be carried out to identify the facilities and equipment costs of centralized materials handling, receiving, storage, recovery, and further processing (comminution or drying) facilities needed to support a sizeable energy conversion complex, based on bale technology. These materials handling systems are already well developed and applied in other industries, typically agriculture. Therefore, implementation and cost analysis should be as straight forward as is possible with any development program.

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APPENDIX A

Steam Generator to Burn Whole Bales

ACKNOWLEDGEMENT

I am grateful for the assistance given to me by

John Burnett and Dave Winship of Combustion Engineering - Superheater Ltd., Ottawa, Canada for freely contributing the concept design and specifications of the Steam Generator to Burn Whole Bales, Appendix A.

APPENDIX A

Steam Generator to Burn Whole Bales

Based on the following description of baled harvesting residues:

Harvesting Residue Bales

Dimensions:	- length	1.8 M
	- width	1.2 M
	- height	1.2 M
Specific Gravity:	- .56 hardwood (ie. maple)	
Moisture Content:	- 100% (dry basis)	
Solid Volume Factor:	- 54% solid volume	
Bale Weight:	- 1570 Kg (green weight)	
Max. Particle Dimensions:	- 15 cm diameter	
	- length 2 M	

Combustion Engineering - Superheater Ltd. of Canada (C.E.) considered the feasibility of using bales as direct fuel to supply the base load of a steam generator. The assumptions made regarding the generator requirements were:

(a) 300,000 lb/hr @ 850°F/900 psig;

(b) 2/3 of heat input from whole bales;

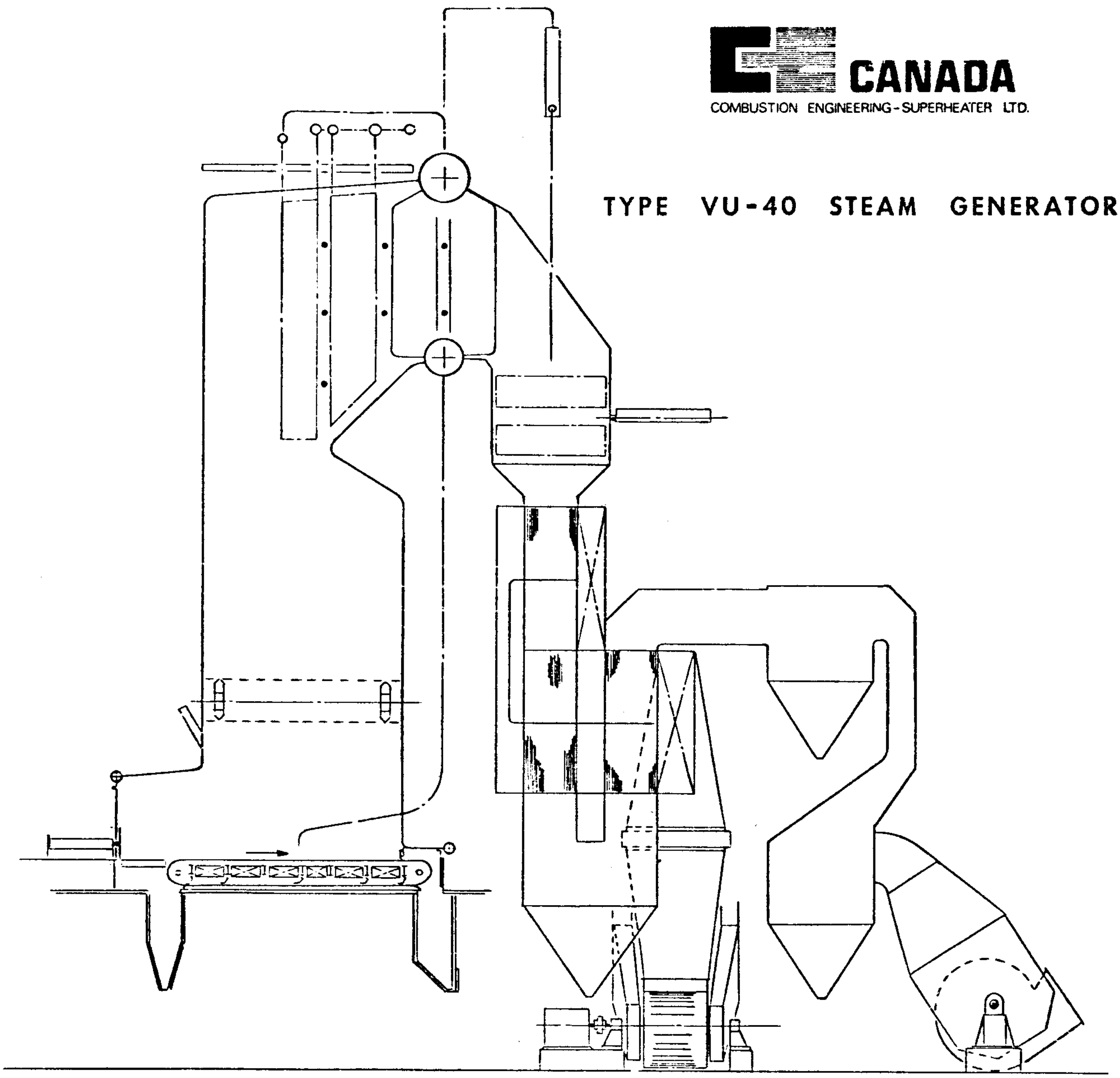
(c) 1/3 input from hogged wood @ 55% MC to accommodate load swings;

(d) allowable grate heat release rate is the same for bales as for hogged wood; and

(e) the furnace leaving temperature will be the same as for the same heat input from straight hogged wood.

Based on these assumptions, a standard unit design known as a C-E VU-40 type top supported, balanced draft, welded-wall furnace with a travelling grate stoker and a two-drum generating bank was chosen. See Figure 1. The furnace dimensions would be:

Width:	7.0 metres
Depth:	6.6 metres
Distance between boiler drum centres:	6.0 metres
Travel Grate Stoker Width:	3.6 metres



An approximate 1981 cost for the hog/oil firing boiler producing similar quality steam would be $6.5 million erected. Combustion Engineering expects that the unique materials-handling equipment required to infeed the bales would raise the cost by 3-4%.

The price would include:

- boiler and furnace;
- travelling grate;
- hog fuel distributors;
- multi cyclone dust collectors;
- force draft fan;
- induced draft fan;
- combustion air and gas ducts;
- steam soot blowers;
- tabular air heater;
- economizer; and
- insulation and lagging.

Not included would be the equipment to recover stored bales and transport them to the boiler infeed mechanism. They would likely cost another $5-6 million.

To supply the steam load, 73 tonnes of wet wood would be needed each hour - 49 tonnes of bales and 24 tonnes of hogged material.

This requires a bale infeed mechanism capable of delivering a bale to the boiler grates every 2 minutes of operating time. Assuming a 365 day-a-year, 24 hours-a-day operation, 430,000 tonnes of bales and 215,000 tonnes of hog would be required.

The principal problem that Combustion Engineering recognized in utilizing these bales was the lack of a suitable infeed mechanism, though they saw no reason why one could not be constructed to deliver bales at the required rate. The existing boiler technology should have no difficulty in burning pieces as large as those proposed in the initial assumptions. The biggest potential problem in the combustion zone would be the disposal of banding material, assuming metal bands were required. The bands would likely cause problems with the interlocking keys of the moving grates and would have to be removed from the ash hopper. Of course, this assumes the worst case where suitable combustible banding material cannot be used.

To minimize tramp air leakage, a double-door sealing arrangement would be used to batch feed the generator. High air infiltration would mean high excess air would be used to burn the wood, thus decreasing efficiency through the dry gas losses in the stack. A similar air lock system has been used in feeding whole, 1.1 m diameter, rolled bales (300-400 Kg green) to crop drying gasifiers, (Piell (13)).

Two methods are proposed for stoking the generator with bales:

Alternative 1: The bales are conveyed to the side of the generator on a conveyor system which passes the bales through a first sealing door immediately before the leading corner. After they pass through, the first door shuts. The conveyor system inside the air/gas lock positions the bales in front of a mechanical or hydraulic ram. A second door then opens and the ram pushes the bale at right angles to the conveyor onto the travelling grate system. The bales would be delivered as required to the appropriate grate location. Figure 2a illustrates this infeed concept.

Alternative 2: The bales are transported to the boiler front and fed through a sealing door by a hydraulic or mechanical ram. After the first door is reclosed, a second door under the bale would be retracted allowing the bale to slide down a water-cooled slope onto the travelling grate. Figure 2b illustrates this concept.

In the opinion of C.E.'s engineers, the technology needed to burn large pieces of roll-crushed wood in bale form exists. There are simply no infeed facilities available with which to test the concept on a full scale basis. Their suggestion was to test burn this type of material on the travelling grate system of an existing installation simply to demonstrate that it was possible to burn long splinters in bale form. Likely the largest bale that could be attempted would be no larger than 2 feet by 2 feet in cross-section. The key point of interest would be to observe the effect on rates of combustion of using bales of very long thin splinters rather than short splinters of roughly the same cross-section. The assumption is that after some minimum length is exceeded, particles will burn (tonnes/hour) at a rate independent of the particle length. The combustion rate would be determined primarily by the cross-sectional dimensions.

A final aspect of this rate of combustion consideration is that bales of slivers, all generally aligned, would have parallel air/gas paths through their lengths. This might result in a greater effective surface area being exposed to the conversion process thus aiding the drying and burning, than is indicated by the particle size. In traditional applications, considerable drying is accomplished in suspension when hogged fuel is delivered to the unit by distributors which throw the fuel across the furnace onto the grate. However, once on the grate these particles can form piles of material which have a low permeability to over-fired air. Bales with a properly designed over-fire air pattern might therefore dry more readily than would the piled hog material.

While this example has concentrated on a moving grate situation, there is no reason why a similar system could not be attempted with a stationary pinhole grate. There, the significance of pile permeability would be more important as would be the use of combustible banding material.

In summary, from a combustion control point of view, there is no reason why bales cannot be used as a direct fuel, particularly for base steam load supplies. Although the infeed equipment is not available, its development is not considered to represent a significant problem. Only an application needs to be found.

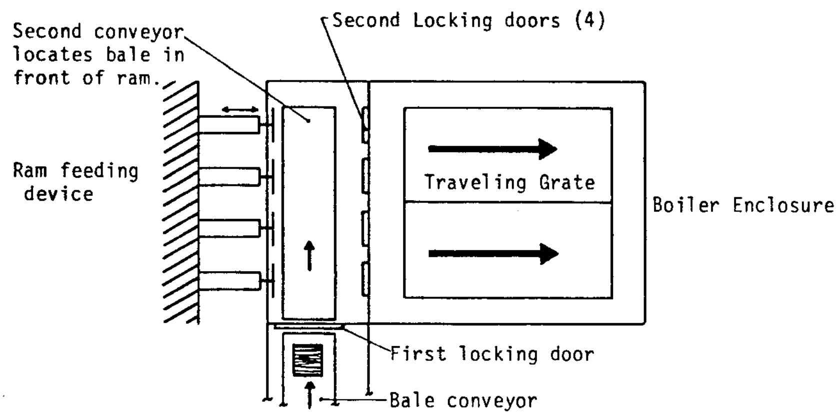


Figure 2a

BALE INFEED: ALTERNATIVE 1

Bales are delivered through the first locking door by conveyor and positioned, stopping in front of the required grate location. The ram then pushes them off the conveyor onto the grate, through the second locking door.

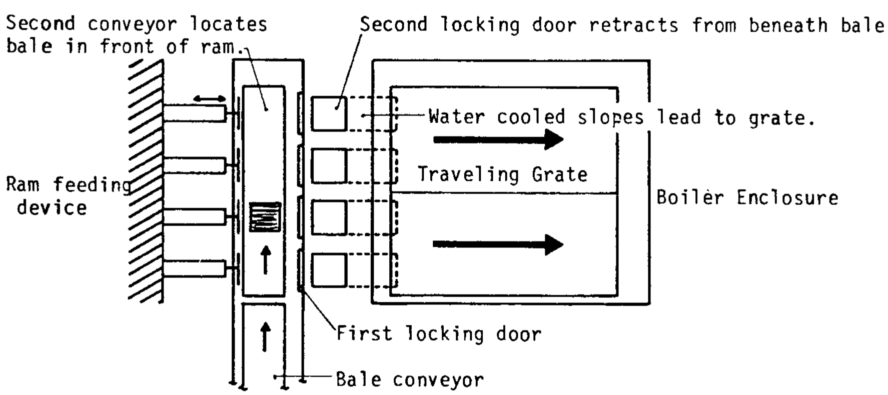


Figure 2b

BALE INFEED: ALTERNATIVE

Bales are delivered in front of ram and are pushed through first door onto the top of the second door. When the first door closes, the second door opens beneath the bale and allows it to slide down a water cooled slope to the traveling grate.

APPENDIX B

FERIC'S EXTENDED BIOMASS HARVESTING PROJECT

APPENDIX B

FERIC's Extended Biomass Harvesting Project

Studies to be undertaken by the Institute pursuant to the forest biomass for energy agreement between the Institute and Canada.

The following described studies are to be included in this program. They deal with inventorying forest biomass after conventional logging operations, with the production of this biomass wood into a useable form, to establish production and cost data and energy-conserving techniques to reduce such biomass to useable form.

Study 1

Title: Inventory of Logging Residues and Unmerchantable Species on Conventional Logging Operations

Objective: To determine the amount of biomass residues recoverable under different conventional harvesting systems, e.g. shortwood, tree length and whole tree systems in various forest types on various sites in selected forest regions. Methodology development and demonstrations are required.

Background: The Canadian Forestry Service's Energy from the Forest (ENFOR) Program is to promote research and development (R&D) to enable the substitution of forest biomass for significant quantities of fossil fuels in the production of energy. In considering forest biomass sources and the R&D to develop them, three scales have been recognized: Scale 1 addresses existing residues at wood-using plants. Scale 2 is concerned with residues from conventional logging operations. These include currently unused portions of trees harvested as well as currently unmerchantable trees and species left behind. Scale 3 visualizes the development of energy plantations and the harvest of these, as well as the harvest of natural forests, for energy.

Study 1 is concerned with Scale 2. Before field scale trials of equipment can be justified, it must be established what residuals exist in terms of weight, their distribution, and the effect of various logging systems upon them. This project then is to assess the amount of residuals, their form and their distribution.

Representative areas in the forest regions of Canada where conventional forest operations are being conducted for both softwoods and hardwoods should be sampled. Sites examined should include pure lowland softwood (usually 100 per cent pulpwood), pure upland softwood types, upland softwood dominant, and upland softwood dominant, and upland hardwood dominant types.

The areas should be recently cutover, within the past year or two. It is expected that most, if not all foliage (leaves and needles) will be off the slash but not necessarily off the residual trees.

There is a marked difference between a survey for residue volume and for biomass. In the former, volumes of wood are measured and/or estimated to predetermined standards of measurement. If considered for conventional consumption by the forest-based industries the specifications are generally related to mill conversion equipment. However in the case of inventorying residues and residuals for biomass, there are no equivalent specifications as we are concerned basically with oven-dry weight of cellulosic material including bark, decayed wood, branches, etc. The result of this is to make the biomass inventory more time consuming.

Study 2

Title: Utilization of Logging Residues and Unmerchantable Species of Conventional Logging Operations

Objective: By undertaking field trials with suitable equipment to establish the following:

1. Effect of weights and form of logging residues on production and cost of reduction to useable material.

2. Effect of total weight per hectare of residues and residuals on productivity and cost.

3. Analysis of effects of components of residues and residuals upon productivity and cost (i.e., utilization of substantial chunkwood only, compared with cleanup of limbs and smaller debris).

4. To assess and establish compatability of various equipment for highest efficiency.

Background: It is essential that productivity and cost of output be determined for various machines and combinations of machines operating under a range of site conditions and biomass weights and shapes.

It is a widely held belief that it is physically difficult and uneconomic to take a second pass through a cutover stand to salvage the residues and residuals. However, there is no information available to support this supposition.

Existing machines may not be suitable for this activity and if not, proposals for new machines should be made, with supporting specifications.

Study 3 K.C.JONES & ASSOCIATES LTD.

Title: To Develop Energy Requirements for theProduction of Biomass in a Form Suitable for Conversion to Energy

Objective: To demonstrate or develop equipment which will be the least energy demanding for reducing forest biomass to a useable form. This may be by chipping, hogging, crushing, producing in chunks, or macerating.

Background: The breakdown of wood into small elements to date usually has been by and for the wood pulp manufacturing industry. The utilization of biomass for energy, as far as is known, does not require wood pulp chip specifications and may take almost any form which can be physically handled and transported.

FOREST ENGINEERING RESEARCH
INSTITUTE OF CANADA
Pointe Claire, P.Q.

Part of
ENFOR PROJECT No. P-28
EXTENDED BIOMASS
HARVESTING

ENERGY REQUIREMENTS AND PRODUCTIVITY OF THE FLING SOLID WASTE DEMOLISHER

Keith C. Jones

K.C. Jones & Associates Ltd.
Ottawa, Ontario
March 1981

ACKNOWLEDGEMENTS

I would like to thank the following people for their co-operation and assistance in completing this test.

MacMillan Bloedel Ltd. and its personnel Ron Greenaugh and Doug Ratton for making the equipment accessible for our tests and their generous assistance during the tests.

FERIC and its personnel Bruce Johnston and Alex Sinclair. FERIC's experience in past residue processing trials was of invaluable assistance in our tests. In particular, the sampling techniques used in gathering the debris description data were developed by FERIC and most of the field and lab work was completed by their personnel.

ABSTRACT

To direct efforts in developing techniques to reduce the energy requirements of comminuting harvesting residues into fuel, the Fling Solid Waste Demolisher (SWD) was tested as it processed sortyard debris. The size distribution of its product, energy requirement distribution and productivity are discussed in detail. The results indicate the SWD's energy requirements are high in comparison to a chipper, and that it is relatively immune to damage by tramp steel and stones. Its productivity and energy efficiency are most seriously limited by the inability of linear infeed systems to maintain a load near its technical capacity.

TABLE OF CONTENTS

		PAGE
1.	INTRODUCTION	C1
2.	OBJECTIVES	C1
3.	MACHINE DESCRIPTION	C1
4.	TEST PROCEDURE	C3
5.	RESULTS	C8
6.	DISCUSSION	C12
7.	CONCLUSIONS	C13
	REFERENCES	C15

LIST OF FIGURES

NO.		PAGE
1.	Fling Solid Waste Demolisher (SWD)	C2
2.	No-load Fuel Consumption vs. Engine Speed	C3
3.	Prototype Debris Processing Set-Up	C4
4.	Material Flow Pattern: Schematic	C5
5.	Instrumentation Set-up	C6
6.	Size Distribution of Raw, Processed, Undersized Debris and Processed Roundwood.	C10
7.	Energy Requirements of the SWD	C11

LIST OF TABLES

NO.		PAGE
1.	Activity and Fuel Consumption Distribution	C8
2.	SWD Energy Losses	C9
3.	SWD Energy Requirements: Processing Sortyard Debris	C10
4.	SWD Energy Requirements: Processing Roundwood	C12

1. INTRODUCTION

This report describes the energy requirements of the Fling Solid Waste Demolisher (SWD) for processing sortyard debris. The energy requirements were measured in a manner which allowed the fuel consumption associated with individual activities to be identified. As well, some brief tests were conducted to identify the energy requirements of the SWD processing roundwood bolts. The energy consumption tests were conducted by K.C. Jones & Associates Ltd. as part of FERIC's Extended Biomass Harvesting agreement with the Canadian Forestry Service's ENFOR program.

At the same time FERIC's own personnel conducted tests to determine the productivity of the entire prototype debris processing system, evaluate the raw material and product, and assess the potential of the overall collection processing and transportation system. Personnel from the two groups assisted each other in gathering samples and data required for their individual efforts.

The results presented in this report are narrower in scope than those of FERIC's Johnston (1), dealing in detail with the performance of the SWD which functioned as the central comminution element of a screen and conveyor system for sorting and comminuting debris gathered from the sortyard.

The debris processing system was built by MacMillan Bloedel Co. Ltd. to determine whether sortyard debris from their China Creek sortyard, 15 km from Port Alberni, BC, could be used as hog fuel in their Alberni-Pacific Pulp Mill. Concurrent with the mill undergoing a shortage of mill-supplied hog fuel, the China Creek sortyard debris dump was nearly full. The high costs of trucking additional hog fuel from east coast saw mills and establishing a new dump site would be reduced and eliminated respectively if the debris could be utilized in the boilers.

2. OBJECTIVES

The objectives of this test were:

- to generate data with which to begin an evaluation of the energy requirements of comminuting harvesting residues on a measured distribution of fuel consumption basis rather than on a batch processing basis which only relates total productivity to fuel consumption;

- to measure the productivity of the SWD in processing loose debris and solid roundwood bolts; and

- to observe the potential for applying the SWD as a processor of slash or whole tree harvesting residues.

3. MACHINE DESCRIPTION

The SWD processing head is illustrated in Figure 1. It uses the kinetic energy of free-swinging hammers to comminute material. Unlike a regular hammermill or hog, the output chute is unrestricted by screens or grates and the hammers are free to rotate 360° about their pivot point. The result is a rather forgiving processor able to pass large rocks without damage while producing an output with a broad size distribution.

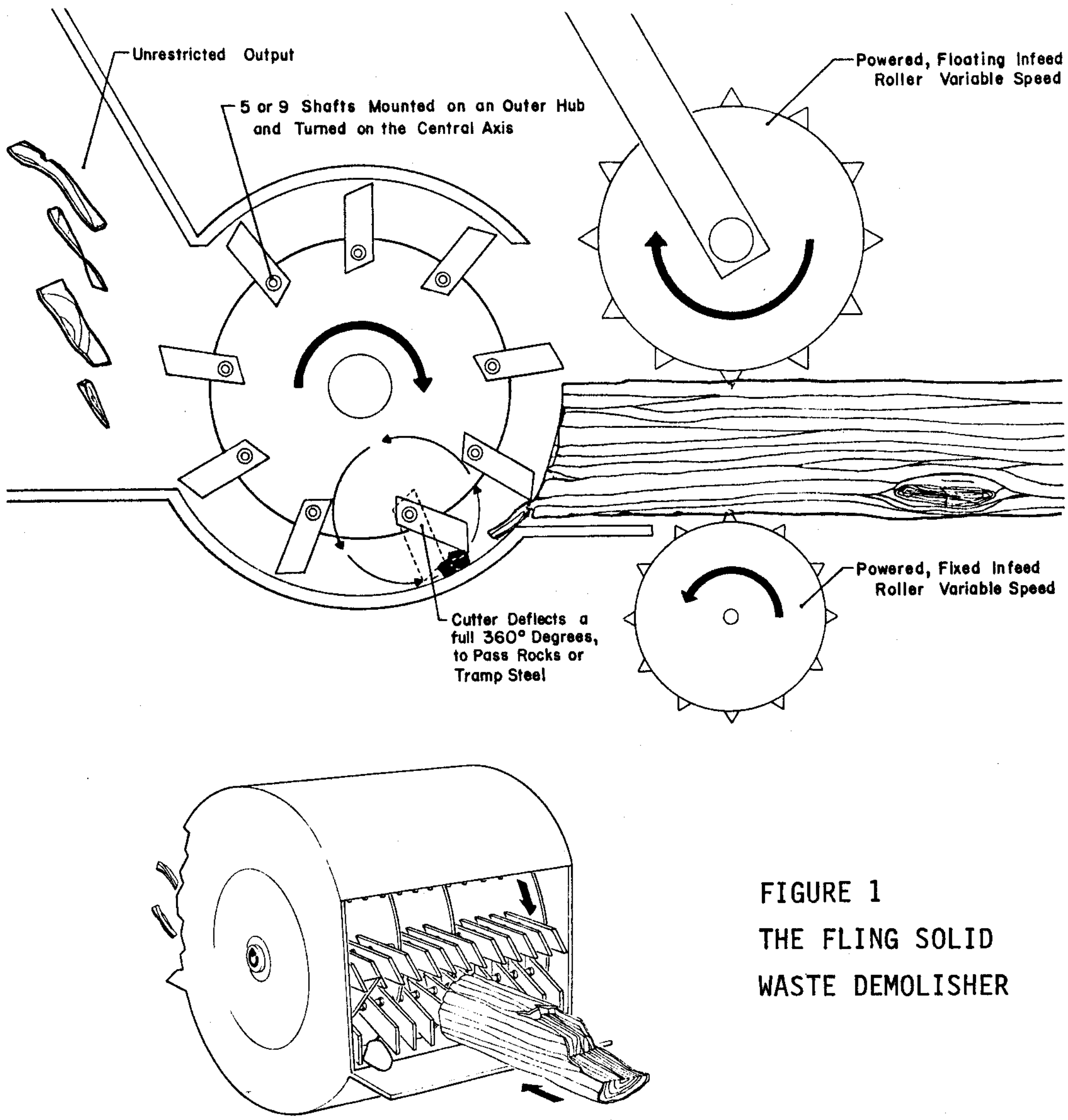
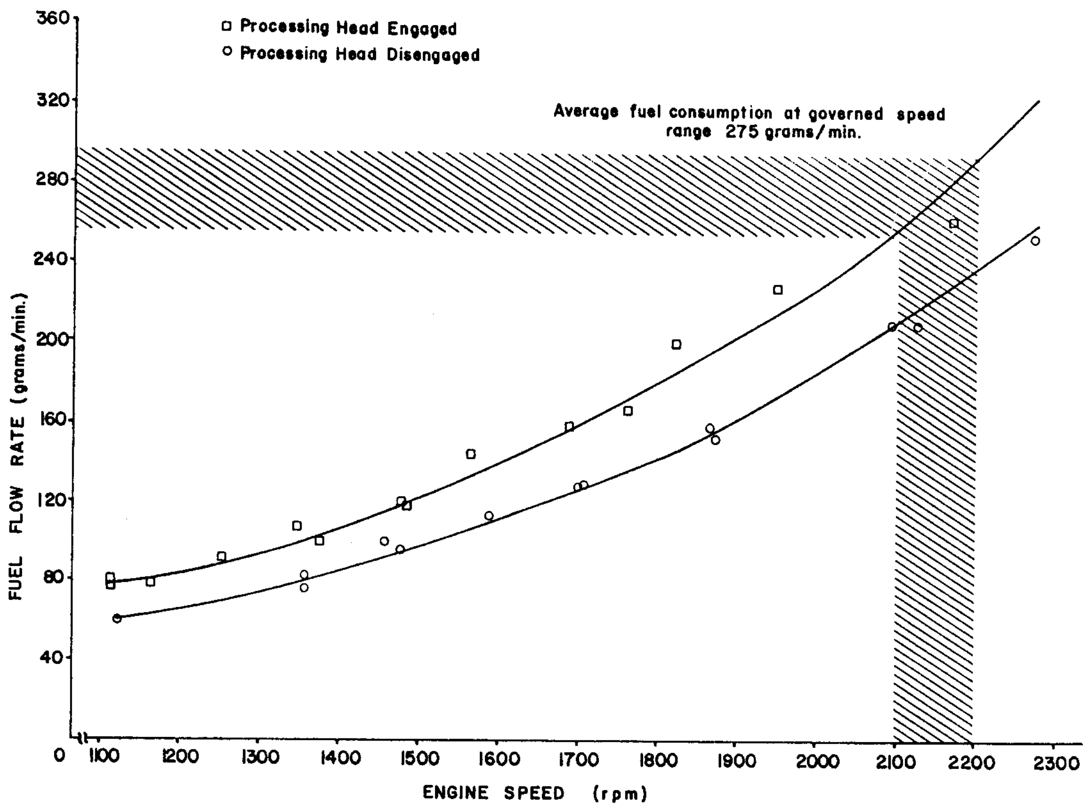


FIGURE 1
THE FLING SOLID
WASTE DEMOLISHER

Since the hammers are free swinging, their performance is significantly affected by rotor rpm. At too low an rpm, the cutters tend to heel in quickly after initial impact. This sensitivity to rotor speed is reflected in the rotor rpm specifications which restrict operating speed to a minimum of 1800 rpm and a maximum of 2200 rpm, the maximum limit being imposed by bearing life requirements. If rotor speed drops below 1600 rpm, the machine quickly bogs out and must be allowed to recover before processing can continue.

In the configuration tested, the SWD was powered by a Cummins NTC 325 diesel engine with a power rating of 242 kwh (325 bhp). The governed processor speed range was 2150-2260 rpm. The no-load fuel consumption of the engine at from idle to full govern speeds, with and without the processing head engaged, is illustrated by Figure 2.

FIGURE 2
NO LOAD FUEL CONSUMPTION : VS : ENGINE SPEED



Assuming a brake-specific fuel consumption rate of .23 kg/kw-hr (.38 lb/bhp-hr) at governed speed, the governed speed power requirement is 72 kw (96 bhp), with the processor engaged and 59 kw (79 bhp) when the processor is not engaged. Only 13 kw (17 bhp) is actually used in turning the processor. The remaining 59 kw is taken up in chassis, fan and hydraulic losses to operate the infeed rolls and conveyor belt. In a portable unit, powered by an IC engine, this difference may be recognized as an unavoidable loss. However, in a stationary electric operation, this loss could be substantially reduced. As well as the possibility of decreasing no-load energy consumption, the superior speed regulation of an induction motor is more suitable to a constant speed application like the SWD.

4. TEST PROCEDURE

The layout of the collection, comminuting and loading facilities of the prototype debris processing system is illustrated in Figure 3. In the test the debris was swept by front-end loaders from the asphalt-covered sortyard up a 2 m incline and into a pile next to a sunken drag chain conveyor. A backhoe pulled the material onto the drag chain at a rate determined by a combination of screen and SWD loading limitations. The drag chain dropped the debris onto a disc separator which passed nominal 5 cm minus material to an inclined conveyor directly into a waiting truck. The over-sized material was passed by the separator onto a horizontal conveyor belt leading to the powered infeed rolls of

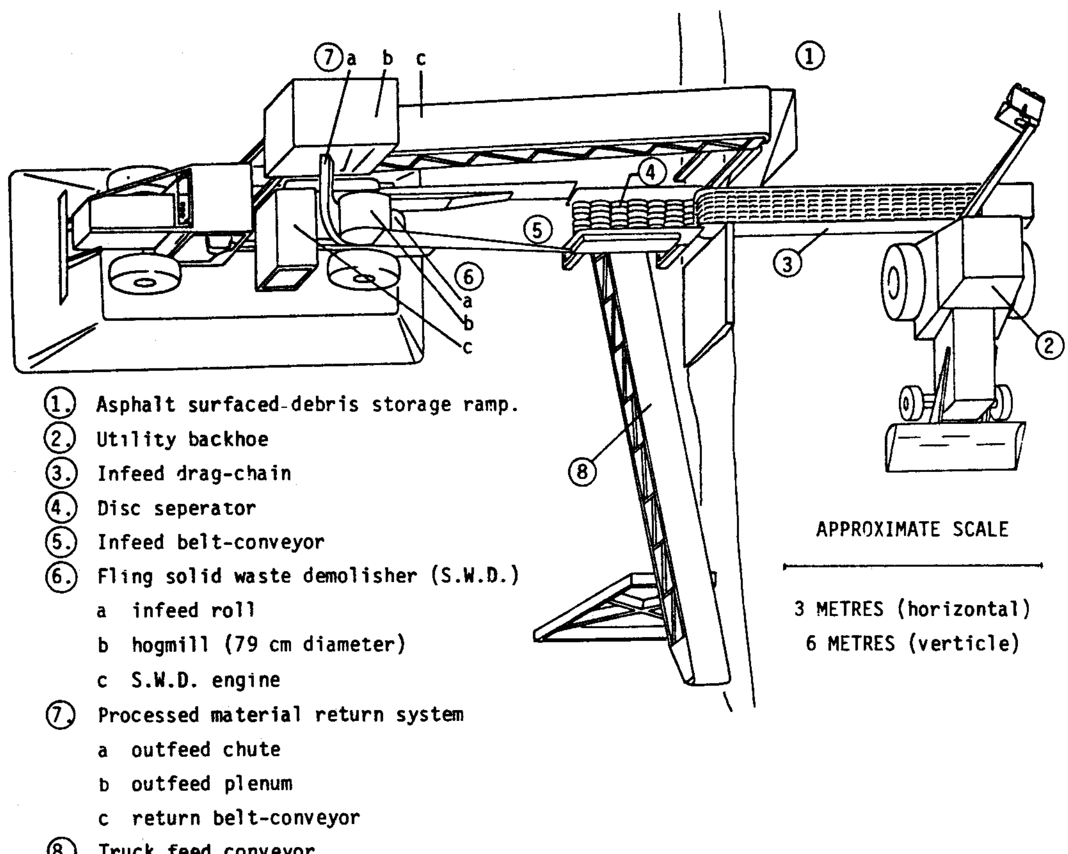


FIGURE 3
PROTOTYPE DEBRIS PROCESSING SET-UP

the SWD. The speed of the infeed rolls was regulated by the SWD operator to maintain a minimum recommended engine rpm. Once processed by the SWD, debris was returned to the input end of the disc separator where it was again sized for further processing or loading into the truck. The material flow pattern of the system is illustrated by Figure 4.

As the debris was processed, the fuel consumption rate and rpm of the engine powering the SWD were recorded on a dual channel strip chart recorder. In parallel with this system, a digital fuel consumption rate and totalizing indicator were observed during processing. The recording and indicating instruments were operated by one observer from inside a vehicle parked adjacent to the SWD. A second person observing the operation from a convenient vantage point controlled event markers running in parallel on the strip chart recorder and maintained radio contact with the instrument operator. By using the event markers, the observer could mark "start" and "end" points of various activities and inform the instrument operator of appropriate notes to record on the strip chart, marking each event. In this manner, a very detailed breakdown of waiting and processing times could be obtained. The rpm recording on one channel

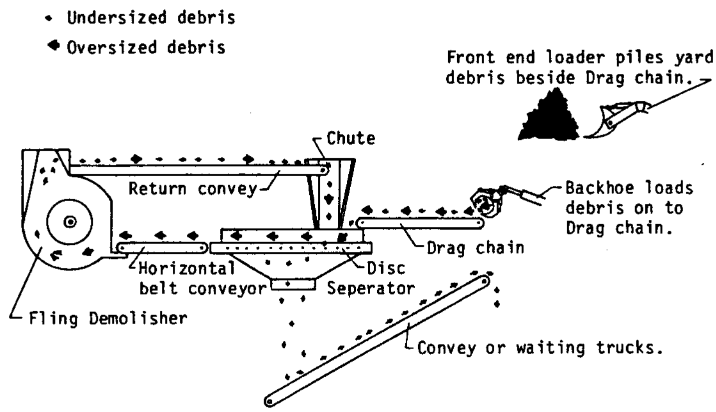


FIGURE 4

MATERIAL FLOW PATTERN : SCHEMATIC

Undersized debris was removed by the disc seperator before reaching the S.W.D. Pieces not sufficiently comminuted by the S.W.D.,were returned by the disc seperator for further processing.

combined with the fuel consumption rate on the other gave an excellent indication of effort levels exerted by the SWD. The digital fuel consumption rate indicator provided an instrumentation check against the strip chart and the fuel totalizing channel yielded an accurate measure of the mass of fuel used to process each truck load. This instrumentation set-up is shown in Figure 5.

During testing, the following activity classifications were marked on each strip chart recording:

PROCESSING: The SWD is performing effective work with debris passing through the processor.

WAITING: The processor is running at full governed speed but is waiting for material to be delivered by the screen and conveyor system. This activity has been further subdivided into the following minor delay classifications such as:

MINOR DELAYS

Infeed Delay: Waiting for material to be delivered to the processor caused by backhoe positioning or moving to reach new material, material hanging up on infeed conveyor, or 100% of the material delivered to the disc separator passed through as undersized, causing the processor to wait.

Remove Oversize: The SWD infeed is limited to a 30 cm maximum diameter. The oversized pieces must be removed by hand or by using a small hydraulic grapple.

Remove Rocks: While the Fling Demolisher will process rocks of considerable size, the infeed must be stopped for by-hand removal of very large stones (15 cm plus).

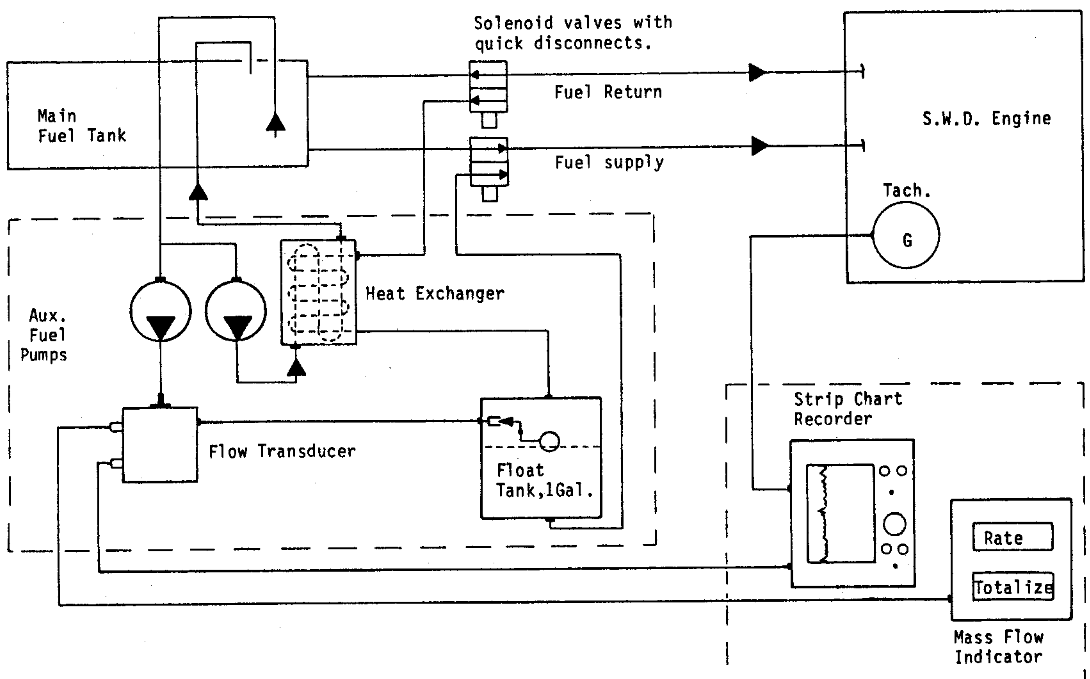
Output Chute Plugged: After exiting the processing head, the material made a 90° turn in the output chute (see Figure 2). On occasion this chute plugged when long splinters were passed through and wedged in the turn of the chute. Excessively wet material also aggravated the situation. This turn would be eliminated in a production machine.

IDLING: The machine is running but not waiting for delivery of material by the conveyor systems. This includes warm-up time and idling while repairs are made to the Fling or conveyor system.

FIGURE 5

INSTRUMENTATION SET-UP

The heat exchanger,float tank and flow transducer were mounted on the S.W.D..The strip chart recorder and digital indicator were located inside a vehicle parked adjacent to the processing system.



Strip chart recording and a remote observer with an event marking system proved to be a reliable and effective means of gathering data and observations, particularly as the prototype nature of the operation caused frequent delays.

In order to consider the application of the SWD in a broader scope (for example, where whole trees are being processed) its fuel consumption was monitored as measured and weighed pieces of wood were processed in a brief test. The pieces were bolts of western hemlock (Tsuga heterophylla), red alder (Alnus rubra) and western red cedar (Thuja plicata), roughly 2.5 m in length, 10-25 cm in diameter and 30-80 kg in weight. Moisture content samples were taken from the bolts immediately after processing.

Besides this breakdown of activities, the energy consumption of the chipper was described in terms of Machine, Cycle and Operational energy requirements as first described by Gasslander et al (2). The definitions of these energy requirements follow.

> **Operational energy** is the total fuel consumption of the processor during any operative period. It includes all fuel consumed during waiting, idling, and warm-up periods.

The Operational energy requirement was calculated by dividing the total energy consumption recorded on the totalizing channel of the flow meter by the dry weight of the material recovered. The dry weight of each chip load was calculated using the green weight of the load and the average moisture content of the sample bags gathered at random during the chipping operation as follows:

$$\text{Operational Energy Requirement} = \frac{\text{Total Fuel Consumption}}{\text{Dry weight recovered}}$$

> **Cycle energy** is the total energy consumption of the processor during productive times. It includes the fixed energy consumed by auxiliary equipment such as fans, pumps and blowers.

The Cycle energy requirement was calculated by subtracting the fuel consumed during waiting and idling times from the total fuel consumption. The fuel consumed during waiting and idling was calculated using the measured no-load fuel consumption rate and the waiting time recorded on the strip chart.

$$\text{Cycle Energy Requirement} = \frac{\text{Total Fuel Consumed} - (\text{No-Load Fuel Rate} \times \text{Waiting Time})}{\text{Dry weight recovered}}$$

> **Machine energy** is the energy consumed by the working tools only. It does not include the fixed energy consumption of a machine as it runs at governed engine rpm to operate fuel pumps, fans, etc.

All these energy levels are expressed in terms of the oven dry weight chipped and blown into the van.

The Machine energy requirement was calculated in a manner similar to the Cycle energy. The no-load fuel consumption rate times the total running time was subtracted from the total fuel consumption. This yielded the energy consumption by the chipping process only, independent of the fixed energy consumption of the equipment.

$$\text{Machine Energy Requirement} = \frac{\text{Total Fuel Consumption} - (\text{Total Time} \times \text{No-Load Fuel Rate})}{\text{Dry weight recovered}}$$

Figure 3 illustrates the relationships between the three energy levels calculated from the test results. The additive nature of errors into the subtraction process used in calculating the Cycle and Machine energy levels obviously introduces errors into the results. However, no other approach was feasible within the restriction imposed by field testing conditions.

5. RESULTS

During the tests period between May 19 and June 3, 1980, 859 minutes of SWD operating time were used to recover 56.82 oven dry tonnes (ODt) at 127% moisture content (MC) with 7% non-combustibles content and an average 20.7 megajoules (MJ)/ODt kg higher heating value.

Several adjustments were made to recording techniques during the first days of testing, therefore only 6 of 10 truck loads were monitored in a manner which allowed a detailed analysis to be made of the processing, idling and waiting times. These six loads contained 34.76 ODt of debris and were processed in 400 minutes, using 137 kg of diesel fuel. The productivity of the system during the recorded time was 5.2 ODt/operative hour. An operative hour is defined as the time when the system is mechanically available and a receiving truck and personnel are on site.

Table 1 summarizes the pattern of activities and fuel consumption measured. From it, 60% of the recorded time was spent processing material, 24.6% waiting for minor delays, 5.4% idling at less than governed speed and 10.0% shutdown to clear a jammed screen or a plugged output chute. Eighty percent of the fuel used was consumed during processing time and the remainder during waiting or idle times.

TABLE 1

FLING SWD
ACTIVITY AND FUEL CONSUMPTION DISTRIBUTION
(Debris Processed = 34.76 ODt)

ACTIVITY	TIME		FUEL CONSUMPTION	
	(min)	(%)	(kg)	(%)
PROCESSING	240.7	60	108.00	78.9
WAITING				
infeed delay	63.2	15.7	17.35	12.7
remove oversize	10.1	2.5	2.78	2.0
remove rock	4.8	1.2	1.32	1.0
chute plugged	18.6	4.6	5.12	3.7
other	1.9	.5	.52	.4
SUBTOTALS	98.6	24.6	27.12	19.8
IDLING	21.5	5.4	1.71	1.2
SHUTDOWN				
screen jammed	21.1	5.2	0.0	0.0
chute plugged	19.0	4.8	0.0	0.0
TOTALS	400.9	100	136.83	100

During **processing** the average fuel consumption rate was .450 kg/min. Of this, .275 kg/min were being used to supply the engine base load, operating fans, pump, etc. Therefore, while the tabled figures indicate that 108 kg of fuel were consumed while processing, only 66 kg of this were consumed as the base load of this processor. In all, engine base load, waiting time and idling accounted for 94.83 kg of the 136.83 kg of fuel used (see Table 2). Therefore, while 79% of the total fuel consumption was used during processing, 69% was consumed as engine base loads or in minor delays.

TABLE 2

SWD Energy Losses

Cause	Kg of diesel fuel lost
energy base load while processing	66.00
waiting time	27.12
idling	1.71
TOTAL	94.83 kg of fuel

Sortyard debris comes from bark and log ends broken off during scaling operations. It is generally wet, 100% MC plus, and contains a high proportion of non-combustibles, rock grit and tramp steel such as bundling cables. Figure 6 describes the size distributions of the raw debris, processed debris recovered in the trucks and raw debris passed by the disc separator before reaching the SWD (undersized debris).

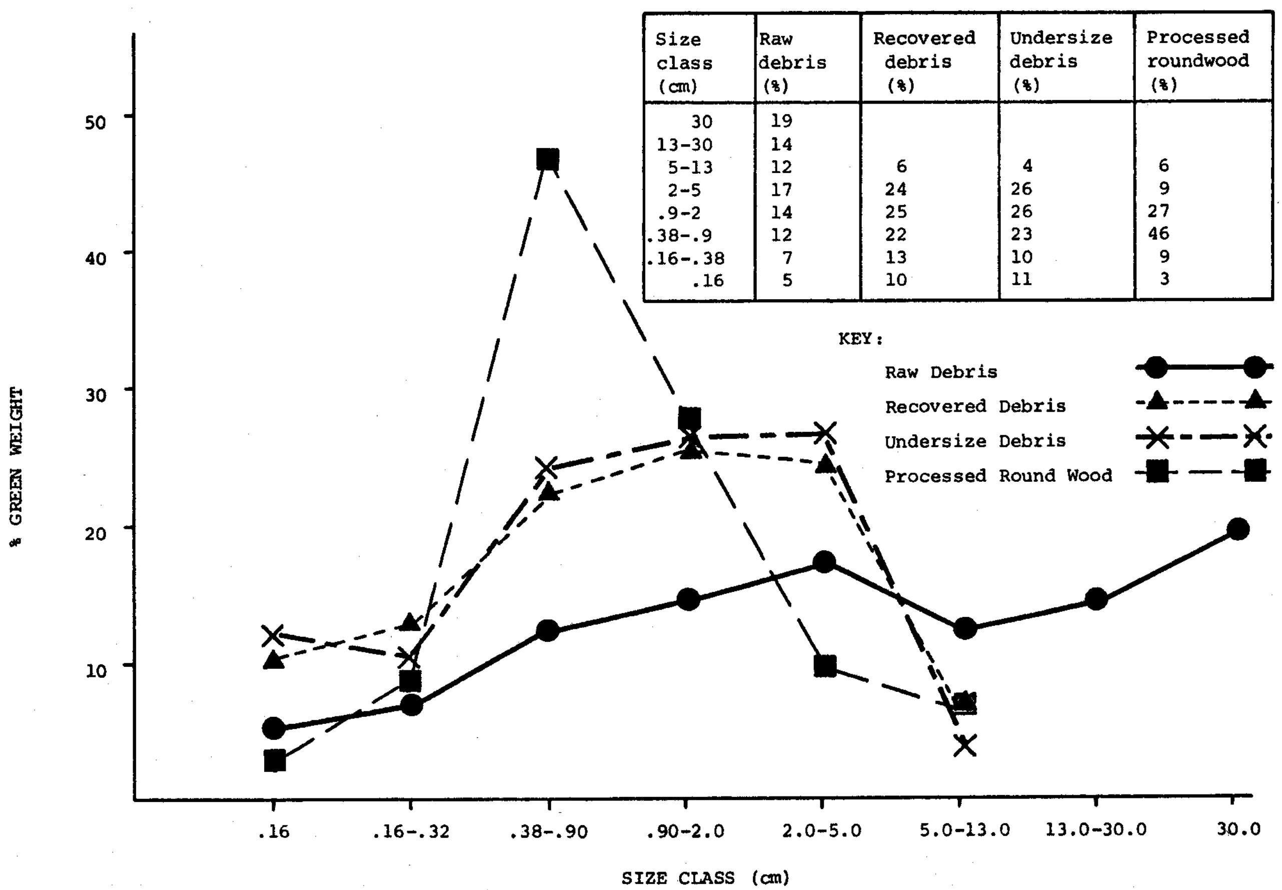
It was not possible to measure the proportion of raw debris removed by the separator before reaching the SWD or the proportion recirculated more than once through the SWD. However, as a best estimate, we have assumed that only the fraction of raw debris greater than 5 cm was processed. This fraction, processed debris, represents 45% of the weight of the recovered debris and agrees roughly with subjective estimates made of the portion of raw debris being processed.

Since only 45% of the recovered debris was actually passed through the SWD, energy levels can be expressed on the basis of either the recovered or processed debris weights. In analyzing the particular system tested, the recovered weight basis is most relevant. On a broader scope, such as using the SWD to process slash without a prescreening operation, the processed weight basis is more significant. Both views have been presented in Table 3. The total weight of material recovered was 34.76 ODt. The weight of material processed has been estimated to be 15.64 ODt of debris.

TABLE 3

SWD Energy Requirements
Recovered and Processed Weight Basis

Basis	ENERGY REQUIRED (MJ/ODt)		
	Machine	Cycle	Operational
Recovered Weight	53	136	172
Processed Weight	117	301	383



Size class (cm)	Raw debris (%)	Recovered debris (%)	Undersize debris (%)	Processed roundwood (%)
30	19			
13-30	14			
5-13	12	6	4	6
2-5	17	24	26	9
.9-2	14	25	26	27
.38-.9	12	22	23	46
.16-.38	7	13	10	9
.16	5	10	11	3

FIGURE 6
SIZE DISTRIBUTION OF RAW, RECOVERED, UNDERSIZED DEBRIS, AND PROCESSED ROUNDWOOD

The differences (losses) between each energy requirement level are illustrated in Figure 7. Also included is the energy requirement distribution measured while processing roundwood.

During the tests to determine the SWD's energy requirements to process roundwood bolts, a mix of 12 measured and weighed bolts of red alder, western hemlock and western red cedar totalling .244 ODt at 100% MC was processed in 202 seconds. The bolts were 2.5 m in length. While it would have been desirable to process more than this very small sample, the SWD and screen system, due to their prototype nature, had been plagued by mechanical problems. Therefore, the sample was small so as not to jeopardize the regular test.

While the results are based on a small sample they are indicative of the Machine energy requirements to be expected from this type of machine. The Operational and Cycle levels are, of course, determined by the materials handling situation and are therefore representative of the experimental nature of the test.

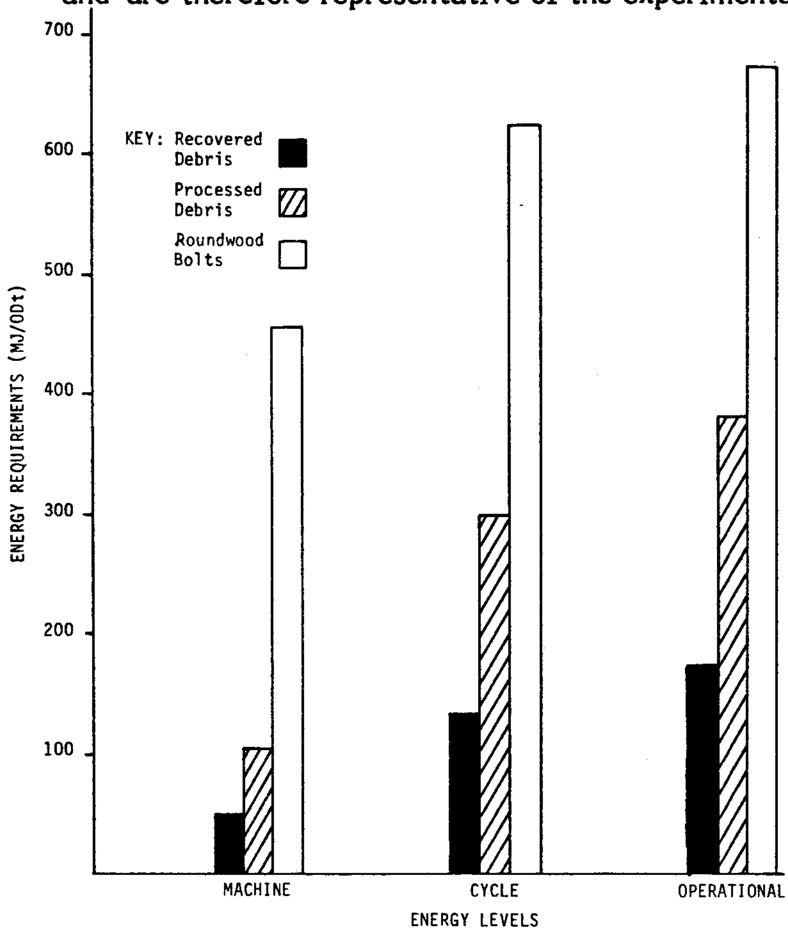


FIGURE 7
ENERGY REQUIREMENTS
OF THE S.W.D.

	Energy required CMJ/ODt		
	Rec.'d	Proc.'d	Round
Mach.	53	117	460
Cycle	136	301	636
Oper.	172	383	682

The size distribution of the roundwood processed during this test is shown in Figure 6. The energy requirements measured are shown in Table 4. Due to the test arrangement, a meaningful Operational energy level could not be measured, but was calculated assuming that the machine would be processing bolts for 75% of each operating hour with the average no-load fuel consumption rate of .275 kg diesel fuel/minute. The productivity of the SWD under these conditions was 3.2 ODt/operating hour (based on 202 seconds to process .244 ODt).

TABLE 4

Energy Requirements
SWD Processing Roundwood

Level	Energy Requirement (MJ/ODt)
Machine	460
Cycle	626
Operational*	682

* calculated (see text for assumptions).

The difference between the Machine and Cycle energy levels (the base load of the machine) is only 176 MJ/ODt or 26% of Cycle energy. During the test, average productive fuel consumption was 1.04 kg/min. Equivalent to a 271 kw load at .23 kg/kw-hr, this is equal to rated power available. The flywheel effect of the processing head was obviously supplying additional energy over the very short time it took to process each bolt. Therefore the Machine energy requirements measured are lower than could be expected for the SWD in long term service.

6. DISCUSSION

The distribution of energy consumed by the SWD (Figure 7) is indicative of the difficulty all harvesting residue processor systems have in maintaining a load factor even close to their technical capacity. In this case, 32% (66 kg) of the fuel consumed while processing debris was used in actual comminuting of the debris. In other studies, the energy distribution has been calculated for chipping piles of slash at roadside, (Gasslander et al (2)). In that case, only 16% of the energy was assumed to have been applied at the Machine energy level. By this comparison, the distribution of energy consumed by the SWD is relatively good. However, our figures do not account for the energy consumed by the drag chain, disc separator conveyor belts and backhoe.

The productivity of the debris processing system, 5.2 ODt/productive hour, is quite good by comparison to other residue recovery operations. Using data from Blakeney's (3) Study of a harvesting residue processing system, the productivity of large grapple-assisted chippers was 2.12 ODt (227 tonnes at 122% MC in 48 operative hours) and 1.28 ODt (102 tonnes at 150% MC in 32 operative hours). The machines tested were a Nicholson Complete Tree Utilizer and a Bartlett chipper, both 450 kw rated machines. This comparison is not to suggest that the SWD is better than either of these machines. It simply points out that the infeed system is in all cases the limiting factor and usually consumes more energy than the comminution.

The size distribution of the material output by the SWD is broader than that of most hammermills and chippers. Further, the size distributions shown in Figure 6 are those of the entire system where the disc separator has recirculated oversized particles. Once the infeed rolls lose their grasp at the end of a large piece, it is pulled instantly into the SWD and often passes through as large splinters 30 cm or long. These large pieces are not included in Figure 7. This type of operation is characteristic of any "hog" operating without a sizing screen to recirculate material. The Montgomery Tie Destroy, a punch and die hog used as a railway tie processor, also operates without the usual sizing screen to prevent damage from rock and tramp steel.

One advantage of the SWD over conventional chipping devices is a wide ranging infeed speed capability from zero to 420 fpm. This allows the operator to maximize productivity, though using high infeed speeds with small infeed elements results in a broad size distribution.

The results of the very brief test run while the SWD processed roundwood bolts suggest that, while it is capable of processing material up to 30 cm in diameter, the energy cost would be roughly 8 times that of a chipper when processing large diameter residues. Adjusting the 460 MJ/ODt Machine energy requirement of a diesel powered SWD to an electric basis yields 160 MJ/ODt as compared to 10-20 MJ/ODt required by a pulp chipper, (Papworth and Erickson (4)). Energy conversion efficiencies of 30% and 85% were assumed for diesel and electric engines respectively.

The productivity of the SWD as measured by FERIC's conventional time sampling studies is in close agreement with those measured by K.C. Jones & Associates Ltd., using observers and a commented strip chart recorder. FERIC measured the productivity to be 5.16 ODt/operative hour over the entire study period (11.2 green tons/hour at 117% MC), and our measurements indicated 5.2 ODt/hour for 6 rather than 12 shifts.

The report prepared by FERIC, Johnston (1), gives a very comprehensive evaluation of the quality of the fuel produced. In particular, it points out the potential for improvement of the quality by screening out the very fine fraction to reduce the non-combustibles content represented by grit and sand. Johnston also speculates on the possibility that this smaller size fraction has a higher than average moisture content, presumably due to its high specific surface area retaining large quantities of water by surface tension. Johnston's laboratory test did not reveal this aspect of fuel quality improvement though he suggests that unavoidable delay in determining moisture content masked this effect. Based on our observation of the same test, we agree with his evaluation.

7. CONCLUSIONS

The energy consumption of the SWD is considerably higher than that of a chipper or knife hog producing a similar size product. However, by comparison, it is also immune to damage by stones or tramp steel.

In the debris processing system tested, its productivity was 5.2 ODt/operative hour, which is high in comparison to other harvesting residue comminution operations. The diesel engine Operational energy requirement to run the SWD was 383 MJ/ODt. When briefly tested, processing roundwood bolts, the productivity decreased to 3.2 ODt/operative hour and the Operational energy requirement increased to 682 MJ/ODt.

The SWD's variable high speed infeed system 130 M is ideally suited for a small diameter residue processing application. It allows the operator to maximize the load applied to the machine which, at the same time increases productivity.

As tested in the debris processing system, the SWD simply operated as a hammermill with its sizing screens removed to the location of the disc separator to prevent damage by tramp material. However, the unique ability of the SWD cutters to rotate a full 360° about their point of rotation, renders them more effective in preventing damage than cutters in the system often used by other impact machines which allow only a limited deflection of the hammers.

The SWD is ideally suited to processing smaller-diameter harvesting residues up to perhaps 15 cm, though it can be extended beyond this range. In a 250 kw model, as a whole tree processor, its useful limit is probably 20 cm diameter material, particularly for large "hard" hardwoods such as maple. It is more suited for processing broken pieces, slash and branches than whole trees.

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APPENDIX C

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FOREST ENGINEERING RESEARCH
INSTITUTE OF CANADA
Pointe Claire, P.Q.

Part of
ENFOR PROJECT No. P-28
EXTENDED BIOMASS
HARVESTING

ENERGY REQUIREMENTS AND PRODUCTIVITY OF A PORTABLE KNIFE HOG

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ABSTRACT

Productivities and energy efficiencies of traditional whole tree chippers processing harvesting residues have, under most test conditions, been poor. To compare these previous test results with a smaller, manually intensive operation, the productivity and energy consumption distribution of a portable knife hog were measured. It was fed manually from green and dry hardwood slash windrowed at roadside. The energy requirements and productivity of this operation are compared to more mechanized systems. They show the same poor results, for the same reasons, the inability of traditional linear infeed systems to maintain adequate load factors on the chipping elements.

TABLE OF CONTENTS

		PAGE
1.	INTRODUCTION	D1
2.	OBJECTIVES	D1
3.	MACHINE DESCRIPTION	D2
4.	TEST PROCEDURE	D4
5.	RESULTS	D5
6.	DISCUSSION	D6
7.	CONCLUSIONS	D12
	REFERENCES	D13

LIST OF FIGURES

NO.		PAGE
1.	Knife Hog	D2
2.	Instrumentation Set-up	D4
3.	Direct Energy Levels	D6
4.	Size Distribution of Knife Hog Chips	D8
5.	Energy Requirements to Knife Hog Elm Slash from Random Piles	D10

LIST OF TABLES

NO.		PAGE
1.	Activity and Fuel Consumption Distributions	D7
2.	Knife Hog Energy Requirements	D8
3.	Energy Loss Distribution	D9
4.	Productivity of Residue Chipping at Roadside	D9

1. INTRODUCTION

In several studies and reviews of energy requirements, intensive manual harvesting operations have been identified as being less energy-intensive than mechanized operations, (Ash, Knoblock and Peters (1), Gasslander, Mattsson and Sundberg (2)). This conclusion has, however, been based on observations and calculations made regarding conventional pulp harvesting operations. Very few data with which to contrast the energy requirements of recovering and processing harvesting residues at roadside are available. Those available, describe mechanized systems employing large, high-powered chipper and grapple combinations. Gasslander et al (2) have calculated, assuming theoretical load factors, the energy requirements of a Bruks 1200 C chipper and grapple combination (250 kw) processing logging slash at roadside. Blakeney (3) has measured the total energy consumption of a Nicklson Complete Tree Utilizer and a Bartlett chipper, both 450-475 kw rated, as they processed harvesting residues windrowed into piles at roadside.

To the writer's knowledge, no data have been gathered to quantify the energy requirements and productivity of a manually-fed system chipping slash into trucks at roadside. In view of the lower energy requirements of intensive manual pulpwood systems, a brief test was made to gather data which would accurately describe the energy consumption and productivity of such a system. A portable chipper used by land clearing crews was used in the test. This type of machine is often referred to as a knife hog, because of its unrestricted infeed speed and consequent tendency to pull branches and slash into itself at high speed.

2. OBJECTIVES

The specific objectives in measuring fuel consumption and productivity of the portable knife hog were:

- to generate data with which to begin an evaluation of the energy requirements of comminuting harvesting residues on a measured distribution of fuel consumption basis, rather than on a batch processing basis, which only relates total productivity to total fuel consumption;

- to measure the productivity of an experienced land clearing crew chipping small diameter branch material windrowed at roadside, much the same as harvesting residues might be accumulated by pushing material into random piles;

- to contrast the productivity of the knife hog while processing green and dried material under the above conditions; and

- to gather data which would allow some reasonable comparison to be made between the productivity and energy requirements of manual and mechanized slash processing at roadside.

The data gathered in a test of the scale attempted here is rather specific but so to is that calculated and measured by Gasslander et al (1) and Blakeney (3). Therefore, the test results only begin the task of reliably quantifying the energy requirements and productivity of these systems. In this case, the tests were made under conditions which provided unlimited access to windrowed piles of branches without the requirement of moving the chipper or waiting for trucks.

While these factors would greatly affect the productivity on a scheduled machine hour basis, and to a lesser degree energy consumption, the scale of test required to take these factors into account was beyond the project's scope. The objective was to gather data based only on productive time by minimizing these external influences.

3. MACHINE DESCRIPTION

The machine used in the tests, an Olathe model 816 chipper, was rented from a local contractor whose personnel had had 2 to 3 years experience in land clearing operations. The machine was two years old and was considered to be in good operating condition. No significance is attached to the make of the machine used. It was simply one of the most powerful machines of its type available. Observation of several crews and machines indicated that its performance was representative of this class of larger knife hogs. Figure 1 illustrates the machine tested. Its pertinent manufacturer's specifications are on the following page.

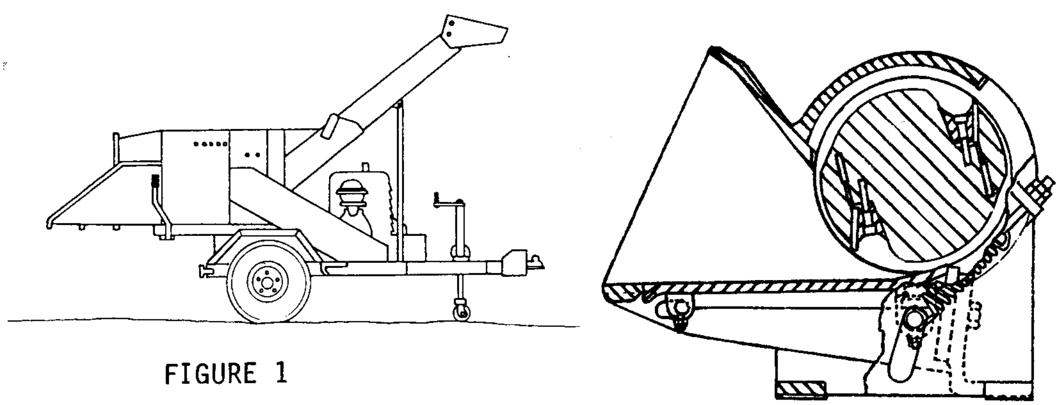

FIGURE 1
KNIFE HOG.

The knife hog tested was regularly employed in land clearing of all types in processing green and dry material, both standing and downed. While it was in good mechanical order, the knives were work-dulled. Unlike pulp chippers whose blades are changed with great regularity, the practice with these machines is to sharpen blades when the crews feel there is a noticeable reduction in the machine's ability to process large limbs. This usually is once over 4 weeks, based on about 3 hours a day continuous working, 5 days a week.

With no infeed rolls to regulate infeed speeds, the particle length tends to vary inversely with the load on the machine. Branches less than 8 cm in diameter are consumed so rapidly that it is usually impossible to measure their feed rate. Even larger branches up to 15 cm are accelerated rapidly.

The speed regulation of the machine is very poor, relying heavily on the flywheel effect to process larger branches. While it is possible to infeed 15 cm diameter branches the machine would not be able to maintain a constant infeed of this size. It would bog out as the engine's rpm is drawn down below its affective operating range.

MACHINE SPECIFICATIONS
KNIFE HOG

Olathe Model 816
Olathe Manf. Inc.
Paola, Kansas

Chipper Unit

Number of knives	- 2
Maximum opening: width	- 42 cm
height	- 23 cm
Chipping cylinder construction	- 63 cm in diameter - 5, 3.8 cm thick plates welded to a shaft. - length, 40 cm - weight, 465 kg
Nominal Chip Size	- varies: dependent on size of input.
Drive System	- belt driven - 1600-1700 rpm - (2000-2400 engine rpm)

Power Unit

Ford Industrial Engine	- 8 cylinder gasoline
Power rating	- 139 kw (maximum brake)
Fuel tank	- 127 litres

General

length	- 3.65 m
width	- 1.7 m
height	- 3.8 m
GVW	- 2270 kg approx.

Applications

Suitable for processing green or dry brush, Christmas trees, kiln dried lumber waste, crating material with nails and banding wire attached and construction form work, 4 x 4's and 2 x 6's.

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4. TEST PROCEDURE

Windrowed piles of elm branches which had been trucked to a contractor's private dumping sight were available as test material. One portion of the sample, considered to be dry, had been accumulated during the fall of 1979. The other portion, considered green, was delivered to the area one to two days prior to being chipped. No particular care had been taken in forming the piles. The material was simply dumped from tilt box trucks onto roadside piles measuring from 1 to 2 metres in height as might be done using a forwarder.

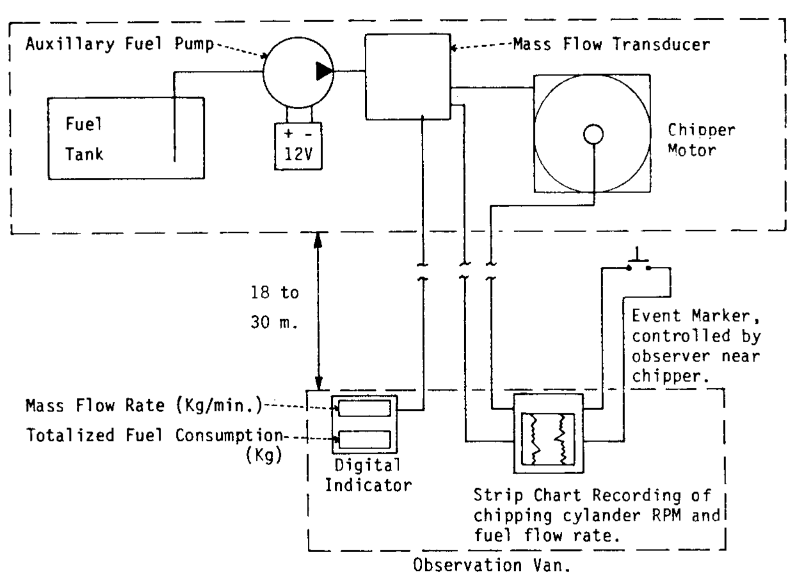
The chipper, trailered behind a close bodied van was backed up to within 3 to 8 metres of the piles. The two operators pulled the branches from the piles and fed them into the chipper. They alternated their operations, one pulling branches free while the other fed a load into the machine. This procedure worked well enough and was the standard procedure used by the crew in its regular land clearing and brush disposal operations.

The chipper had been instrumented to record fuel consumption rates and engine rpm continuously. A mass flow transducer was placed between the electric fuel pump and carburetor system. The regular mechanical fuel pump was not used since internal cavitation often caused large errors in the fuel monitoring system, particularly during the hot weather (25-30°C) prevalent during the test period.

Figure 2 illustrates the instrumentation set-up used during the test. The mass flow meter produced both an analog and digital signal proportional to the mass flow rate. The analog signal was recorded on one channel of a strip chart

FIGURE 2

INSTRUMENTATION SET-UP



The fuel consumption was monitored and activity analysis recorded using the strip chart recorder in conjunction with event markers and digital totalizing indicators.

recorder, while the output from a tacho-generator directly coupled to the chipper rotor was recorded on a second channel. The strip chart recording provided both a continuous record of all activities and a convenient form on which to record observations and notes as the test progressed.

The strip chart recorder was stationed inside a van parked some 18 to 30 metres from the chipping operation. The van was parked so that the observer located in the van could watch the chipping operation as he commented the strip chart recordings. A second observer was stationed near the chipping operation, controlling an event marker connected to the strip chart recorder. With it, he marked the times during which the machine was actively processing material during the test. This in conjunction with the observers' comments on the strip chart provided a detailed and permanent summary of the test proceedings.

The digital signal from the flow meter was transmitted to a dual channel digital indicator also located in the van. One channel displayed mass flow rates - and the other totalized fuel consumption throughout the test.

At random intervals during each day's testing, bags of chipped material, weighing 3 - 5 kg, were gathered for moisture content and size distribution analysis.

The observer controlling the event marker differentiated between **processing** and **waiting** times only. The operation was so simple that further time breakdown during operating intervals was not necessary.

> **Processing** time was considered to be any time during which branches were on the infeed chute of the machine. Once the blades grabbed the branches, they fed in so quickly that measurement of actual chipping time was impossible. Even measuring the intervals that chips were issuing from the outfeed spout was not practical.
>
> **Waiting** time was any time the machine was running at full governed speed, and able to accept branches, but not being fed. This was due either to the difficulty operators had in pulling branches free of piles or simply to the logistics of two operators feeding the same machine. This type of equipment is exceptionally dangerous and considerable care must be taken to avoid being whipped or more seriously injured as branches are pulled rapidly into the machine.

After each test period, the van in which the chips were collected was weighed to determine productivity.

Besides this breakdown of processing time, the energy consumption of the chipper was described in terms of Machine, Cycle and Operational energy requirements as first described by Gasslander et al (1). All these energy levels are expressed in terms of the oven dry weight, hogged and blown into the van. The definitions of these energy requirements follow:

> **Operational energy** is the total fuel consumption of the processor during any operating period. It includes all fuel consumed during waiting, idling, and warm-up periods.

The Operational energy requirement was calculated by dividing the total energy consumption recorded on the totalizing channel of the flow meter by the dry weight of the material recovered. The dry weight of each chip load was calculated using the green weight of the load and the average moisture content of the sample bags gathered at random during the chipping operation as follows:

$$\textbf{Operational Energy Requirement} = \frac{\text{Total Fuel Consumption}}{\text{Dry weight of chips}}$$

Cycle energy is the total energy consumption of the processor during productive times. It includes the fixed energy consumed by auxiliary equipment such as fans, pumps and blowers.

The cycle energy requirement was calculated by subtracting the fuel consumed during waiting and idling times from the total fuel consumption. The fuel consumed during waiting and idling was calculated using the measured no-load fuel consumption rate and the waiting time recorded on the strip chart.

$$\textbf{Cycle Energy Requirement} = \frac{\text{Total fuel consumed - (No-load Fuel Rate x Waiting Time)}}{\text{Dry weight of chips}}$$

Machine energy is the energy consumed by the working tools only. It does not include either the fixed energy consumption of a machine as it runs at governed engine rpm, or operates fuel pumps, fans, etc.

The Machine energy requirement was calculated in a manner similar to the Cycle energy. The no-load fuel consumption rate times the total running time was subtracted from the total fuel consumption. This yielded the energy consumed by the chipping process only, independent of the fixed energy consumption of the equipment.

$$\textbf{Machine Energy Requirement} = \frac{\text{Total Fuel Consumption - (Total Time x No-load Fuel Rate)}}{\text{Dry weight of chips}}$$

Figure 3 illustrates the relationships between the three energy levels. The additive nature of errors applied to the subtraction process used in calculating

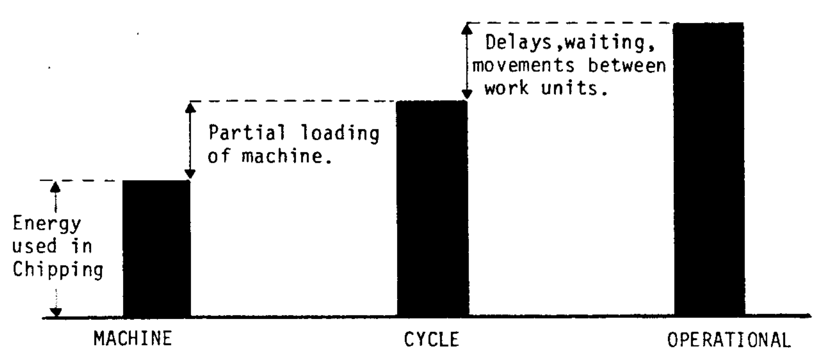


FIGURE 3

DIRECT ENERGY LEVELS

The difference between energy levels represents an energy loss which can be assigned to the higher level.For example the losses associated with the Operational level are due to delays and waiting times.

the Cycle and Machine energy levels obviously introduces errors into the results. However, no other approach was feasible within the restriction imposed by field testing conditions.

5. RESULTS

During five separate days of testing between July 23 and August 13, 1980 a total of 6.0 oven dry tonnes (ODt) of elm slash was chipped and loaded into vans. A total of 671 minutes of machine operating time was needed and 109.9 kg of gasoline was consumed (147 l @ SG = .75) A total of 2.43 ODt of dry slash, moisture content (MC) 39% dry basis, which had been cut and piled in the fall of 1979 was processed. A total of 3.57 ODt of green slash, MC = 54%, piled from 2-7 days before chipping was processed. The average no-load fuel consumption rate was .154 kg/min at a governed engine rpm of 2800 rpm (chipping cylinder-head speed of 2000 rpm). Table 1 summarizes the activity and fuel consumption pattern recorded for both dry and green slash.

TABLE 1

KNIFE HOG
Activity and Fuel Consumption Distributions

2.43 ODt of dry slash processed (54% MC)
3.57 ODt of green slash processed (39% MC)

ACTIVITY	DRY SLASH		GREEN SLASH	
	TIME (min)	FUEL (kg)	TIME (min)	FUEL (kg)
Processing	212	35.6	144	24.2
Waiting	184	29.6	141	20.4
TOTALS	396	65.2	275	44.6

Dry & Green Total Fuel = 109.9 kg

Based on the no-load fuel consumption rate and activity distribution in Table 1, thermal conversion inefficiencies and waiting time accounted for 103.2 kg of the 109.9 kg of fuel used. Therefore, while 54% of the fuel was used during processing times, 94% of the fuel was consumed in transmission, energy conversion and waiting time losses. Only 6.7 kg of fuel was used to process the 6.00 ODt of material.

Examination of the size distributions of green and dry material indicates a greater concentration of fines in the green material, a reversal of the expected results. However, the green material contained green leaves which were produced primarily as fines. As well, the smaller fractions of the dry material tended to blow out of the truck during chipping. On two occasions the engine overheated as fines blown back from the chute plugged the radiator. The size distribution of the chipper product is shown in Figure 4.

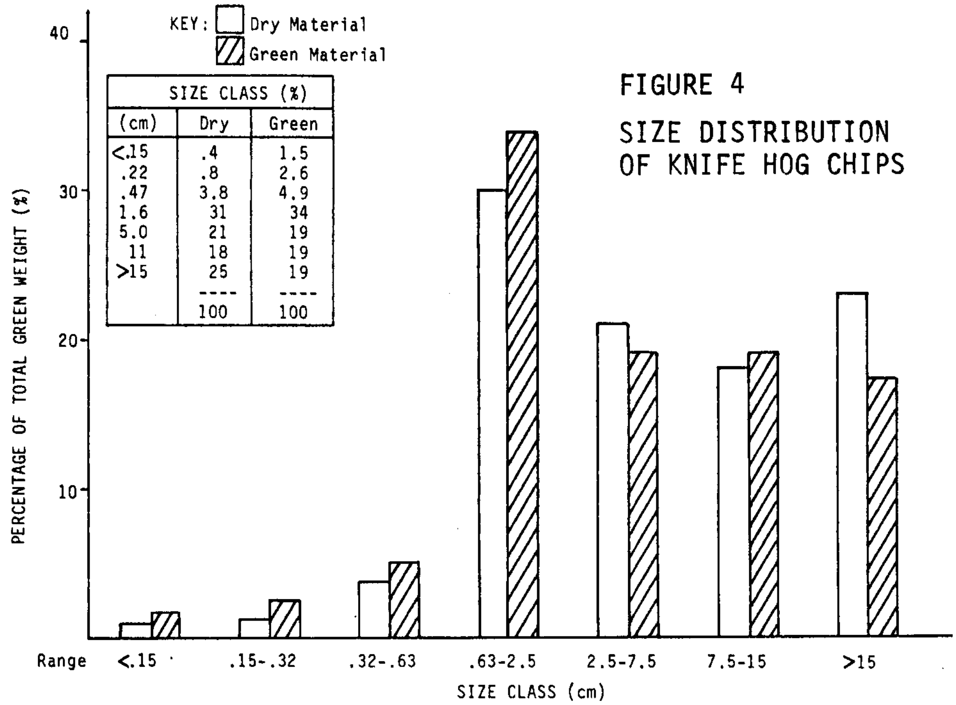


FIGURE 4
SIZE DISTRIBUTION OF KNIFE HOG CHIPS

The distribution of Machine, Cycle and Operation energy levels are shown in Table 2.

TABLE 2

Knife Hog Energy Requirements

(MJ/ODt)*

LEVEL	**DRY** (MJ/ODt)	**GREEN** (MJ/ODt)
Machine	31	23
Cycle	656	303
Operational	1202	536

* Conversion from kg of Gasoline made assuming:
Specific Gravity gasoline = .75
1 Litre gasoline = 33.6 MJ

Table 3 shows the relative proportions of energy losses between each energy requirement and the cause of the loss. Included in this table are the energy requirements calculated by Gasslander et al (2) and measured by Blakeney (3) for large, grapple-equipped chippers processing logging residues.

TABLE 3

Energy Loss Distribution

INTERVAL	LOSS (MJ/ODt)				CAUSE
	KNIFE HOG		DISC CHIPPER*		
	Dry	Green	(1)	(2)	
- Machine	31 (3)**	23 (5)	62 (16)	N.A.	Effective work accomplished by chipping action
Machine - Cycle	625 (53)	279 (52)	216 (55)	N.A.	Fixed fuel consumption while processing
Cycle - Operational	546 (44)	234 (43)	112 (29)	N.A.	Fuel consumed during waiting times.
TOTAL	1202	536	390	770	

(1) Source Gasslander et al (2); calculated energy requirements for a Bruks 1200 c grapple assisted chipper processing slash 42% M.C. at roadside.

(2) Source, Blakeney (3) measured energy requirements while chipping logging residue at roadside using a Nicholson Complete Tree Utilizer.

** Numbers in brackets express the energy loss as a % of total fuel consumed during operation.

Table 4 contrasts the productivity of the knife hog with that of other chipping operations when processing slash or comparable material at roadside.

TABLE 4

Productivity of Residue Chipping at Roadside

Literature Reference N°	Machine Description and Harvesting Situation	Productivity ODt/effective working hour
	Knife hog (OLathe 816)	
	- dry slash random piles	.37
	- green slash random piles	.79
	- 139 Kw engine	
(5)	Knife hog (manf. unknown)	
	- green saplings, hand piled	.87
	- 24 Kw engine	
(4)	Disc chipper (ABC 1000 M)	
	- green saplings, skidder piled	
	- hand fed	1.84
	- grapple assisted	2.22
	- 56 Kw engine	
(3)	Vee Drum chipper (Nickolson CTU)	
	- logging residues, random piles	2.12
	- 450 Kw engine	
(3)	Drum chipper (Bartlett)	1.27
	- logging residues, random piles	
	- 450 Kw engine	
(6)	Disc chipper (Morbark 22)	8.30
	- large hardwood tops	
	- 0.6 green tonnes/top	
	- skidded to roadside	
	- 450 Kw engine	

6. DISCUSSION

The direct energy requirements of processing dry and green slash shown in Table 2 are illustrated in Figure 5. While the magnitudes are much higher at all levels of examination for chipping dried slash, the proportions utilized between each level are similar. (See Table 3.) Despite the fact that roughly twice as much fuel is used to process dry material, the energy losses between levels agree within a few percentage points. Most significant is that in all cases, including energy distribution calculated by Gasslander et al (2), more than 50% of the direct energy consumption occurs between the Machine and Cycle energy levels. This indicates a general inability to supply the processing element at a rate equal to its technical capacity. Further, if the Machine energy level is expressed as a percentage of the Cycle energy level (Table 2), then less than ten percent of the fuel consumed while actually chipping the elm slash is used to comminute residues. The rest is simply consumed as transmission and energy conversion losses.

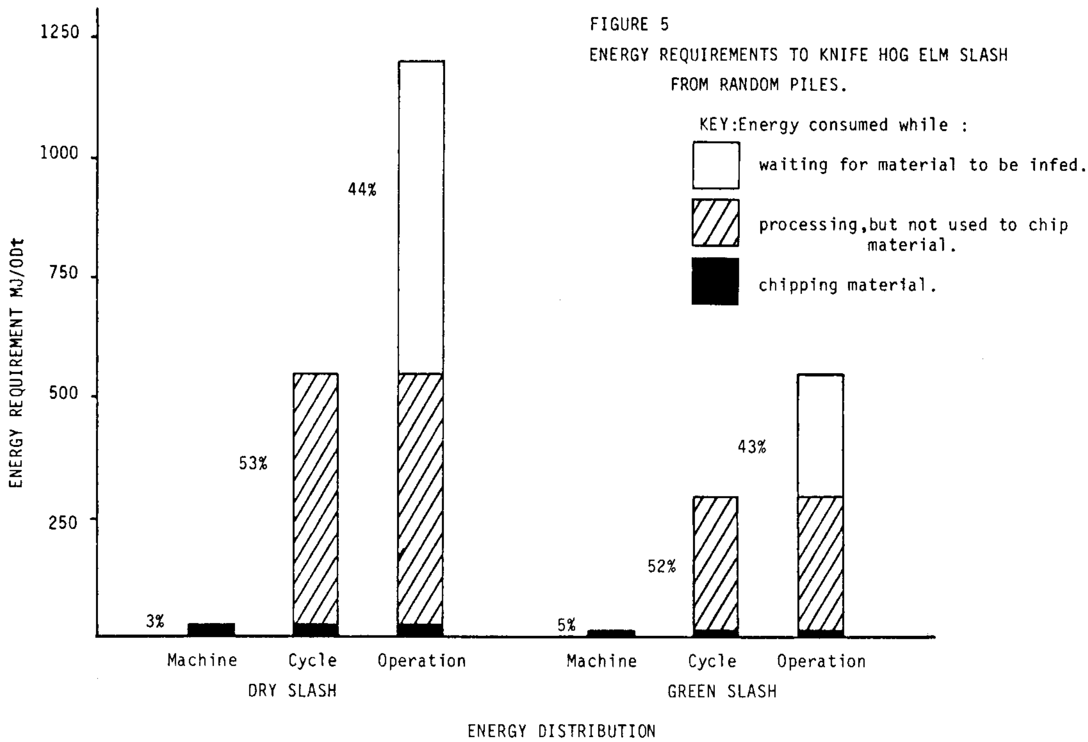


FIGURE 5
ENERGY REQUIREMENTS TO KNIFE HOG ELM SLASH FROM RANDOM PILES.

The difference in energy required to process slash piles, whose moisture content differed only by 15% (green-54% MC, and dry-39% MC,) was due as much to differences in their materials-handling characteristics as to the difference in actual moisture content. The dried material had lost most of its flexibility and no foliage was in place. The green material, particularly the smaller branches and twigs, had not lost its flexibility.

The dry material was extremely difficult to pull from the piles due to its greater rigidity and it was difficult to feed into the knife hog. In particular, forked branches would hang up on the infeed shoot and small dried branches would bridge across the infeed opening. In contrast, the flexible green material seldom kicked back or required re-setting in the mouth of the chipper. Once it first contacted the blades it was almost invariably pulled rapidly through the machine.

Because it lacked a powered infeed roll, too much time was spent by the operators in placing branches in the machine. Moreover, because of the unrestricted infeed system, operators had to be careful to avoid being whipped as they inserted branches. A simple infeed roll on this type of machine would enhance its performance significantly. Unlike most powered infeed rollers, it would be best if it only assisted and did not restrict infeed rates, free wheeling if the feed rate capability of the chipping process were to exceed its driven feed rate. This would result in broad particle size distributions as in Figure 4, but would not limit the unit's productivity as operators waited to set branches in the mouth of the chipper.

The productivity of the machine during the test was limited only by waiting times associated with pulling slash from piles and carrying it 3 to 8 metres to the machine. However, by traditional pulpwood harvesting standards its productivity of .37 and .79 ODt per operative hour are extremely low. The productivity of a large grapple-equipped chipper, processing skidder-piled whole trees in a pulpwood operation, was measured as 14 ODt/operative machine hour, (Folkema (7)). This was a cold-logging operation, processing hardwood species for pulp.

An operative machine hour is defined as the time the chipper is running at full governed engine rpm, either processing or waiting to process material. This definition applies only when the waiting time is caused by the inability of the infeed system (grapple or manual) to deliver material to the processor, but not when it is caused by the absence of material immediately at hand. Comparing productivities on this basis eliminates the effects of external influences such as mechanical delays and periods spent awaiting trucks.

In other experiments where harvesting residues were chipped, the productivities, though higher than those measured in this test, also fell far short of traditional productivity levels. Table 4 illustrates this fact. The productivity quoted for each example has been calculated using data supplied in each reference based on as near to the same definition of operative machine time as possible.

The effects of using chipping equipment in conjunction with randomly piled material is demonstrated by comparing the productivity achieved in this test .37 to .79 ODt/hour, and that realized 30 years ago, .89 ODt/hour, using a 25 Kw machine fed from neat piles of straight saplings, Arend, Smith and Ralston (5). Similar results are noted when large pulp chippers are used to chip random piles. The Nicholson CTU produced only 2.12 ODt/operative hour from windrowed piles of residues, Blakeney (3), while a very similar machine, the Morbark 22 managed 8.3 ODt/hour from skidder piled material, though of generally large sized elements and as part of a "hot" logging system, Mattson, Arola and Hillstrom (6).

A demonstration of the problems inherent to "cold" logging appears in Folkema's (6) measurements, which placed the productivity of "hot" and "cold" whole tree chipping at 20.6 and 14.7 ODt/operative machine hour respectively. The lower productivity of the "cold" system was attributed to a higher "tangle" factor due to inter-locking of branches in whole tree stock piles, to an indirect effect of the frequent moves necessary to operate from stock piles, and to some degree a greater proportion of "hard" hardwoods. In both cases the trees processed in this system were skidder-piled in relatively neat piles. In an operation where a random piled method is used in windrowing material at roadside, the productivity can be expected to decrease even more markedly than these figures indicate.

Comparisons among tests, such as those made in Table 4, are difficult to make due to the individual characteristics of each application. However, it appears that with traditional chippers, there is generally little likelihood that they will be adequate as harvesting residue processors without major design changes being made to infeed systems. Comparing the productivity of small, manually fed knife hogs and chippers with that of large and expensive pulp chippers applied as residue processors, emphasizes the inadequacies of current chipper infeeds. (See Table 4.)

7. CONCLUSIONS

The data gathered during the test constitute a representative sample of the energy distribution to be expected when using a manually fed knife hog to comminute and load slash and branches accumulated at roadside in random piles or windrows. The effective use of less than 5% of the fuel consumed during the operation emphasizes the necessity of finding an alternative use for the energy lost as exhaust in the energy conversion process. The most effective use would be to design a system which uses exhaust and radiator heat to dry the processed fuel in the waiting trucks as it is loaded.

The productivity of this test, though very low by traditional standards (.4 to .8 ODt), is representative of what can be expected feeding this type of device from random slash piles. Due to the difficulty in manually handling and feeding dried as opposed to green slash, the green slash is preferred. It would be better to dry the material after comminution. Evaluating to what degree transportation systems would be affected by the higher bulk densities of green material is beyond the scope of this report.

The low productivity achieved while processing various forms of randomly piled logging residues recovered following conventional harvesting is not likely to be improved by major redesigns of conventional chipping equipment. The limiting factor is the act of transferring material from roadside to the processing unit. In small-scale operations, such as those tested here, human strength is the limiting factor. For large-scale operations where whole trees are randomly piled, it is the inability of a grapple to deliver quantities in a single load large enough to tax the processor's technical capacity. This is not to suggest that a random infeed system into a large chipper is neither feasible nor desirable. Rather, the problems associated with disentanglement and small grapple loads (which limit the concept of using random loose piles of residues in conjunction with conventional chippers and knife hogs) severely restrict the potential of a random infeed system.

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THE ENERGY REQUIREMENTS TO ROLL SPLIT WOOD

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Ottawa, Ontario
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ABSTRACT

The preparation of fuel stocks from harvesting residues has traditionally been accomplished by chippers or hammermills, both of which are succeptable to damage by tramp metal or stones. The roll splitting mechanism, described in this report, is one possible alternative to these machines, which may be more resistant to this type of damage.

Laboratory tests were conducted on four tree species to determine the energy requirements of comminuting roundwood into a loose mat of slivers using a double roll crusher with axelike splitting wedges welded to its surface. Water is squeezed from the wood coincident with this comminution action. The energy requirements of this dewatering function are compared to thermal drying energy requirements.

TABLE OF CONTENTS

		PAGE
1.	INTRODUCTION	E1
2.	OBJECTIVE	E3
3.	MACHINE DESCRIPTION	E3
4.	TEST PROCEDURE	E4
5.	RESULTS	E7
6.	DISCUSSION	E16
7.	CONCLUSIONS	E22
	REFERENCES	E23

FIGURES

NO.		PAGE
1	TVA Processing Concept	E1
2	Roll Gap Adjustment	E2
3	Product of TVA and Roll Splitter	E2
4	Roll Splitter: Tooth Pattern	E3
5	Instrumentation Set-Up	E6
6	Machine Comminution Energy :vs: Dry Weight of Bolt	E10
7	Cycle Comminution Energy :vs: Dry Weight of Bolt	E11
8	Machine Dewatering Energy :vs: Dry Weight of Bolt	E12
9	Cycle Dewatering Energy :vs: Dry Weight of Bolt	E13
10	Machine Dewatering Energy :vs: Initial Moisture Content	E15
11	Moisture Content Change :vs: Initial Moisture Content	E15
12	Roll Splitter Dimensions to Process 30 cm Diameter Bolts	E21

TABLES

NO.		PAGE
1	Description of Test Samples	E5
2	Summary of Test Results	E8
3	Comparison of Roll Splitting and TVA Comminution Energy Requirements	E14
4	Moisture Content Change Through Roll Splitting	E16

1. INTRODUCTION

One of the principal impediments to the utilization of harvesting residues as fuel is the absence of a comminution device rugged enough to resist damage by tramp steel and stones. Whether recovered from the forest floor in a second pass situation or taken as part of an integrated lumber, fibre and energy harvest, these residues contain a high enough fraction of tramp steel or stones to regularly damage chipper knives or hammermill screens. However, recognizing that for energy conversion purposes the traditional pulp and saw timber objective of preserving fibre integrity (which makes the chipper so popular) does not apply, allows one to consider equipment until now not widely acceptable as a processor of woody material in other than a waste disposal role. Hammermills or "hogs" are the traditional devices used to prepare mill waste for use as fuel, but their application is as much directed at waste disposal as it is fuel preparation. Combining these facts with the objective of reducing the energy requirements to produce fuel has prompted the Forest Engineering Research Institute of Canada (FERIC) to examine alternative means of comminuting woody material as part of their Extended Biomass Harvesting Agreement with the ENFOR Program.

A test of the Tennessee Valley Authority Fiberizer (TVA) concept indicated that not only was it possible to comminute harvesting residues using a roll crusher, but that free water could be removed simultaneously at a significantly lower energy cost than by thermal drying operations.

The TVA was a prototype machine, developed by the Tennessee Valley Authority, with the objective of cleaving rough lumber into long slivers for use in the fibre board industry, Harvey (6). In concept, it resembled the type of double roll crusher used to process coal or coke. Since it was originally intended as a wood processor, it does have some unique features, as illustrated in Figure 1. The tooth pattern on the 25 cm diameter top roll consists of opposing buttress threads which are intended to cleave and tear wood parallel to the grain as the

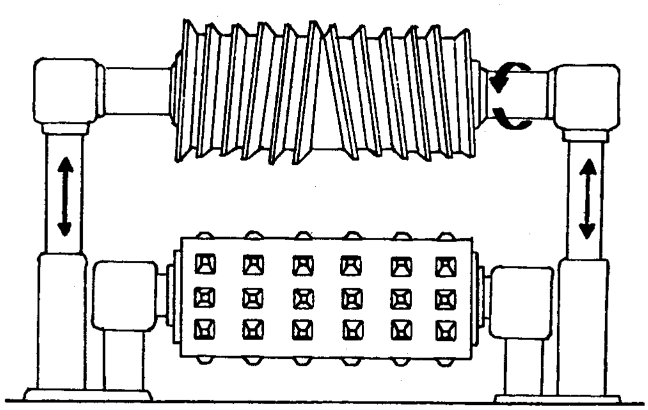

FIGURE 1

THE T.V.A. FIBERIZER

The T.V.A. Fiberizer uses opposing buttress threads to split, cleave and tear wood apart while applying a crushing force of roughly 42,000 Kg.

top roll slips on the upper surface. The bottom roll, also 25 cm in diameter, has a cross hatch pattern of teeth which provides the tractive force necessary to draw the wood between the rolls. These teeth also limit the infeed speed to their fixed peripheral speed of 7 metres/min. The top roll speed can be varied from 7 to 30 metres/min to produce the necessary slip to tear the wood parallel to the grain. The gap between the rolls can be adjusted from 1 cm to 20 cm by hydraulic cylinders which are also used to apply a crushing force of up to 42,000 kg.

The gap between the rolls is adjusted by rotating the top roll about a pivot point, using a 1.6 m long lever arm (Figure 2). Its movement is controlled by a flow splitter which prevents one cylinder from travelling further than the other when a bolt is fed in off-centre. A sprocket and chain, gear reducer, variable speed Reeves belt drive and induction motor drive the top roll. This entire assembly is mounted on the frame which is levered by the hydraulics.

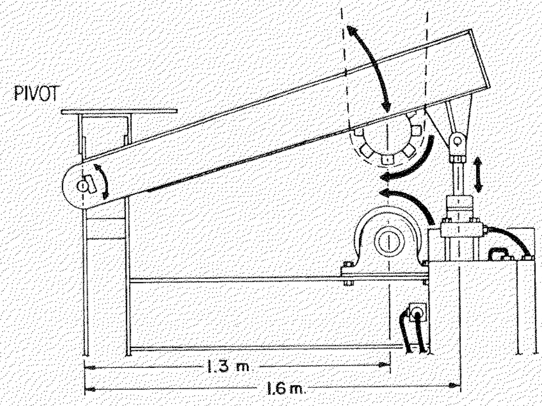

FIGURE 2
GAP ADJUSTMENT

The gap between the rolls is adjusted by rotating the top roll about a pivot point.

The first tests showed that when 9-18 cm diameter logs are processed, the threaded top roll accomplished very little cleaving by means of the buttress threads. (If flat boards were processed, these threads would presumably have the intended effect.) Instead, the comminution is accomplished by the crushing force applied by the hydraulics; that is, a log is split into a mass of slivers (Figure 3). As well, since the rolls were virtually smooth in comparison to the size of the element being processed, the slippage of the material was excessive and the teeth of the lower roll ineffective.

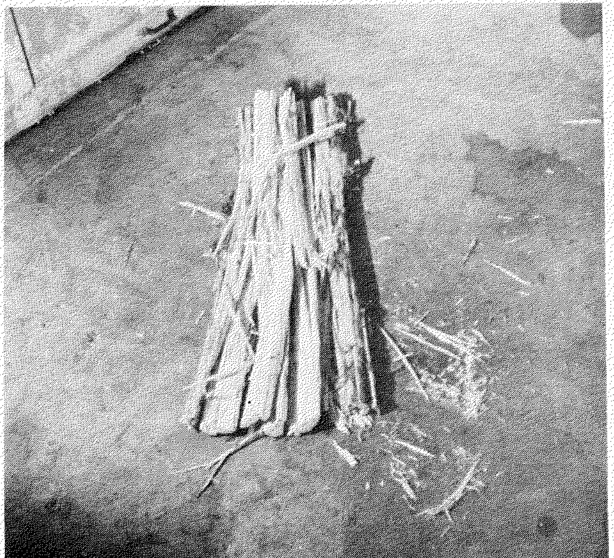

FIGURE 3

THE PRODUCT OF A T.V.A. FIBERIZER OR ROLL SPLITTER is a loose cohesive mass of slivers roughly 3 cm in cross section.

In the first tests, the electric energy required to crush logs into 1.7 m long slivers roughly 3 cm by 3 cm in cross section, was greater than that needed to produce 2.5 cm long pulp chips and less than that needed to produce 2.5 cm minus hammermilled material. Since this was a concept test and the tooth pattern considered only marginally adequate, these results were considered very encouraging.

2. OBJECTIVE

The first test indicated that by modifying the tooth pattern to a series of axe-like teeth to prevent slippage and accentuate splitting rather than crushing, the energy requirements of the machine process could be greatly improved. Consequently, a second test was arranged in which a modified top roll with axe-like teeth was installed and tests parallel to those made of the TVA fiberizer were conducted. The remainder of this report presents and discusses the results of this second test to investigate the energy requirements of simultaneously comminuting and dewatering roundwood.

3. MACHINE DESCRIPTION

The modified TVA fiberizer, from this point on called a Roll splitter, is illustrated in Figure 4.

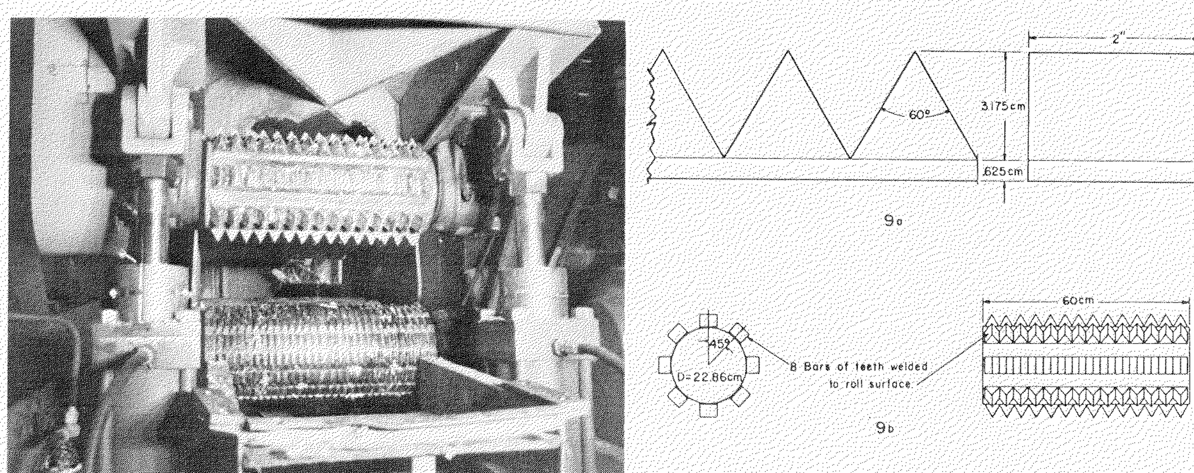

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FIGURE 9
TOOTH PATTERN

Eight bars of axe like teeth were welded to the roll core. The teeth were flame cut from 5 cm steel plate. The axe points, 3.175 cm long with 60° angle included, were aligned circumferentially about the roll.

The bottom roll of the Roll splitter was left as it was in the TVA configuration, its sole purpose being to grip the material as it feeds into the rolls. A modified top roll was exchanged for the TVA's thread one.

Its tooth pattern was changed to a series of axe-like teeth. The new teeth were aligned axially in parallel rows about the circumference of the roll surface. Eight bars of 15 teeth were flame cut from two-inch steel plate in the pattern shown in Figure 4a. These bars of teeth were then welded onto the surface of a spare, smooth roll, 23 cm in diameter, producing the tooth pattern shown in Figure 4b. The axe head sections were aligned point to point circumferentially. Staggering the teeth so that points and valleys alternately aligned was considered as a means of ensuring that slip would be eliminated. However the pattern in Figure 4 was chosen to accentuate splitting since it was expected that traction would be sufficient in either case.

The choice of a 60° included angle for the axe head was based on a variety of observations, manufacturing constraints and space limitations of the prototype. The principle objective was to use as long a tooth as possible without producing flats between the teeth in each row. This would minimize the amount of material jammed between teeth. In practice, material often jammed between the rows, but this problem was considered unavoidable due to the small ridge of material backing the bars of teeth. In subsequent work, a properly manufactured roll would eliminate this ridge, though for the prototype the costs justified the sacrifice in performance.

The core of the new splitting roll was generously supplied by Dr. Allan Marra of the Wood Science and Technology Department, of the University of Massachussetts, Amherst, Mass., where the TVA Fiberizer is located. With Dr. Marra's permission, this roll was modified to the form shown in Figure 4. His assistance in this test and the one previous is gratefully acknowledged, as is the field work and effort made by Denis Morin of the Forestry Department of the University of Massachussetts. Their assistance was instrumental for the success achieved in these tests.

A further modification made during the test was to remove 3 idler feed rolls located immediately before the splitting rolls. From the first test it was apparent they hindered infeeding when crooked or knotted pieces were processed. The rolls often forced crooked sections down onto the idlers causing the material to hang up and the rolls to slip. Removing them during this test eliminated the problem though it made it slightly more difficult and dangerous to feed the machine by hand.

4. TEST PROCEDURE

Samples of 4 species local to the test facility, eastern hemlock (Tsuga canadensis), aspen (Populus tremuloides), red oak (Quercus rubra) and red maple (Accer rubrum), were gathered one week before the test commenced. The samples, 2 metres long and from 9 to 18 cm in diameter, were cut from live standing trees. Knots and forks were trimmed off so that each was relatively straight. The bolts were numbered and moisture content (dry basis) and specific gravity (green volume-dry weight) samples taken immediately before each was processed. To minimize the effects of end drying, 15 cm was removed from the end of each bolt before the samples were taken. The final length of the bolts was trimmed to $1.7 \pm .05$ metres before processing. Table 1 describes the material processed.

TABLE 1

ROLL SPLITTING

Description of Test Samples
(1.7 m long bolts)

	Hemlock	Aspen	Red Oak	Red Maple
Diameter (cm)				
Mean	11	13	13	12.0
St. Dv.	2.3	2.4	3.1	2.0
Min.	8	8	9	9
Max.	18	18	18	16
Moisture Content (%)				
Mean	134	100	81	70
St. Dv.	22	21	15	8
Min.	96	66	57	58
Max.	177	138	104	89
Dry Weight (kg)				
Mean	7.7	10.7	14.7	10.9
St. Dv.	3.0	9.0	4.7	4.0
Min.	4.2	5.2	6.9	5.7
Max.	16.6	21.8	24.1	23.4
Specific Gravity*				
Mean	.43	.45	.57	.53
St. Dv.	.09	.03	.05	.04
Min.	.23	.39	.45	.46
Max.	.59	.53	.65	.64
No. of Samples	40	36	36	33

* (Green Vol. - Dry Weight)

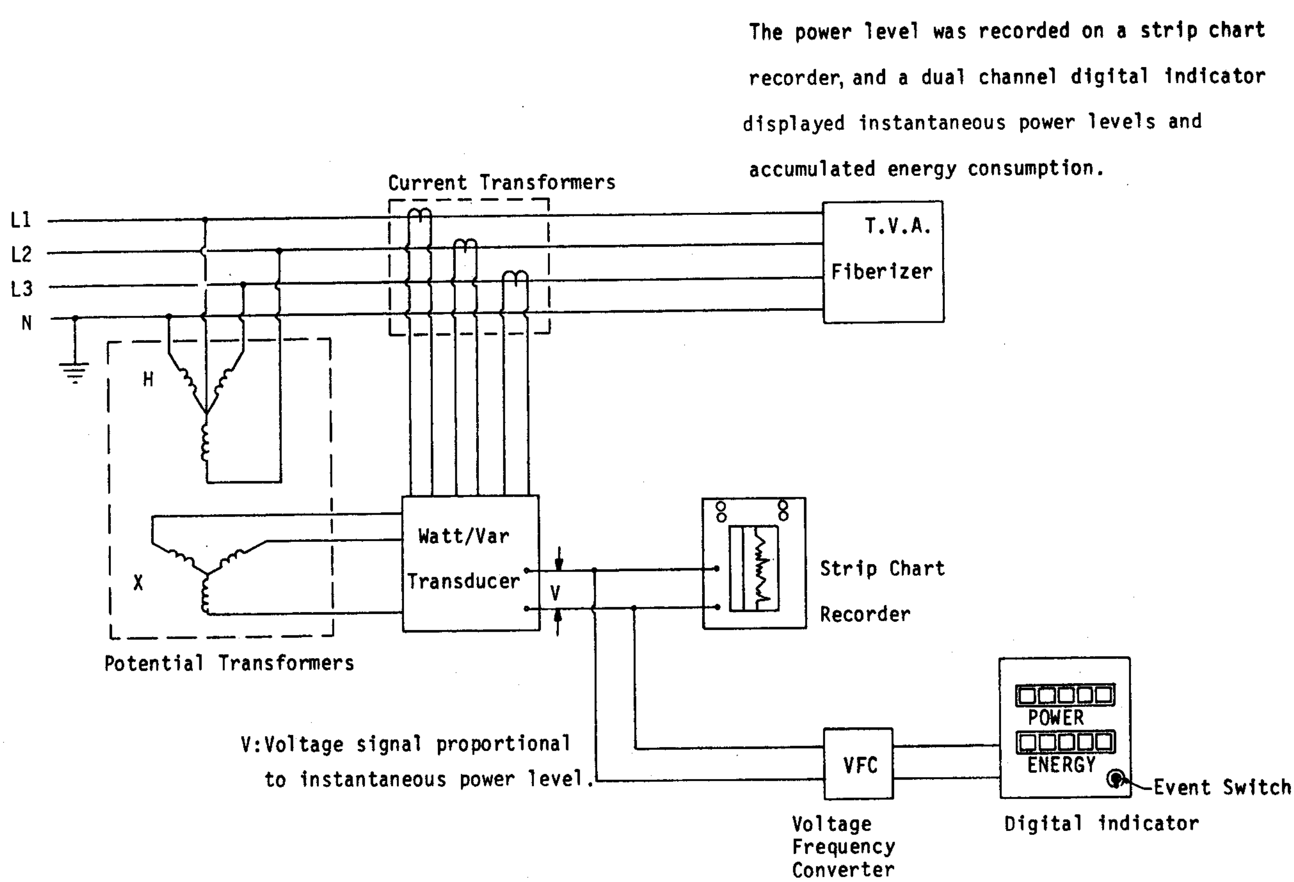
Since the samples were stored outside and the average midday outdoor temperature during the test period was -10°C, the logs were heated for two days in the laboratory to bring their temperature to 15°C.

Immediately before processing, each bolt was weighed and the end diameters recorded. The small end of the bolt was then placed onto a rest immediately before the splitting rolls. With the top and bottom rolls running at 9 rpm (7 m/min surface speed), the roll gap was adjusted to grip the piece when it was pushed between the logs. Once gripped by the rolls, the operator could devote attention to controlling the hydraulics to crush the material, while at the same time not allowing the machine to stall by the application of excessive pressure.

The instant the bolt was pushed between the rolls an instrumentation system was activated by an event switch to record processing time, power levels, and total energy consumption. When the material exited the rolls, the same event switch marked a strip chart recording of power levels, a freeze digital stop watch showed processing time, and a digital totalizer displayed total energy consumption at halt. Figure 5 is a schematic of the instrumentation set-up.

FIGURE 5

INSTRUMENTATION SET-UP



A screen (1.2 mm x 1.2 mm holes) suspended below the rolls caught material which was split or torn off the logs and allowed the water squeezed from the wood to drain into a drip pan. Since considerable quantities of water were forced from the end grain of the bolt, one operator held a container below the free end of the bolt, collecting what would normally have fallen on the floor of the lab.

The gap between the rolls could be adjusted from .5 cm to 12 cm between the axe-points and lower roll. The material was passed through the machine as many times as it took for this gap to be maintained at less than 1 cm through the entire passage of the bolt. In all but exceptional cases this was not more than twice.

After processing, the water collected from the end of the bolt was added to the drip pan contents and the total weight of water removed was calculated.

5. RESULTS

The energy requirements of roll splitting are described in terms of Machine and Cycle energy requirements as first proposed by Gasslander, Mattson and Sundberg [8].

Machine energy 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 Megajoules per Oven Dry tonne (MJ/ODt) of material processed:

$$E_M = (E_{TOTAL} - E_{NO\ LOAD} \times t)/W_d \qquad (1)$$

E_M	=	Machine energy
E_{TOTAL}	=	Total measured energy consumption
$E_{NO-LOAD}$	=	Energy consumption rate at no-load
t	=	Total time to process
W_d	=	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 energy 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 removed, MJ/kg of water. Table 2 presents the results of the tests to determine comminution and dewatering energy requirements.

The energy requirements were calculated by assuming that, for a given comminution process, the energy needed to achieve a change of state (size) is

TABLE 2

ROLL SPLITTING

Summary of Test Results

	Hemlock	Aspen	Red Oak	Red Maple
Comminution Machine Energy (MJ/ODt)				
Mean	28	23	25	32
St. Dv.	7	6	8	8
Min.	16	10	11	20
Max.	44	42	55	50
Comminution Cycle Energy (MJ/ODt)				
Mean	41	33	37	46
St. Dv.	10	9	12	10
Min.	29	15	15	29
Max.	63	57	74	68
Dewatering Machine Energy (MJ/kg H_2O)				
Mean	.200	.50		1.5
St. Dv.	.100	.40		1.3
Min.	.100	.11		.3
Max.	.650	2.10		5.9
Dewatering Cycle Energy (MJ/kg H_2O)				
Mean	.29	.71		2.20
St. Dv.	.14	.54		1.90
Min.	.14	.24		.47
Max.	.97	2.60		8.60
Moisture Content Change (%)*				
Mean	15.9	6.3		3.6
St. Dv.	5.6	3.6		2.1
Min.	24	1		1
Max.	5	19		9

* **Initial MC – (weight H_20 Removed/dry weight of bolt x 100) = MC Change %**

independent of the path of comminution. That is, the energy consumption of all passes through the machine were totalled to determine the energy requirement to process that weight of material to a nominal 3 cm sliver, regardless of whether 1, 2, or 3 passes were needed. This assumed path-independent change of state process can obviously be questioned, but within the limits of our experimental conditions it was the most reasonable approach to use.

Regression and scatter plot analysis revealed no dependence of Machine or Cycle comminution energy requirements on the diameter, moisture content or weight of the bolt processed. Figures 6 and 7 illustrate this, using hemlock and red maple.

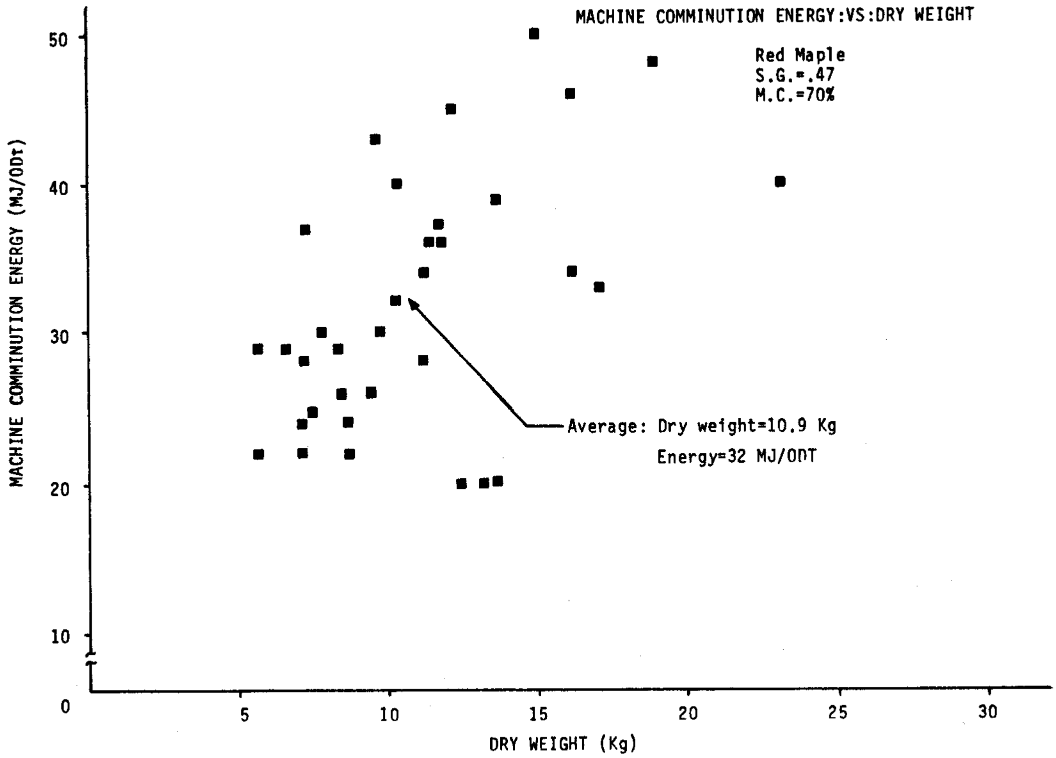
During the tests the roll splitter was only able to process the smaller diameter pieces (9-12 cm diameter) in a single pass. Consequently, the machine was working at maximum load at most times. Certainly during the first pass of any large bolt, the machine worked at its maximum rate. Therefore, average and peak power levels recorded had little meaning in relation to bolt diameter or weight. This also accounts for the lack of correlation between input size and Cycle comminution energy in Figure 7. If it had not been working at full load nearly all the time, the proportion of energy consumed as a base load would have increased as the dry weight of the bolt decreased, driving up the Cycle comminution energy level.

The most significant result of the tests, with regard to comminution, is the decrease in energy requirements at all levels compared to those measured for the TVA. In Table 3 the average Machine and Cycle comminution energy requirements of the TVA and roll splitting processes are compared for hemlock, the only species which was processed in both tests in an unfrozen condition. The lower energy requirements of the roll splitting operation are obvious. The sample populations test significantly differently at the 99% confidence level.

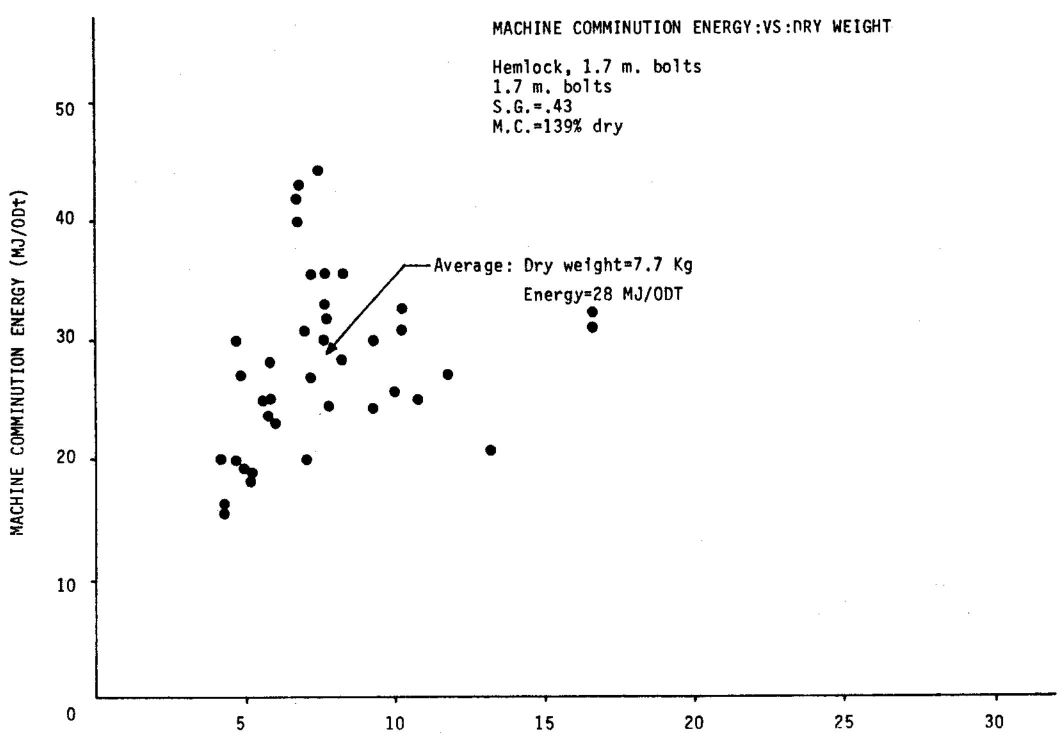
Certainly the rolls used in the two tests were quite different, but the product of each was judged to be very similar. The same personnel conducted both tests, within a two-month time frame, and had the material from both tests at hand for comparison. In their opinion, the size of the slivers produced and the degree of structural integrity destroyed was the same for each species whether processed by the TVA or roll splitting concept.

The energy requirements of dewatering through roll splitting show the same independence from input size by diameter and weight as do the energy requirements of comminution. This is shown by the Machine and Cycle dewatering energy requirements of aspen and hemlock in Figures 8 and 9. The Machine and Cycle dewatering energies are, however, dependent on the initial moisture content of the material processed. Unfortunately, the distribution of initial moisture content of any one species was relatively narrow. Therefore, when Machine dewatering energy is plotted as a function of initial moisture content for a single species, data are not sufficient to justify using regression analysis to predict energy requirements over a broad range of

FIGURE 6
MACHINE COMMINUTION ENERGY :VS: DRY WEIGHT OF BOLT



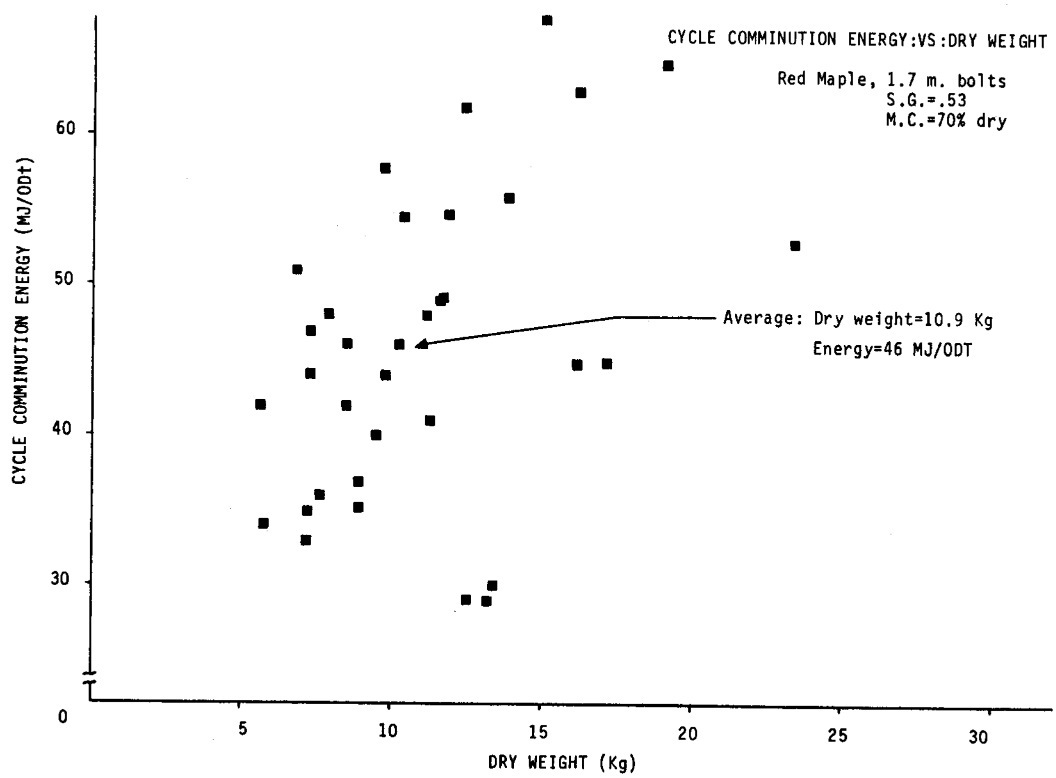
RED MAPLE ■



HEMLOCK ●

FIGURE 7

CYCLE COMMINUTION ENERGY :VS: DRY WEIGHT OF BOLT



RED MAPLE ■

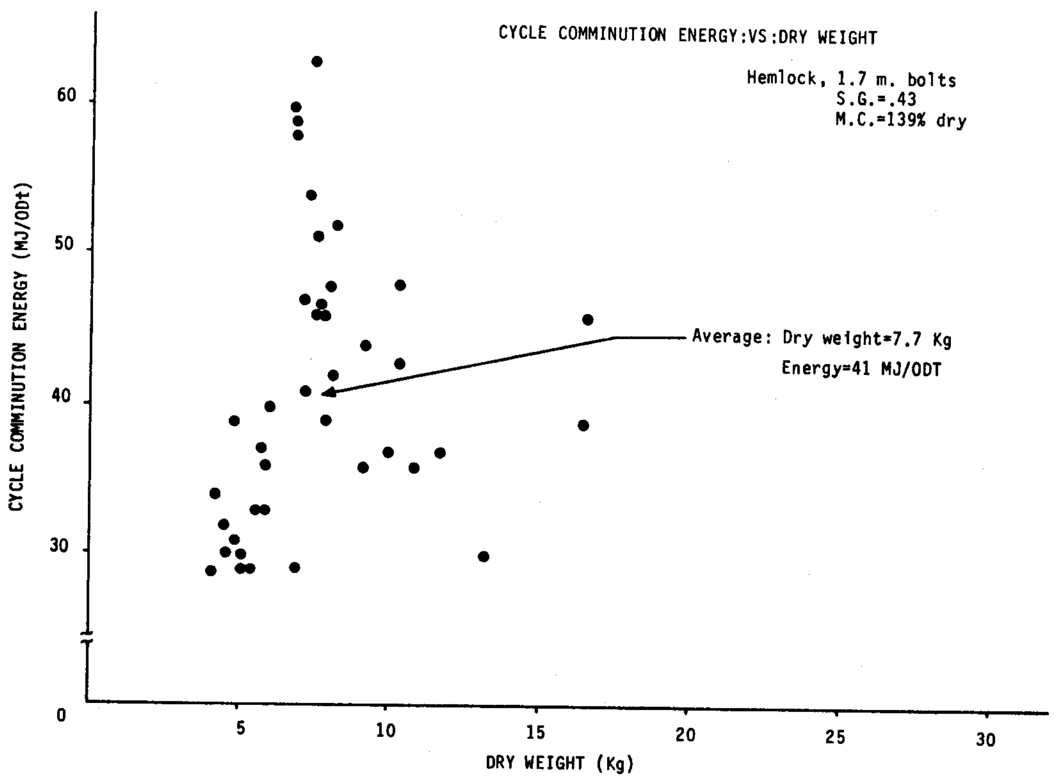


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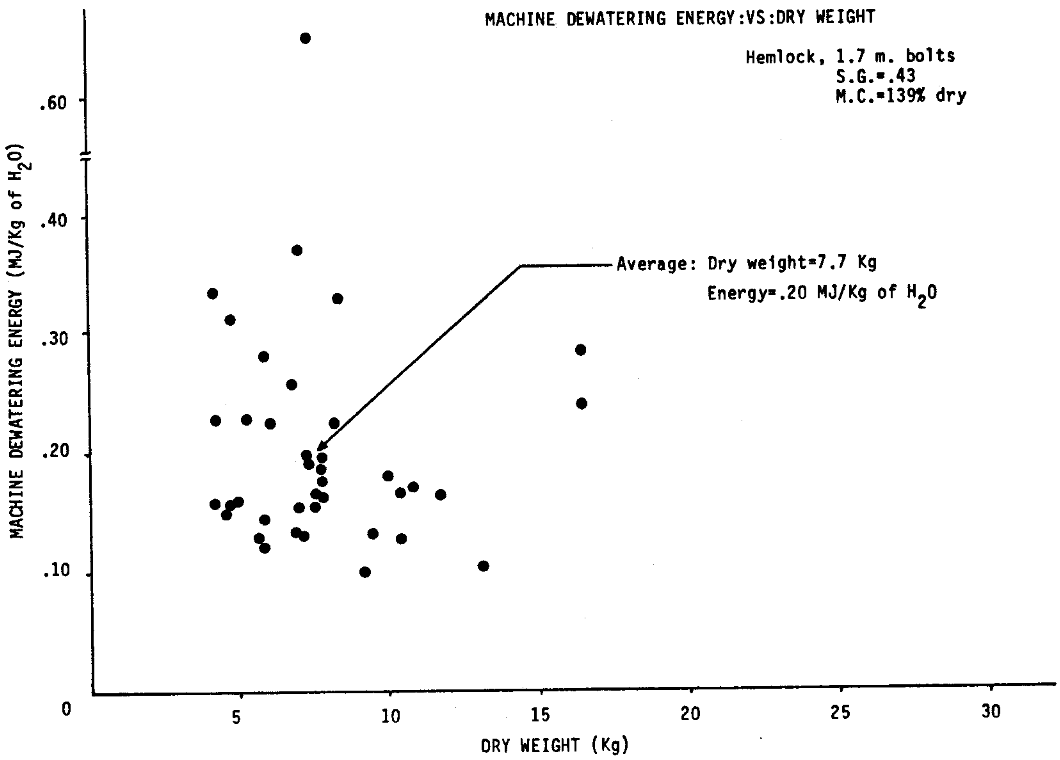
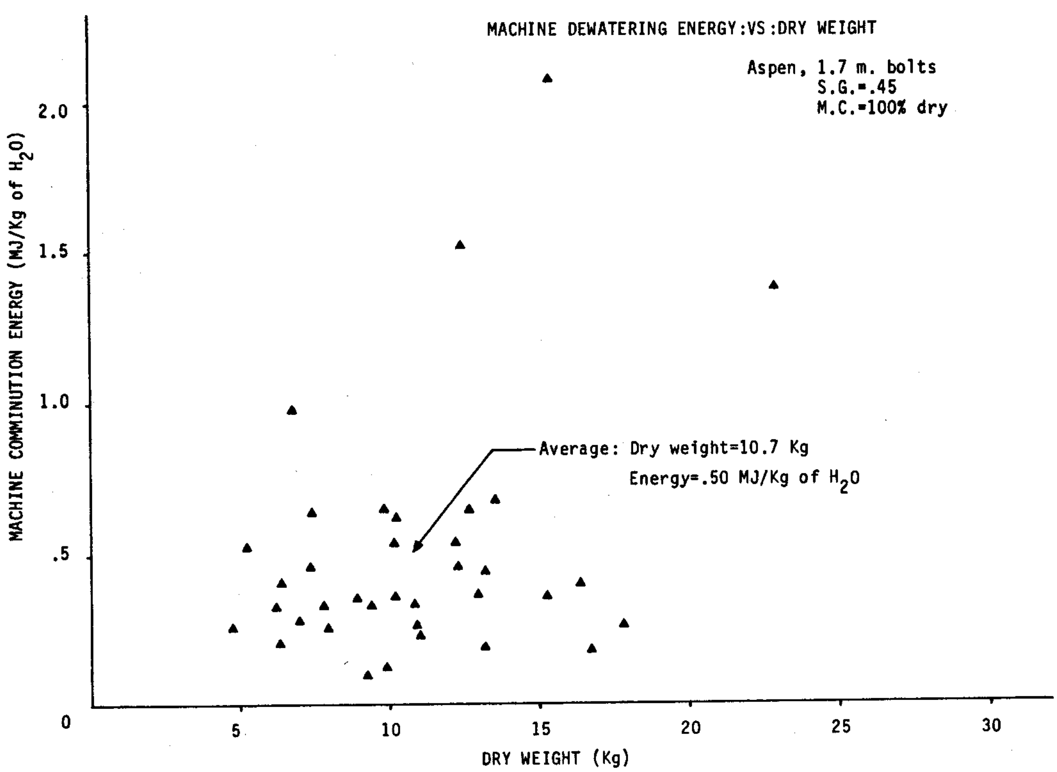
FIGURE 8

MACHINE DEWATERING ENERGY :VS: DRY WEIGHT OF BOLT



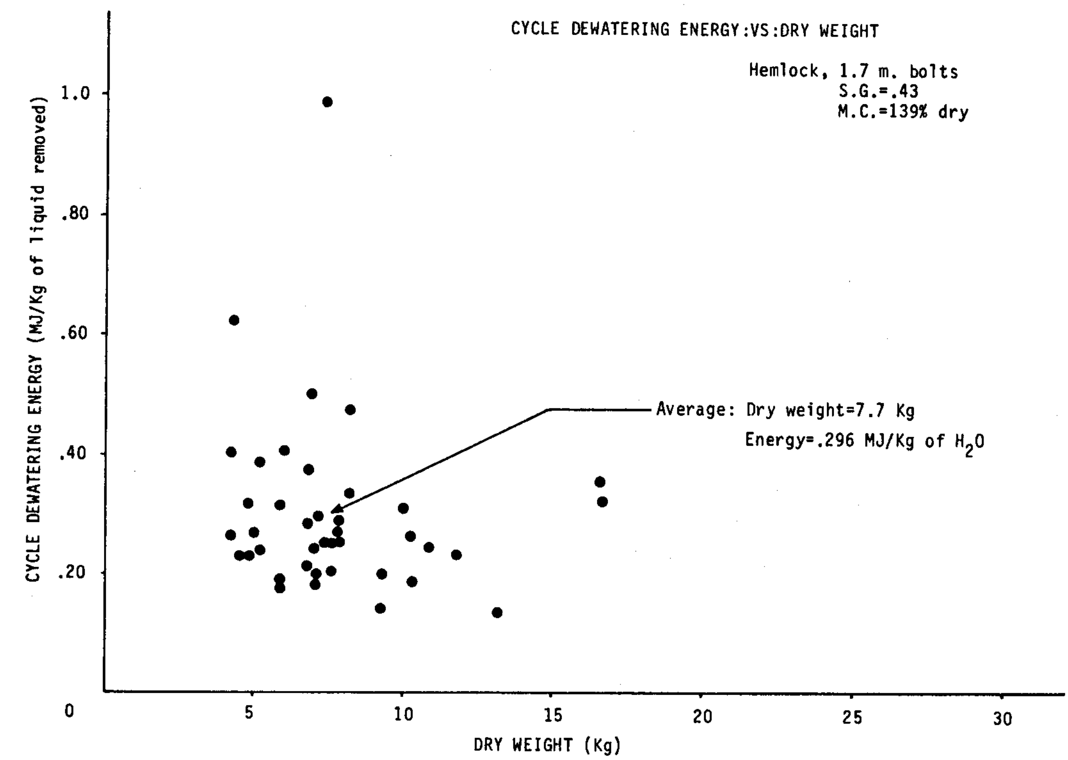
HEMLOCK ●



ASPEN ▲

FIGURE 9

CYCLE DEWATERING ENERGY :VS: DRY WEIGHT OF BOLT



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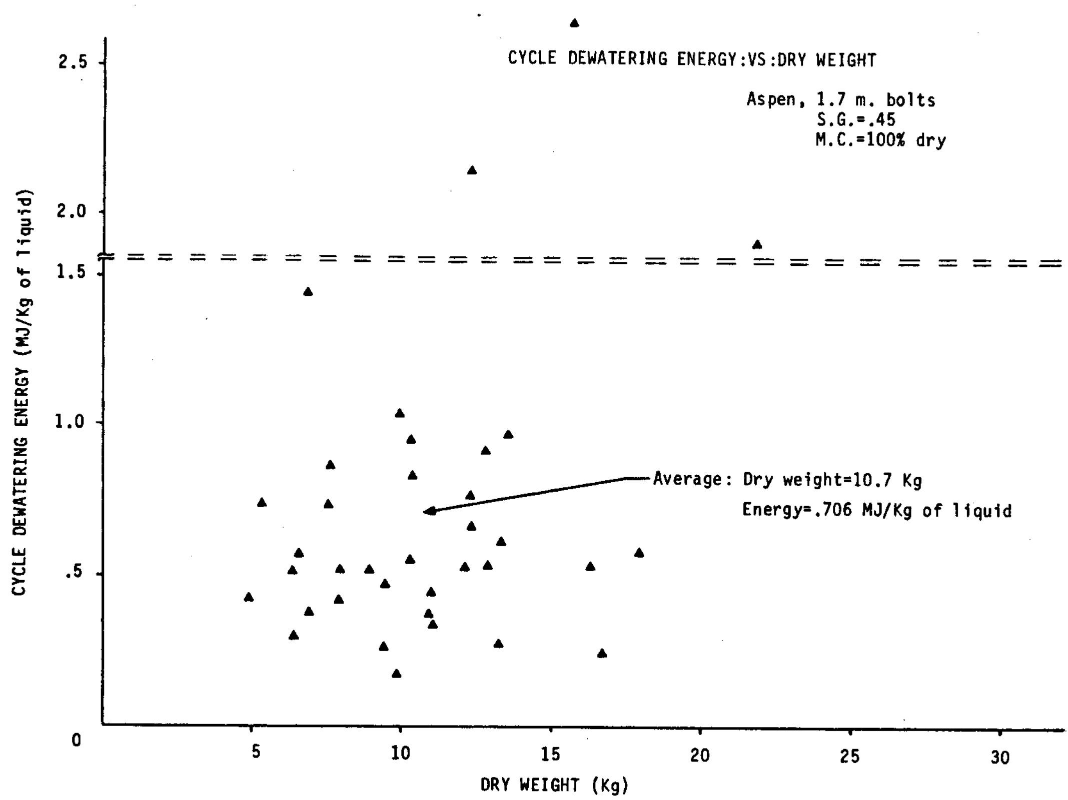

ASPEN ▲

moisture contents. However, combining data from all species which could be dewatered (hemlock, aspen and red maple) produces the scatter plot in Figure 10. Its shape indicates the expected relationship of increasing Machine dewatering energy as initial moisture content decreases. The results of the TVA test were not able to demonstrate this dependence due to the difficulty of maintaining an even and continuous crushing action.

TABLE 3

Comparison of Roll Splitting and TVA Comminution Energy Requirements

(Hemlock Not Frozen)

	TVA*	ROLL SPLITTING**
Machine Energy (MJ/ODt)	40	28
Cycle Energy (MJ/ODt)	64	41

* 100% MC
** 140% MC

Figure 10 also demonstrates that at some point the Machine dewatering energy requirement becomes greater than that of thermal mechanisms. A well-accepted concept, but these data begin to quantity at what MC the break-even point can be expected to occur. Data from Figure 10 and Table 2 further suggest that this break-even point will vary significantly for different species. Oak with a moisture content of 80% could not be dewatered by roll splitting while red maple at 70% was dewatered for less Machine energy than thermal requirements.

The percentage change in moisture content as a function of initial moisture content is illustrated in Figure 11. The data has been combined from the three species which were dewatered successfully. Due to the differences in pore structures and, therefore, permeability of each species, no attempt has been made to develop equations by regression analysis techniques. However, the expected decrease in moisture content is visible with the combined data, though less strongly evident within the small MC range of individual species.

Table 4 summarizes the data illustrated in Figure 11 and shows the average moisture content changes for each species. Hemlock is the only species for which dewatering energy requirements were measured for the TVA and roll splitting processes and both are contained in Table 4. They indicate a superiority of the TVA as a dewatering mechanism. This is logical since in the TVA test the roll surfaces were able to approach within 1 cm of each other while in this test they could only approach within 3 cm. As well, while the majority of the water was ejected in the first pass through the roll splitter, more water was removed by the TVA process during the second or third pass.

FIGURE 10

MACHINE DEWATERING ENERGY :VS: INITIAL MOISTURE CONTENT

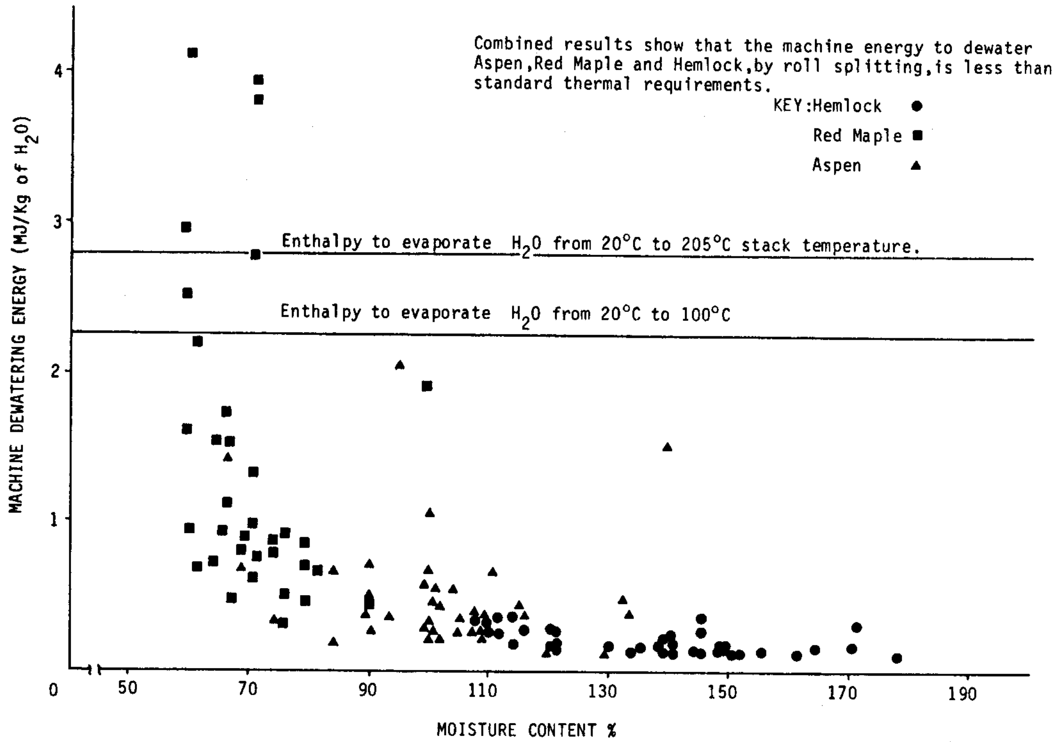

FIGURE 11

MOISTURE CONTENT CHANGE :VS: INITIAL MOISTURE CONTENT

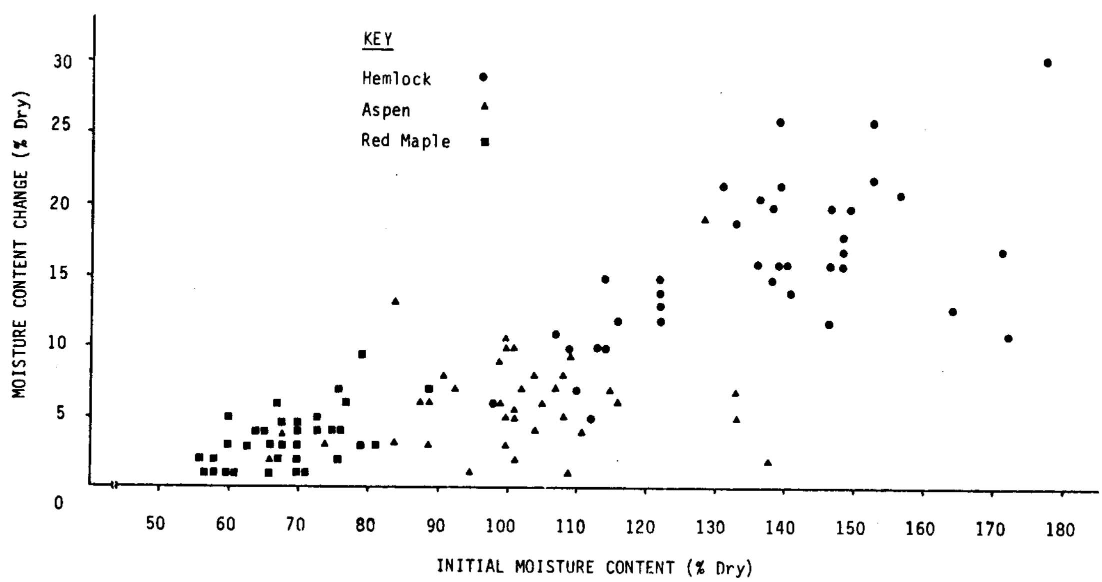

TABLE 4

Moisture Content Change Through Roll Splitting

	Red Maple	Aspen	Hemlock
Average Initial MC (% dry)	70	100	134 (100)*
Average Change MC (% dry)	3.6	6.3	15.9 (19.7)*

* The figures in brackets were measured for the TVA Fiberizing concept (1).

6. DISCUSSION

The Roll Splitter product is so different from that of any other processor that it is difficult to make comparisons, either by size of product or energy requirements. Nonetheless, pulp chippers at the Machine energy level typically require 16 and 20 MJ/ODt to produce 2.5 cm chips from hemlock or oak, Papworth and Erickson (1). Hogging or hammermilling similar material requires 100 and 240 MJ/ODt respectively, Geundler (2). In this test the roll splitter has produced slivers, roughly 3 cm in cross section and 1.7 m in length, for 23 to 32 MJ/ODt, somewhere between chipping and hogging energy requirements.

In developing the roll splitting concept, productivity and, therefore, the effect of roll speed, is of great interest. It is doubtful whether increasing the infeed speed from 7 to 30 m/min will greatly affect the torque or energy requirements of the process. Thirty m/min is chosen as a reasonable upper limit since the infeed speed of large chippers is in this range. Shearing tests conducted by Arola (3) showed no significant change in forces needed to cross-cut shear roundwood bolts over a speed range of 3 to 18 m/min. At much higher tool speeds, Koch (4) also has reported machining tests that showed similar independence of cutting forces on tool speed, or at least a complex relationship that made it difficult to directly relate tool speed to force requirements. The flywheel effect of a heavy rotor is speed dependent but, as a load smoothing effect, it should not reduce overall energy requirements.

While the roll splitter did have the ability to turn the top roll as fast as 30 m/min, after preliminary tests it was obvious that hand feeding the machine at roll speeds in excess of 9 rpm (7m/min) was too dangerous for the operator. When the rolls gained hold of the bolt, it would often whip so violently to the side or up and down that the operator risked serious injury. A set of powered infeed rolls would have been required to operate at speeds much in excess of this minimum roll speed. Even at 9 rpm, crooked bolts had to be fed into the rolls with considerable care.

While recorded tests were not run at high speed, observations during pretest trials at 14 and 30 m/min gave no indication that the mechanism's effectiveness in comminuting or dewatering was adversely affected. The overall failure pattern remained unchanged, though more loose particles of wood and bark were produced. This is attributed to an increased cutting action by the ridge formed by the .5 cm thick backing bar joining each row of teeth (Figure 6). By removing this ridge, the increase in the proportion of loose material, if not desirable, could probably be eliminated.

Frozen oak and red maple were processed in earlier tests of the TVA Fiberizer. Despite the frozen materials brittleness, there did not appear to be a change in the proportion or size of loose particles formed when the roll splitter was used to process these species in an unfrozen state.

With other comminution mechanisms, energy requirements increase with specific gravity (SG) but the opposite was measured in this test where oak, SG = .57, required significantly less energy than hemlock, SG = .43. (tested at the 99% confidence interval). Likewise, red maple, SG = .53, requires considerably more energy than the red oak, though the normal relationship asserts itself between red maple and aspen (Table 2). The comminution energy requirements are more a function of grain and pore structure than SG. A possible explanation for this behaviour is that the expected SG dependence may appear only within the two types of hardwood pore structures, diffuse and ring porous. Oak, as a ring porous structure, is more easily split along the prominent discontinuities between annual rings than is the less dense but more uniform diffuse porous red maple. By this reasoning, the expected SG dependence would probably hold more generally for softwoods due to their relatively consistent ring structure, though being affected to some degree by species with grain structures that have a high differential between early and late wood SG.

Other spot tests of the roll splitter suggested aspects of the concept which should be investigated in conjunction with further development work. Red maple and oak logs air dried to less than the FSP were processed by the splitter with no more apparent difficulty than green logs. The development of cracks in these dried logs was very rapid, as would be expected with embrittled material. Green material tended to be split more by the crushing forces than the axe heads.

Initially, the test procedure had called for the de-coupling of the lower roll drive motor. In this way it had been hoped that the energy requirements could be more directly related to the performance of the axe-like teeth on the top roll. As well, it would be far more economical to manufacture a machine in which only one roll, preferably the bottom one, is driven. Unfortunately, in this case, the most powerful roll was also the top roll, and with the lower roll acting only as an idler, the infeed would usually stop if the top roll was lifted slightly to prevent it from being stalled. However, several trial attempts did demonstrate that the concept would have been successful if the aggressive teeth had been on the lower roll. As well, this also demonstrated that a pressure control valve would be more useful than the present volume flow control valve in maintaining a constant feed rate. By varying the maximum crushing pressure, rather than the roll displacement, the torque of the roll could be used to lift the roll up and onto the material while still accomplishing a maximum amount of crushing.

Of course, defining the lowest moisture content at which dewatering can be accomplished is of considerable interest. In general, 100% MC is considered the useful limit of application for vee and auger presses. The results of these tests, however, suggest that on an energy requirement basis, the lower limit for dewatering by roll splitting is significantly lower than 100%, depending on the species.

The species dependency of this lower moisture content limit is considered to be a reflection of the effect of pore structure and therefore the longitudinal permeability of different species to flow of water in wood. In general, hardwoods are more permeable than softwoods and sapwood is more permeable than heartwood as seen in Siau, (7).

The concept that sapwood is more permeable than heartwood is supported by the observation that the majority of the water expelled through the end grain of each bolt came from its outer annual rings. That softwoods are less permeable was demonstrated by the fact that, as splitting progressed, proportionally less water was removed from the end grain of hemlock than red maple, despite the hemlock's higher moisture content. In addition, the instant a red maple bolt was placed between the rolls, water was forced from the opposite end approximately 1.5 metres away. In the case of hemlock the log had to be split very much closer to the end before water was expelled in quantity from the end grain.

Red oak does not follow these conventions concerning flow of water in wood. It has the highest permeability, Siau (7), of any wood in North America (this was one of the reasons for it being chosen as a test species). Despite this, it was not possible to dewater it appreciably at 80% MC. Earlier observations of green wood felled during the summer and processed by the TVA had revealed that measurable quantities of water were being removed. On this basis, it is assumed that a decrease in green moisture content between summer and winter conditions was the reason for this shortfall in expected performance.

The successful removal of water from red maple with an average moisture content as low as 70% was unexpected. Therefore, additional moisture content samples were taken from several places in the middle of surplus test bolts to confirm whether end drying had affected the moisture content sampling. This sample tested as being from the same population as the initial moisture content samples, at the 99% confidence level.

The reason for the unexpected success in removing water from red maple may be linked to its diffuse pore structure. Diffuse porous wood was discussed earlier as being tougher to split than ring porous woods such as red oak. The opposite situation may hold for dewatering, as the tough diffuse porous material is more effective in transmitting hydrostatic pressures longitudinally and maintaining the continuity of vessel paths more readily than brittle wood such as oak. This ability to transmit pressures longitudinally may result in an end effect occurring. An optimum length might exist which minimizes dewatering energy requirements.

While an end effect for dewatering is only conjectured, it definitely exists for comminution, as the end of each bolt is much easier to split than the middle. In cases where the bolt was passed through more than once, the second pass was usually only needed to crush the middle portion. In expanding roll splitting to a whole tree process, much as a large chipper, this end effect may prove to be a problem though one that could be answered by billeting prior to roll splitting.

While the relatively low energy requirements and dewatering capabilities of roll splitting are interesting, its scope of application will be very limited until the concept is developed to the point where only one pass is needed to achieve the desired product. In all but isolated instances, the machine tested was only able to reduce 9-12 cm diameter bolts to 3 cm slivers in a single pass. Therefore, the principal aim of further development work should be to improve the concept until it can process larger, for example, 30 cm in diameter, into 3 cm slivers in a single pass. In this state, it would be in a position to compete with mobile chippers, such as the Morbark 12 Total Chiparvester which can handle 30 cm diameter material but can still be trailered behind a truck without a fifth wheel.

To improve the concept demonstrated in this test, the total length and roll diameters must be adjusted to produce the desired product. While theoretical and empirical formulae describing the relationship of roll crushing configurations to infeed and outfeed characteristics are available, they deal with rock and other brittle materials, Lowrison (5). Virtually no similar references exist with which to make calculations for woody materials. Therefore, the following description of the rolls needed by a roll splitter capable of processing 30 cm material to 3 cm slivers in a single pass is based primarily on the experience gained while testing the TVA (1) and roll splitting concepts.

Since the 60 cm long rolls of the test machine were sufficient to accommodate up to 20 cm diameter bolts, and the roll length required will most logically be a function of the bolt cross sectional area, the roll length, L_2 needed is:

$$\text{Roll Length } (L_2) = \frac{A_2}{A_1} \times L_1$$

$$= \frac{r_2}{r_1}^2 \times L_1$$

$$= \frac{.15}{.10}^2 \; 60$$

$$L_2 = 135 \text{ cm}$$

A_1 = Area @ 20 cm bolt diameter

A_2 = Area @ 30 cm bolt diameter

L_1 = Roll length to process 20 cm diamater

L_2 = Roll length to process 30 cm diameter

Development of the roll diameter and tooth length and pattern shown in Figure 12 was based on the experience gained during field testing, experimentation with cardboard models, and preliminary stress analysis which limited roll and shaft materials to standard mild steel. This approach resulted in a ratio of tooth length to maximum input diameter of 1:3. As well, the use of a ratio of 1:1 for the roll core diameter to maximum input diameter seemed satisfactory.

In the test described here the included angle of each tooth was 60°, chosen to keep the axe points roughly 3 cm apart and as long as possible (Figure 6). To improve the concept, we feel the included angle should be roughly 30° and the distance between points 5 cm.

Besides the roll dimensions, the maximum gap between the rolls must be sufficient to enable each bolt to be started into the rolls. For this purpose, a gap between tooth points equal to 1/3 the maximum input diameter is considered adequate.

In summary, this results in the following proposed roll dimensions:

ROLL DIMENSIONS
(to roll split 30 cm diameter wood)

Length	= 135 cm
Diameter	= 50 cm (outside tooth points)
Teeth	= 10 cm in length 30° included angle 5 cm between points 10 cm cutting edge
Maximum roll gap	= 10 cm between tooth points

Figure 12 illustrates to scale the proportions represented by the above description of the required rolls. Also shown is a peak-to-peak relationship of the tooth points on the two rolls. This pattern would be used to maximize particle size, much like firewood. A point-to-valley relationship would be more useful in producing smaller particles.

The next most important parameters to estimate after roll dimensions are the crushing forces and power requirements. The force used by the test machine, 42,000 kg, was adequate in all cases to crack any log up to 20 cm in diameter, even though the rolls were almost smooth and much of the comminution was still accomplished by crushing rather than splitting. For want of better data, and assuming that the use of large axe-like teeth will considerably improve the comminution action, this 42,000 kg crushing force is considered an adequate maximum.

The power requirements of a larger roll splitter can be estimated using the measured Machine comminution energy requirements and an assumed mass flow rate through the rolls. While the maximum input diameter is 30 cm it is not reasonable to assume that this load could be maintained at the maximum infeed rate of 30 m/min. Instead, a maximum continuous load of 20 cm diameter material at 15 m/min is assumed. Using this and the lowest Machine comminution energy of aspen, Table 2, the power requirement is:

$$\text{Power} = \text{Machine Energy} \times \text{Mass flow rate}$$

$$= 23 \frac{MJ}{ODt} \times \text{Area} \times \text{feed rate} \times SG$$

$$= 23 \times (.1)^2 \times 3.14 \times 15 \times \frac{1}{60} \times .45 \frac{MJ}{sec}$$

$$= 81 \text{ kw}$$

A similar calculation for the highest machine comminution energy requirement, 32 MJ/ODt for red maple, predicts a power requirement of 133 kw. A 100 kw power requirement is probably as convenient a mid-range estimate as any for a prototyping program.

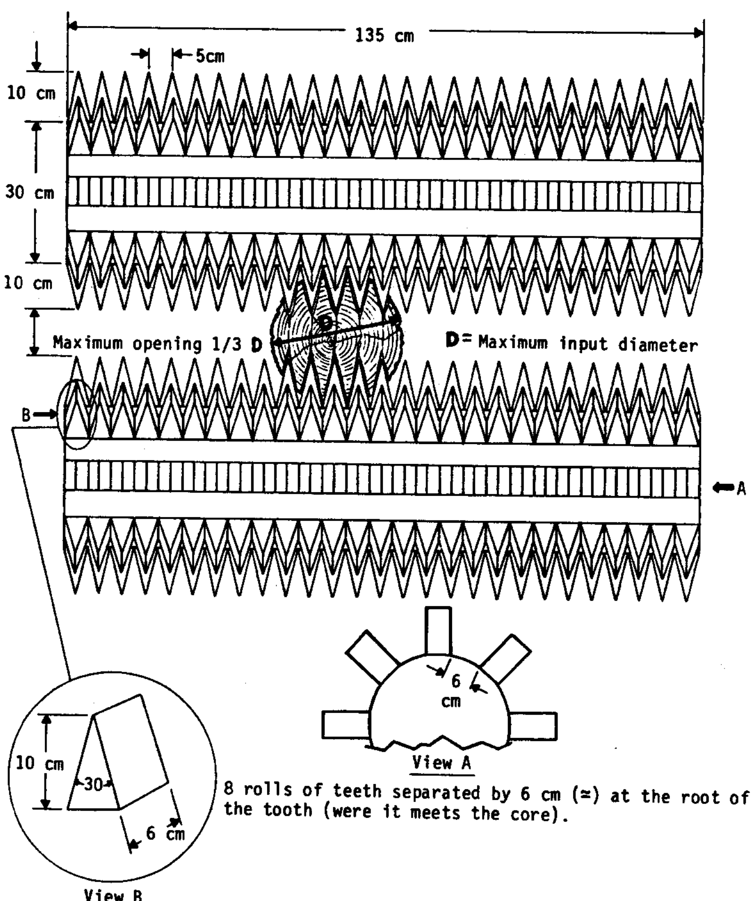

FIGURE 12

SPLITTING ROLL DIMENSIONS

To process 30 cm diameter logs into 3 cm slivers,in a single pass.

As a final comment, the personnel involved in testing the TVA and roll splitting concepts feel that with properly designed splitting rolls, the energy requirements will eventually be less than one half of those of a pulp chipper producing 2.5 cm chips.

7. CONCLUSIONS

Roll splitting bolts of wood has been introduced as a comminution concept which can reduce whole logs to a loose cohesive mass of slivers roughly as long as the original length of the bolt. Depending on the degree of size reduction achieved, the particles can be used as direct "hog" fuel, feed stock to further comminution processes, firewood in the home heating industry, or a material to be compacted and/or baled prior to transportation. Combined with the comminution action is the processor's ability to remove measurable quantities of water at a lower energy cost than thermal drying. Water was removed from aspen at 100% MC using .5 MJ/kg of water. At a comparable level, 2.8 MJ/kg would be used to evaporate it by a standard boiler.

The comminution energy requirements of the roll splitting mechanism tested were roughly 2/3 of that measured for the TVA Fiberizer concept (1). This reduction was due to the use of aggressive axe-like teeth on the top crushing roll rather than the TVA's small buttress thread pattern. These axe-like teeth concentrated more on splitting the logs than crushing them, and eliminated the slip which had been so great a problem in feeding the TVA.

The comminution energy requirements of roll splitting are not as closely related to the specific gravity of the material processed as are standard mechanisms, such as chippers. Instead, they are strongly influenced by the grain structure of the species, as ring porous hardwoods are more easily splintered than diffuse porous hardwoods. For example, red oak, SG = .57, required only 25 MJ/ODt to be processed to the same state as red maple, SG = .53, which required 32 MJ/ODt. Presumably, a similar relationship would hold between even-textured softwoods such as white pine (Pinus strobus) and those with distinct late and early wood such as jack pine (Pinus banksiana. Lamb.)

The dewatering energy efficiency of the process is also tied to pore structure of the species, and works better for diffuse porous hardwoods than ring porous ones. For example, it was possible to dewater red maple from 70% MC to 67% MC while no water could be removed from the red oak at 80% MC.

While the use of 3 cm axe-like teeth on the top crushing roll improved the comminution action over the TVA concept, too much effort was still being expended in crushing rather than splitting. Enlarging the teeth to 10 cm in length on both the top and bottom rolls will further reduce energy requirements.

The change from the relatively smooth rolls of the TVA to the more aggressive roll splitter decreases the percentage of moisture content change realized by the comminution process though it does not appear to have increased the energy required to remove a unit of water.

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FOREST ENGINEERING RESEARCH
INSTITUTE OF CANADA
Pointe Claire, P.Q.

Part of
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EXTENDED BIOMASS
HARVESTING

BALING ROLL-SPLIT HARVESTING RESIDUES

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Ottawa, Ontario
March 1981

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ABSTRACT

Past experiments have identified the need for an infeed mechanism particularly suited to the requirements of harvesting residue balers. This report describes tests carried out to bale rolled crushed slash and roundwood. Tests were intended to determine whether this process could be used to pre-process, dewater and infeed material to a baler. The energy requirements to roll crush slash are presented, as are the solid volume factors and bulk densities achieved by baling crushed wood.

TABLE OF CONTENTS

No.		Page
1.0	**Introduction**	F1
2.0	**Roll Crushing Slash**	F1
2.1	Objective	F1
2.2	Machine Description	F1
2.3	Test Procedure	F3
2.4	Results and Discussion	F4
2.5	Conclusions	F7
3.0	**Baling Roll-split and Crushed Wood**	F7
3.1	Objectives	F7
3.2	Machine Description	F8
3.3	Test Procedure	F9
3.4	Test Results	F10
3.5	Discussion	F13
3.6	Conclusions	F14
4.0	**Recommendations**	F15
References		F16

LIST OF FIGURES

No.		Page
1.	Sorghum Mill	F2
2.	Instrumentation of Sorghum Mill	F4
3.	Harvesting Residue Baler	F8
4.	Harvesting Residue Bales (a) Roll-split Wood (b) Roll-crushed Slash (c) Mix of Whole Trees and Roll-split Wood	F12
5.	Volume Reduction to Compaction Pressure Relationships (a) Pine Slash (b) Pine Chips	F14

TABLES

No.		Page
1.	**Roll-crushing Wood using a Sorghum Mill** Data Summary and Test Results	F5
2.	**Moisture Content and Specific Gravity of Baled Wood**	F9
3.	**Baling Roll-split Wood** Data Summary and Test Results	F11

1.0 INTRODUCTION

This report describes the results of harvesting residue baling and roll-crushing tests. In November 1980 and January 1981, studies had been carried out at the University of Massachussetts, Amherst, to determine the energy requirements of roll-crushing roundwood bolts into slivers. As a continuation of this investigation, the slivers produced were shipped to the Virginia Polytechnic Institute and State University (VPI) Blacksburg, Virginia. These were baled using a prototype harvesting residue baler. At the same time the energy requirements of a suger cane crusher (sorghum mill) also located at VPI were measured as it crushed hardwood slash having a maximum butt diameter of 4 cm through a 0.6 cm gap. This crushed slash was then included in the baling test.

The description and results of the crushing and baling tests are presented separately, in sections 2 and 3, respectively of this report.

2.0 ROLL-CRUSHING HARDWOOD SLASH

2.1 OBJECTIVE

The objective of this test was to determine the energy requirements for:

roll-crushing hardwood slash; and
dewatering slash using a roll-crushing apparatus.

2.2 MACHINE DESCRIPTION

The roll-crushing operation involved use of the sorghum mill shown in Figure 1. This is a 2.5 kw test mill salvaged from a sugar cane processing plant where it had been used in sample processing to determine sugar content. Although it proved rugged and strong enough to crush the slash in the roll-crushing test, it had not been designed with as severe an application in mind.

On this mill, the gaps between the front and back rolls and the top roll can be adjusted independently. During the test, the gap between the top and front bottom roll was set at 1.2 cm and that between the top and back bottom roll at 0.6 cm. A deflector plate, located between the bottom rolls, directs the incoming material upwards between the back and top rolls. The plate has a saw tooth pattern on the leading and trailing edges which mates with the surfaces of the bottom rolls.

All three rolls are driven by finger gears, which allow significant shifting of the rolls. The maximum possible gap between the top and bottom rolls is 2.5 cm. Although the rolls are not spring-loaded, some deflection of the frame was observed under very heavy loads.

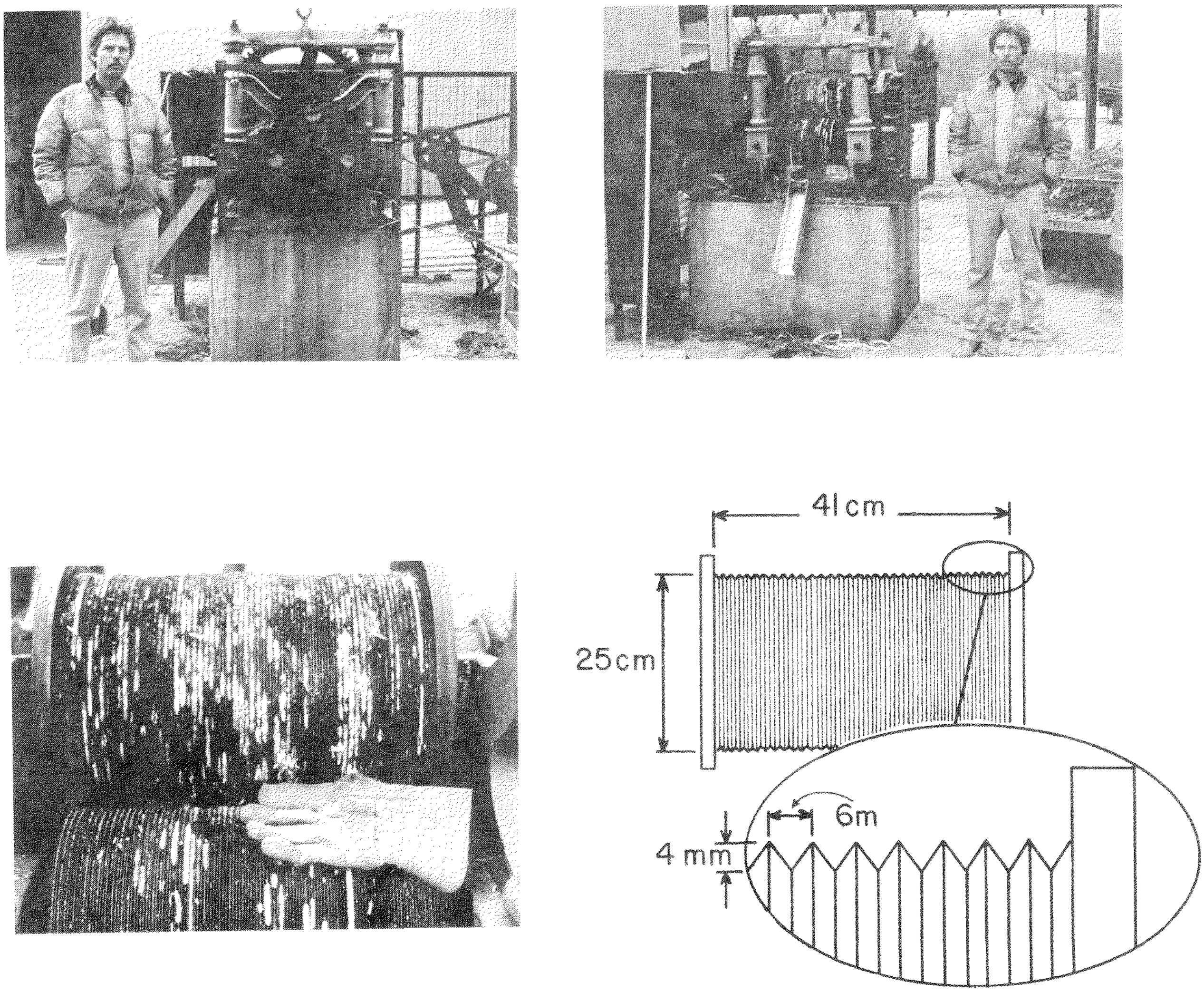


FIGURE 1

SORGHUM MILL SPECIFICATIONS

The sorghum mill used to roll crush slash prior to baling had the following specifications:

Roll	Motor
Width = 41 cm	3 phase
Diameter = 25 cm	1760 rpm
Speed = 8 rpm	7.8 amps
	3 Kw

2.3 TEST PROCEDURE

One week before the test, approximately 1500 kg (green weight) of hardwood coppice and small saplings were felled and bundled at roadside. The material consisted of a random mix of hardwoods native to the area: red maple (Accer rubrum L.), dogwood (Cornus florida L.), oak (Quercus L.) etc. "Hard" hardwoods (SG greater than 0.50) were predominant.

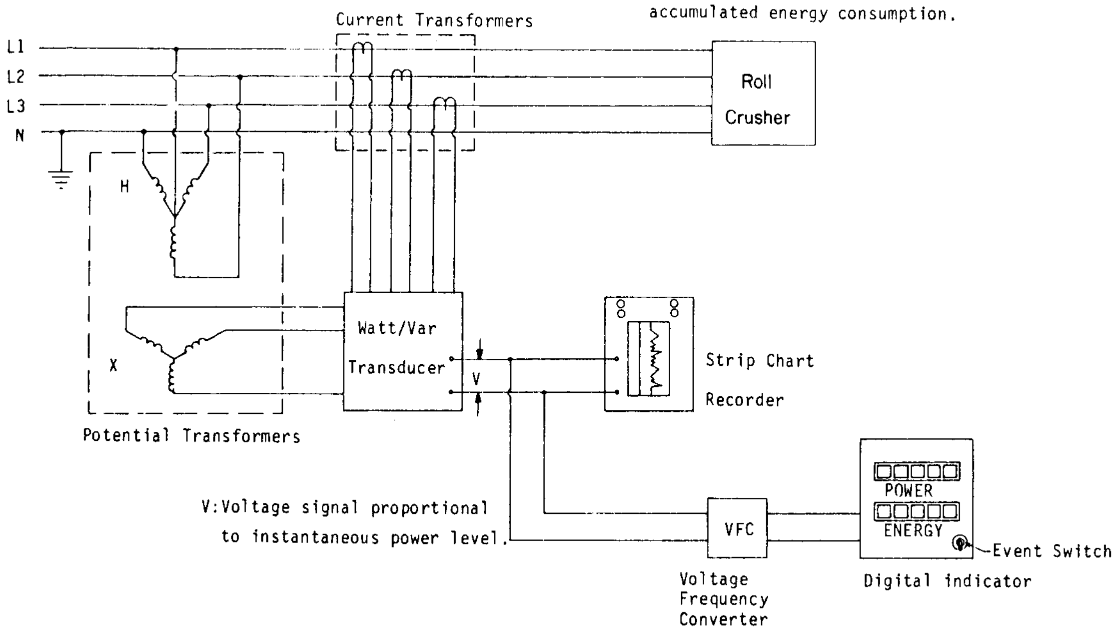
The 50-60 kg bundles of 5-metre long coppice growth were brought to the processing area and weighed immediately before crushing. Material too large to process was removed and its weight subtracted from that of the initial bundle to determine the green weight of the processed material. Moisture content (MC) samples taken from each bundle were used to calculate the oven dry weight of the material crushed.

The electric power supply to the crusher motor was instrumented, as shown in Figure 2, to permit recording of processing time, power levels and total energy consumption. An event switch was used to produce a strip-chart recording of power levels. This procedure provided the basis for records of power levels,

FIGURE 2

INSTRUMENTATION SET-UP

The power level was recorded on a strip chart recorder, and a dual channel digital indicator displayed instantaneous power levels and accumulated energy consumption.



processing time and total energy consumption. The event switch also controlled a digital stopwatch and dual-channel digital indicator which displayed power levels and total energy consumption. Before each bundle was fed into the machine, the time and totalizing channels were set to zero. When a bundle of slash was fed through the rolls, these indicators were activated. Immediately after the bundle had been processed, the event switch stopped the stopwatch and energy totalizing channels. These values were then recorded.

With the gap between the front bottom roll and top roll set at 1.2 cm, the nip angle was not sufficient to infeed (butt end first) material cut with a square end and having a diameter greater than 2.5 cm. Sharpening these butt ends with a hatchet to a 30-45° angle, enabled the machine to crush even very hard dogwood slash up to 4 cm in diameter without slippage. (The 4 cm diameter limit was chosen simply to minimize the risk of overloading the equipment.)

The slash was fed into the mill butt end first. Usually 3-4 branches were passing through the mill at one time with the operator maintaining as high a load as possible at all times. Because of the very slow infeed speed of 6.3 meters/minute, the operator had no difficulty keeping a continuous stream of slash flowing through the mill.

After leaving the mill, the slash was piled loosely on a trailer and taken to another area for use in the baling tests described in Section 3 of this report.

A drip pan was placed below the rolls to collect any liquid squeezed from the material by the crushing operation. This liquid was weighed to determine the percentage change in moisture content and the energy requirement of dewatering through crushing.

2.4 RESULTS & DISCUSSION

The energy requirements of roll crushing are described in terms of Machine and Cycle energy requirements as first proposed by Gasslander, Mattson and Sundberg (6).

Machine energy 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, multiplied by the processing time. It is expressed in terms of Megajoules per Oven Dry Tonne (MJ/ODt) of material processed:

$$E_M = E_{TOTAL} - E_{NO\text{-}LOAD} \quad x \quad t / Wd \qquad (1)$$

E_M = Machine energy
E_{TOTAL} = Total measured energy consumption
$E_{NO\text{-}LOAD}$ = 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 of energy consumed by 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.

Cycle energy 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.

Table 1 summarizes the data recorded and the results calculated from these data.

TABLE 1

Roll-crushing Wood Using a Sorghum Mill Data Summary and Test Results

Bundle No.	Weight Green	Energy Consumed	Time	No Load Power	Dry Weight	Machine Energy	Cycle Energy
	(Kg)	(MJoules)	(min)	(MJ/min)	(Kg)	(MJ/ODt)	(MJ/ODt)
1	38.2	1.528	6.87	.092	18.9	47.5	80.8
2	27.7	1.104	5.45	.092	13.7	43.9	80.5
3	18.2	.934	4.26	.1045	9.0	54.3	103.1
4	27.7	1.934	8.83	.1045	13.7	73.8	141.7
5	37.7	1.042	5.62	.104	18.6	24.5	56.3
6	50.0	2.139	9.33	.104	24.7	47.1	86.5
7	43.6	2.491	10.55	.100	21.6	66.5	115.3
8	43.6	1.901	6.96	.098	21.6	56.4	88.0
9	27.3	1.279	6.50	.100	13.5	46.6	94.7
10	16.4	1.605	8.30	.0998	8.2	95.0	195.7
11	46.3	2.268	11.80	.098	22.9	48.5	99.4
12	48.2	3.920	20.15	.098	23.9	81.4	164.0
13	40.5	2.965	6.06	.098	20.1	117.9	147.5
14	51.4	3.784	16.12	.098	25.4	86.8	148.9
15	70.0	2.542	14.03	.099	34.7	33.2	73.2
16	40.0	2.255	13.05	.097	19.8	49.9	113.9
17	31.8	1.866	9.00	.099	15.7	62.1	118.9
18	41.0	2.761	13.03	.096	20.3	74.4	136.0
19	38.2	2.596	13.96	.097	18.9	65.7	137.0
20	30.9	2.224	13.45	.098	15.3	59.2	145.0
21	31.8	1.836	10.78	.096	15.7	51.0	116.9
Total	800.5	-	214.1	-	396.2	-	-
Mean	38.1	2.140	10.20	.098	18.8	62.1	116.3
ST.DV	12.1	.800	4.07	.003	5.9	21.5	31.3
Max.	70.0	2.964	20.15	.104	34.7	117.8	164.0
Min.	16.4	0.934	4.26	.096	8.2	24.5	56.3

The mean Machine energy was 62.1 MJ/ODt. This contrasts with a Machine energy consumption of 20-32 MJ/ODt for roll-splitting roundwood to slivers 3 cm in cross section, and from 16-20 MJ/ODt for producing 2.5 cm-long pulp chips from "hard" hardwoods.

The Cycle energy requirement was 116 MJ/ODt. Therefore of the total energy measured, 54% was consumed as Machine energy (i.e., as useful work), and 46%, the difference between Machine and Cycle levels, as no-load energy losses.

In comparison to chipping Machine energies, those of crushing seem relatively high. The crusher drive system however, consisted of a series of old Vee belt, flat belt pulleys and finger gears , the mechanical efficiency of which is likely quite low. Although instrumentation for measuring the mechanical efficiency of the drive train was unavailable, the performance certainly appeared inferior to that of present-day gearmotors.

The energy requirements for the crusher are, however, similar to those measured for the TVA Fiberizing concept which was tested as part of the early stages of this project. Data from these earlier tests is available as unpublished notes through FERIC.

In the TVA tests, green roundwood averaging 13 cm in diameter was crushed into slivers 3 cm across (i.e., the rate of reduction in cross-section dimensions was roughly 4 to 1). This operation consumed 40-68 MJ/ODt in Machine energy and the machine involved had virtually smooth rolls and a modern drive train. The sorghum mill crushed slash averaging 2.5 cm in diameter through a gap of 0.6 cm, achieving a similar rate of reduction as the TVA machine for close to the same energy cost. This suggests that a roll-crushing operation which reduces cross-section dimensions by a factor of 4 and uses smooth rolls can be expected to consume 40-60 MJ/ODt in Machine energy.

It was evident that roll-crushing resulted in a considerable reduction in loose piled volume. Although this aspect was not measured during the tests, we estimate that the volume was reduced by one half once roll-crushing had destroyed the branch structure.

The mean moisture content of the slash before processing was 102%. We had expected to squeeze measurable quantities of water out of the slash, but were unable to do so. Even when the roll surfaces were set less than 1 mm apart, no measurable amount of liquid dripped from the rolls. However, the roll surfaces, the bark and exposed wood surfaces, did become wet and slick. Since we had previously had such good success in removing water from roundwood using the TVA and roll-splitting methods, this result was rather surprising. It is probable that the amount of water removed by crushing action varies with the diameter of material. A large wood mass allows hydrostatic pressures to build up for a greater distance down the length of the material and therefore results in greater flow through exposed end grain, as well as an increase in free water content in the section of wood immediately preceding the section nipped between the rolls.

Although we did not succeed in collecting measureable amounts of water while crushing, we noted that during the 1-3 day delay between roll-crushing and baling, the average MC of the crushed slash dropped from 102% to 18% MC. The crushed slash had been piled in loose piles exposed to wind and sun, but not precipitation, for this period. Average afternoon temperatures ranged from 10 to 15° C and night temperatures -5 to 0° C with clear conditions prevailing throughout.

2.5 CONCLUSIONS

A machine with smooth-surfaced rolls which reduces cross-sectional dimensions by a factor of 4 can roll-crush slash using approximately 40-60 MJ/ODt of Machine energy.

Roll-crushing is an effective means of reducing the loose piled volume of slash. We estimate that a factor of 2 reduction in volume can be expected.

Roll-crushing increases the drying rate of slash by exposing end grain and longitudinal surface areas.

Roll-crushing of slash in the 0-4 cm diameter range does not directly dewater hardwood slash in the 100% MC range.

It is unlikely that the Machine energy requirements of roll-crushing slash can be reduced much below 40 MJ/ODt. The disproportion between roll diameter, tooth size, and maximum material dimensions precludes the use of splitting rolls with axe-like teeth as is possible with larger diameter material.

3.0 BALING ROLL-SPLIT AND CRUSHED WOOD

3.1 OBJECTIVES

The objectives of this test were the following:

- to observe the effect of roll-splitting roundwood into a mass of long slivers on the subsequent operations of shearing and compacting;
- to compare the bales formed after roll-splitting with those formed from whole trees not previously roll-split;
- to determine the solid volume factor of the bales formed from this roll-split material; and
- to observe the effect of roll-crushing slash (4 cm maximum diameter) through a 0.6 cm gap on the compacting characteristics of the material produced.

3.2 MACHINE DESCRIPTION

The baler selected was a prototype, trailer-mounted machine, built in 1979 as part of a United States Department of Energy program to investigate the recovery, processing and storage of biomass fuels. The machine is approximately 2.4 m wide, 7.3 m long, 2.1 m high and weighs 10,000 kg. It is powered by a 74 kw GMC 353 diesel engine driving a 190 litre/min hydraulic pump with an operating pressure range of up to 146 kg/cm^2, Walbridge and Stuart (1). Figure 3 shows photographs of the baler.

The baler combines both the shearing and compacting operations in a single stroke of its compacting platten. Material is fed into the machine through a rectangular opening (.81 m high x .91 m wide) on one side of the baler, into a .91 m-deep baling chamber. The platten is then pushed forward across this opening by a hydraulic cylinder 25 cm in diameter. A stationary shear at the far side of the opening trims any protruding material. The platten advances approximately 30 cm past the shear edge, compacting the material in the baling chamber. The surface of the platten is .91 m wide by .76 cm high and, with the compacting ram fully extended, the bale chamber measures 1.1 m in length.

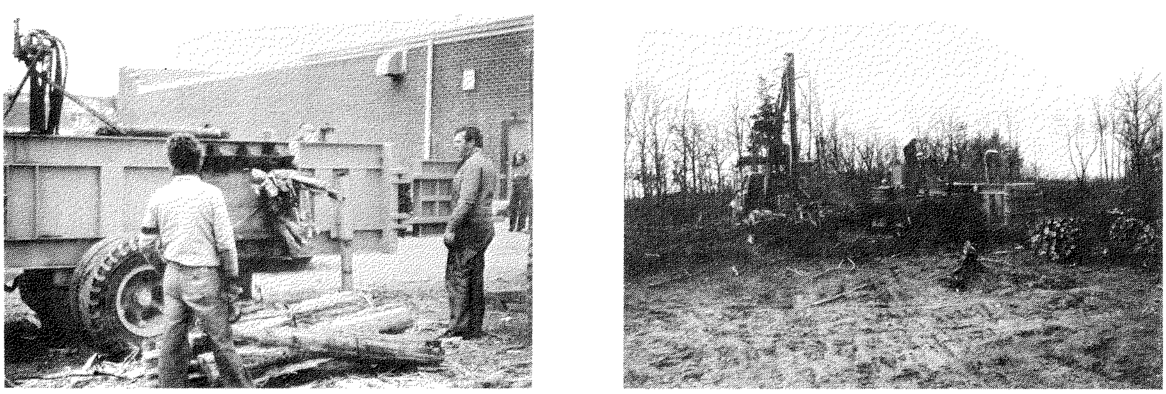


FIGURE 3

THE HARVESTING RESIDUE BALER

Forming a bale is a cyclical operation, requiring between 4 and 10 shearing and compacting strokes to fill the chamber. The chamber is considered full when the platten cannot be fully extended against the packed material.

With this prototype machine, the bales are tied by hand. Before each bale is formed 3 strands of annealed, No. 10 steel wire are threaded through slots in the bottom and top of the chamber. Once the material has been fully compacted, the wires are passed up around it in grooves machined into the face of the platten. The wires are then tied on top of the bale by hand, but are left loose, with about 3-4 cm slack between the bale surface and the wire. Once released from the bale chamber, the bale expands and tightens the wires; without the slack the wires would break. Steel strapping material has been tried as an alternative to wire, but it lacks sufficient resiliance to accommodate bale expansion and tends to break during handling.

Once the bale is tied, the bale chamber door is opened by a hydraulic latching device. The wires immediately tighten when the door is opened. The bale is then forced part way (20 cm) out of the chamber by the platten, and as a result of expansion.

As the next bale is formed, it pushes the first one out of the chamber and onto the ground. Once the bale has fallen out, new wires are threaded for the next bale, next to the chamber door; the door is then closed, locked and the compacting operation continues. Finished bales are removed from the area by a grapple and can be rolled along level surfaces by two or three men, despite their 300-600 kg weight.

3.3 TEST PROCEDURE

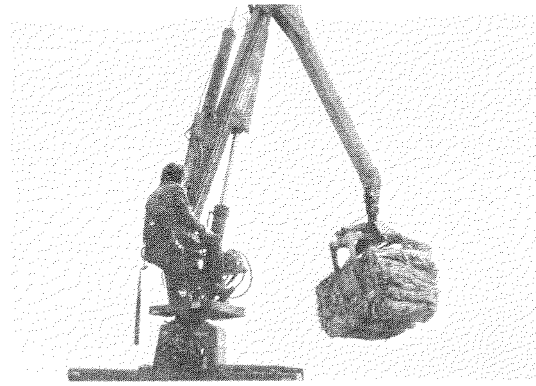
The roll-split material, which had been shipped in from the University of Massachussetts, was separated into piles by species: hemlock (Tsuga canadensis L. Carr.), spruce (Picea rubens Sarg.), white birch (Betula papyrifera Marsh), quaking aspen (Populus tremuloides Michx), red maple (Acer rubrum L.), red oak (Quercus rubra L.) and white pine (Pinus strobus). Moisture content samples were taken from the centre portions of the bundles during the baling operations. Specific gravity (SG) samples had previously been taken during the roll splitting tests. Both sets of data are summarized in Table 2.

TABLE 2

MOISTURE CONTENT AND SPECIFIC GRAVITY OF BALED WOOD

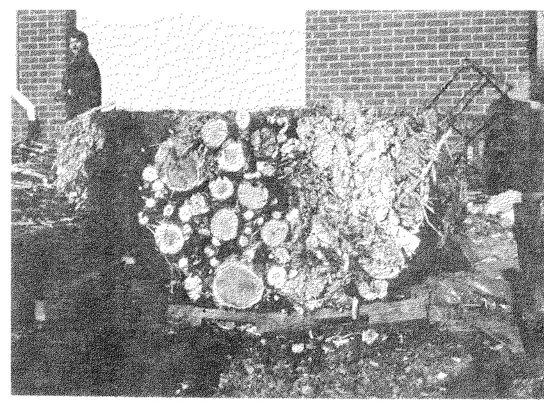
	Hemlock	Pine	Spruce	Aspen	Birch	Red Maple	Red Oak
Moisture Content (% Dry)	130	109	130	120	97	79	72
Specific Gravity	.43	.31	.38	.45	.54	.54	.58

4a



4a

4b



4c

FIGURE 4

HARVESTING RESIDUE BALES

4a) Roll split wood

4b) Roll crushed slash

4c) Mixed whole trees and roll split wood deliberately left in the banding wires. The length and height of the bales were also slightly greater than the chamber dimensions because of a slight misalignment of individual pieces within bales.

Of all the bales formed, only bale No. 1 had a solid volume factor greatly below 50% (see Table 3). In this case two of the three banding wires had broken and had to be retied outside the bale chamber.

As indicated earlier, the slash which had been crushed in the sorghum mill was also baled; there was only enough material to form one bale. This bale also had the highest solid volume factor of any bale formed, 62%.

3.5 DISCUSSION

It appeared as though the roll-split material was much more easily sheared than an equivalent cross section of whole tree bolts. This was not surprising; splinters lack the rigidity and bending strength that normally cause high friction forces on shear blade surfaces.

The bales formed from roll-split material appear to be much tighter than those formed from whole trees. The solid volume of these bales (47% and 53%) was, however, less than expected. The calculated solid volume is, however, the result of three rather conservative measurement techniques: (i) recording the maximum outside dimensions of bales; (ii) taking MC samples of the roll-split splinters from the centre portions alone; and, (iii) including data even from poorly formed bales that had broken wires. (On the latter point, we feel that properly formed bales of roll-split material could be expected to achieve 60% solid volume factors.) The solid volume values are therefore "worst case" results which might be realized in practical situations (e.g., on a loaded truck).

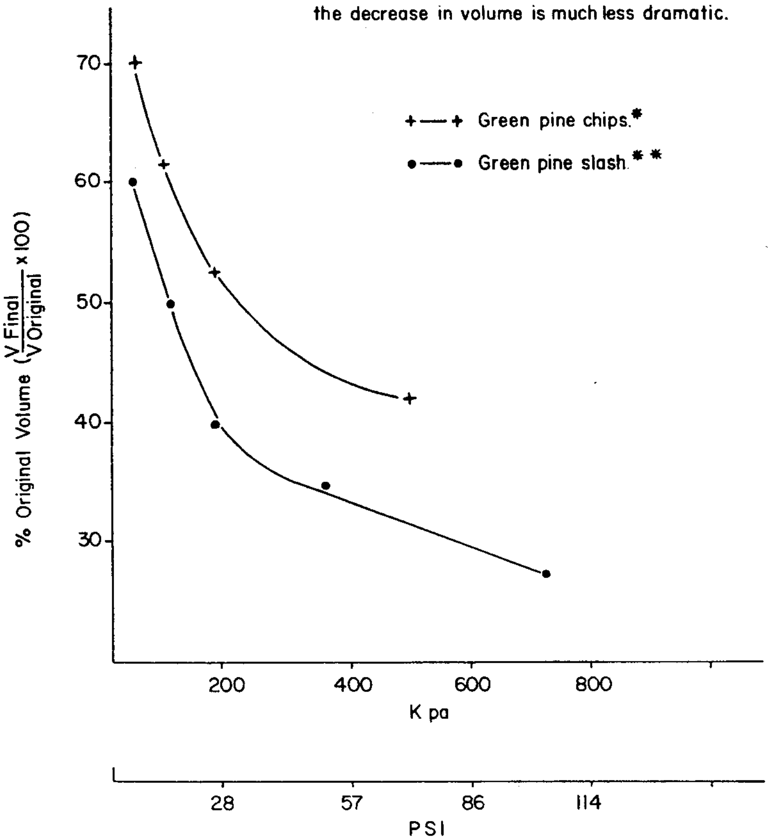
We also feel that the compaction pressures of 640 and 1000 Kpa used during the tests are excessive. These high pressures were necessary to facilitate the shearing operation. In other tests of slash and chip compaction 350 Kpa (50 psi) has been sufficient to maximize compaction. (See Hassan (2) Danielsson, Marks and Sall (3).) Figure 5 cites the results taken from these tests; it appears that little additional solid volume is gained when compaction pressures greater than 350 Kpa are used.

The solid volume factors resulting from compaction are higher than those achieved using whole tree chippers. Solid volume of loose-packed pulp chips, is normally 40-45%, although it may be slightly higher for blower-packed chips. The solid volume of chunkwood material with particle lengths roughly equal in all dimensions - such as that produced by the short log method, Morimasa (4) and by spiral head and involuted disc chippers, Arola (5) - can be expected to reach 50%.

FIGURE 5

VOLUME REDUCTION BY COMPACTION

To compact chips or slash, 350 Kpa appears to be a reasonable design limit. At higher pressures the decrease in volume is much less dramatic.



* Estimate based on graphical data: Hassan (4)
** Estimate based on graphical data: Danielsson (7)

3.6 CONCLUSIONS

The force required to sheer material which has been roll-split is less than that required to shear an equivalent cross section of solid roundwood.

Roll-split material is more resilient than solid roundwood. Since resilience prevents banding straps from loosening during handling, roll-split material may be a preferable baling stock.

It was not possible to determine whether roll-splitting prior to compaction increases the solid volume of bales beyond that resulting from simple shearing and compacting.

Because of its resilience, the roll-split material forms a bale that may develop slightly rounded corners.

In a fully developed process, the minimum solid volume factor (by truck load) that should be expected when transporting roll-split wood baled with 640 to 1000 Kpa pressures is 50%. A 60% solid volume factor is a reasonably average solid volume factor to expect.

Roll-crushed slash closely resembles hay when baled. The bales maintain their shape and sharp corners.

A roll-splitter could be operated as an effective device to infeed material to a residue baler. Its action would significantly improve the physical properties of the infeed material by increasing its uniformity and destroying its structural integrity.

4.0 RECOMMENDATIONS

Two programs should be implemented.

(1) A residue baler should be constructed using roll-crushing to pre-process and infeed material. The standard squared bales or the rolled bales should be considered. In the case of the rolled bales, the requirement for cutting is eliminated and is a reasonable approach to consider in view of the scale of input elements. This concept might be applied to energy plantation systems as an alternative to the concepts of chipping or billeting material into trailers towed behind a felling device.

(2) A large diameter (whole tree) residue roll-splitter and compaction unit should be prototyped. The roll-splitter should be hydraulically driven as a pre-processor and intermittent infeed device to a baling chamber. The system could employ a billeting operation either before or after the roll-splitting device. We suggest that the billeting occur after, particularly if a shearing device is used rather than a saw. The infeed system should employ a purely gravity or gravity-assisted infeed concept, a sloped conveyor (30° - 60° off horizontal).

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APPENDIX F

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