Evaluation of Forest Biomass Compaction Systems

by

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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.

This report is the result of a study performed by the Forest Engineering Research Institute of Canada performed under contract with the Government of Canada.

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SUMMARY AND CONCLUSIONS

Forest biomass produced at the logging site, such as tree tops and branches left behind delimbers and small trees from pre-commercial thinning, remains by and large underutilized as a source of energy in Canada. A major reason for this situation is the difficulty of handling, transporting and processing low value, high bulk and low density forest biomass fuel economically . Chipping the material in the woods (or comminuting it by other means) is the most common method presently used to reduce forest biomass, make it homogeneous and prepare it as a fuel. The report investigates compaction as an addition to comminution, or as an alternative to comminution. The main purpose of compaction is to reduce the bulk density of the material and to form it into uniform and manageable units. Data from U.S. and Swedish literature show that logging slash and small trees generally have a bulk density ranging from 130 to 220 kg/m^3 and a solid volume factor of 20 to 25% (i.e. 75 to 80% of the pile is airgaps between the various pieces of the material). When such a material is loaded in a truck, the truck's maximum volume capacity is reached much before its maximum payload--the truck is underloaded. It can be shown that truck transport in a trailer van is not optimum unless the material transported has a bulk density of 300 kg/m^3 or greater. For optimum truck transport, logging slash and small trees should be compacted to a volume reduction ratio of 0.3 to 0.5. The bulk density of fuel chips is also usually less than 300 kg/m^3 and compaction would also, to some extent, reduce their transport cost.

The objective of the state-of-the-art study was to identify all types of compaction systems whether or not they were used for forest biomass. It was surprising to find that most pieces of equipment that are used by other industries like agriculture, recycling and waste disposal, have been tried at some point during the last ten years for the compaction of woody material. The report presents the results of such tests with the following equipments:

- round agricultural baler
- square baler (paper and scrap metal presses)
- garbage truck
- garbage container-compactor
- cotton module builder

It was found that among these systems, the square baler and the cotton module builder showed the most promise for the compaction of forest residues at roadside.

Among the prototypes specifically develop to handle woody biomass three major types were found:

- balers and bundlers
- on-truck compactors
- densifiers

The VPI baler concept, especially the "second generation" VPI baler, appears particularly well suited to the Canadian need for a baler that can handle logging slash at roadside. On-truck compactors are mainly of interest when transporting tree sections or whole trees. Densification is an energy hungry process best suited for fixed installation.

In the forest biomass harvesting system, compaction can be performed either before or after chipping (or other comminution); compaction could also be used as an alternative to comminution in which case new energy conversion systems capable of handling whole bales have to be designed.

I. INTRODUCTION

Historically forest biomass has always been an important source of renewable energy. With the rapid increase in fossil fuel prices during the 1970's, there has been a renewed interest among the industrialized countries in developing forest biomass as an alternate energy source to cushion against future oil price increases. Accordingly better methods and equipments are sought to collect, harvest, transport and convert forest biomass into usable energy.

Most forms of raw forest biomass have low bulk density and are physically very heterogeneous; as a result, handling, transporting and storing forest biomass, without processing it, is very inefficient. As an example, tops and branches loaded in a trailer van without any special preparation occupy only 20 to 25% of the volume of the van, the remaining 75 to 80% being air gaps between the material. In most cases when transporting bulky material, transport vehicles are loaded up to volume capacity before they reach their maximum allowable gross weight and are therefore under utilized. Similarly, storing bulky material requires much more space than if the material is denser. Most handling equipment is slow and inefficient when dealing with bulky and heterogeneous material.

The most common method used to increase the bulk density of forest biomass and make it more homogeneous is comminution by chipping and hogging. Comminution also prepares the biomass into a form directly usable as a fuel in energy conversion systems.

A second alternative to reduce the bulkiness and heterogeneity of forest biomass is to compact it. Compaction can offer several advantages over comminution:

- it can increase the bulk density of biomass using less energy than comminution
- it can produce uniform units that can be efficiently handled and stored
- it can increase trucking efficiency by optimizing the payload
- it can increase system flexibility by disconnecting harvesting and transport (as opposed to a system using comminution where a chip van has to be present on the landing during the harvesting operation)
- it permits optimal use of subsequent processing or conversion units like chippers. The subsequent processors can be stationary or centralized
- it allows flexibility in choosing final product characteristics (bales can be burned as is, or chipped, or hogged, etc...)
- bales can be left in the woods for natural drying (which further increases handling efficiency)
- compaction may reduce the moisture content by squeezing out water.

Although compaction is a widely accepted technique in industries like agriculture, recycling and waste disposal it is not commonly used in the forest industry (fuel densification is an exception).

It appears that there is a lack in the transfer of a well known technology and its application to forest biomass processing. Given the potential benefits to be gained from biomass compaction, this study was undertaken to investigate the state-of-the-art in compaction technology.

The general objective of the study was to investigate the use of compaction systems in conjunction with the harvesting and transport of forest biomass.

More specifically the objectives were:

a) to review existing technology used for biomass compaction;

b) to investigate compaction systems used by other industries (i.e. recycling and agriculture) and determine how they might apply to woody biomass;

c) to evaluate how different compaction systems would fit technically within biomass harvesting and transport systems and what economic gains (or losses) might be expected;

d) if suitable equipment is not available to compact a given biomass type to a desired form, an attempt to draw-up preliminary specifications for such equipment will be made.

A computerized data bank of existing compaction equipment was first developed. Fifty-five different pieces of equipment were catalogued (a complete listing is given in the Milestone I report for this study [Guimier 1985]); about half was equipment developed specifically for agriculture, recycling or waste industries; the other half were prototypes or commercial equipment used for woody biomass compaction.

This report presents the results of the state-of-the-art study in forest biomass compaction based on the equipment data bank and on published literature.

II. DEFINITIONS

Several terms describing the physical properties of woody biomass related to compaction are used throughout the report and should be accurately defined. Many of the terms are more easily explained using the example of Figure 1. Figure 1-a shows a container of volume Vo filled with uncompacted biomass; Figure 1-b is the same container after compaction.

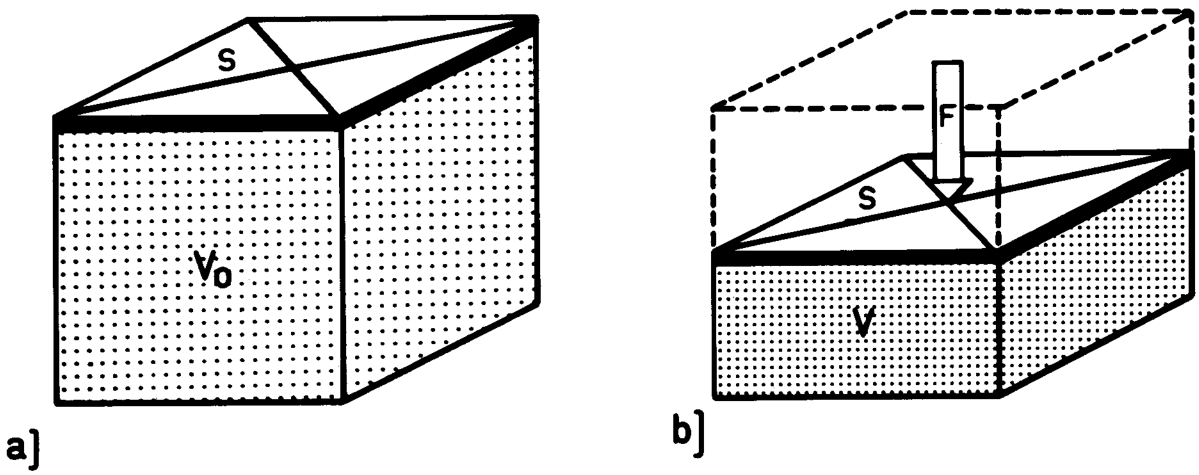


Figure 1. Material in a container before and after compaction.

- **Green weight** (W(green)) is usually expressed in kilogram (kg) and represents the total weight of the biomass including the moisture contained in the wood. W(green) remains constant during the compaction process if no water is squeezed out.

- **Dry weight** (W(dry)) is usually expressed in over-dry kilogram (o.d. kg) and represents the weight of the biomass excluding the moisture.

- **Percent moisture content** (MC%) is expressed throughout this report on a green weight basis:

  $$MC\% = 100 \times [W(green) - W(dry)]/W(green)$$

Percent moisture content can also be expressed on a dry weight basis the expression is 100 x [W(green) - W(dry)]/W(dry). A graph to convert from dry weight basis to green weight basis is given in Figure 2.

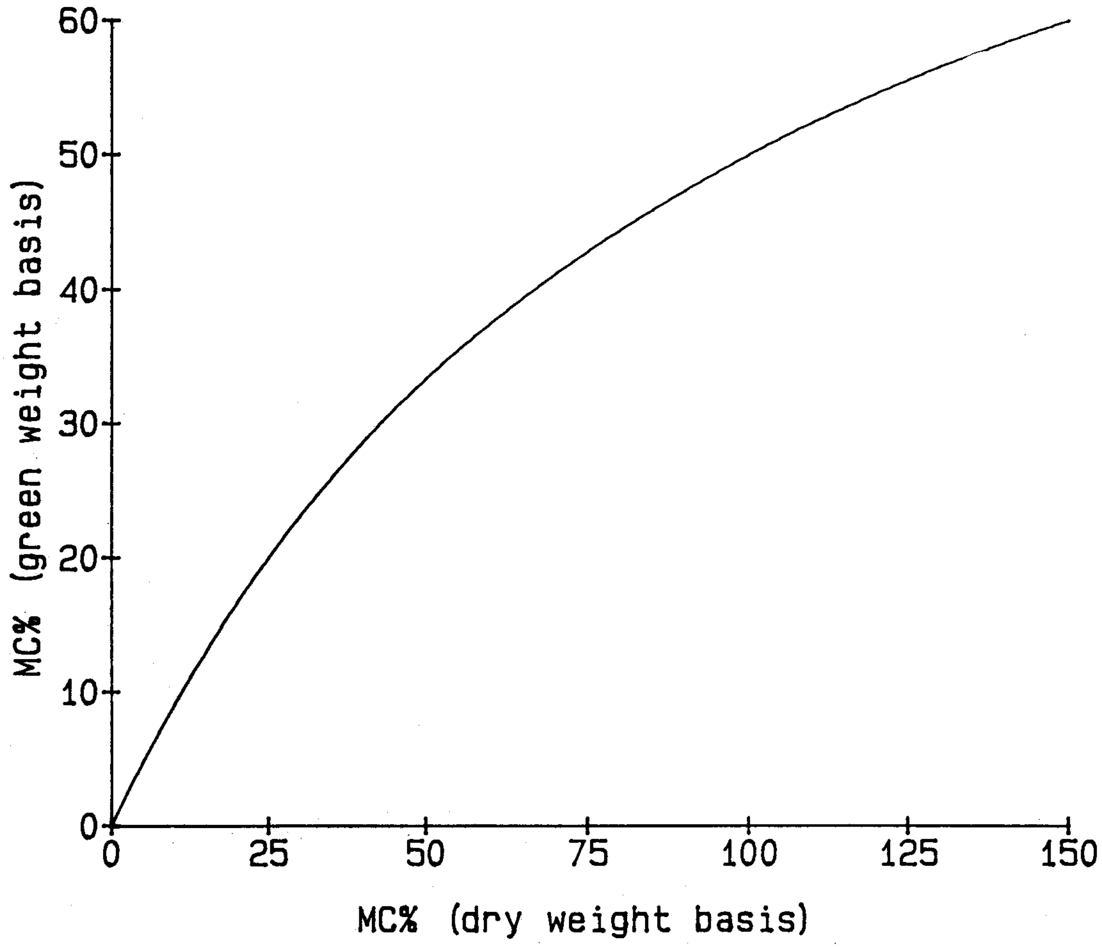


Figure 2. Relationship between moisture contents expressed on a dry weight basis and green weight basis.

- **Bulk Volume** (V(bulk)) in cubic-metre (m^3) is the physical volume occupied by the biomass including the airgaps between the biomass pieces.

- **Bulk Density** (d(bulk)) is equal to the weight divided by the bulk volume. By using green weight or dry weight, bulk density can be expressed in kg/m^3 or o.d. kg/m^3 respectively.

- **Solid Volume** (V(solid)) is the volume occupied by the biomass alone and excludes the airgaps between the biomass pieces. It is computed as the sum of the volume of each individual pieces of biomass. V(solid) is expressed in cubic metres (m^3), and is always less than the bulk volume.

- **Solid Density** (d(solid)) is equal to the weight divided by the solid volume. Similarly to bulk density it can be expressed in green kg/m^3 or o.d. kg/m^3.

- **Solid Volume Factor** (SVF) is expressed as a percentage and defines the bulkiness of a material:

  SVF = V(solid)/V(bulk) x 100 which is also equivalent to:

  SVF = d(bulk)/d(solid) x 100

  The smaller the SVF, the bulkier the material.

- **Volume Reduction Ratio** (VRR) (no unit). As shown in Figure 1 as the material is being compacted its bulk volume decreases from Vo to V. VRR is expressed as:

  VRR = (Vo-V)/Vo

- **Compaction Force** (F) in Newton (N) is the load applied to compress the material.

- **Compaction Pressure** (P) in Pascal (Pa) is the pressure exerted on the material by the force F in Newton (N) and the face plate of area S in square metre (m^2).

  P = F/S

  A typical plot of the Volume Reduction Ratio (VRR) versus the compaction pressure for a nonelastic material like woody biomass is shown in Figure 3. It illustrates several points:

  - the maximum value for the VRR is 1 and is never reached in practice;

  - the relationship between P and VRR is nonlinear. The pressure increment required to achieve a same VRR increase is much greater at the end of the compaction cycle than at the beginning. In the example, only 200 kPa are needed to compact the material from 0 to 0.5 VRR but 300 kPa are required to compact it from 0 to 0.6.

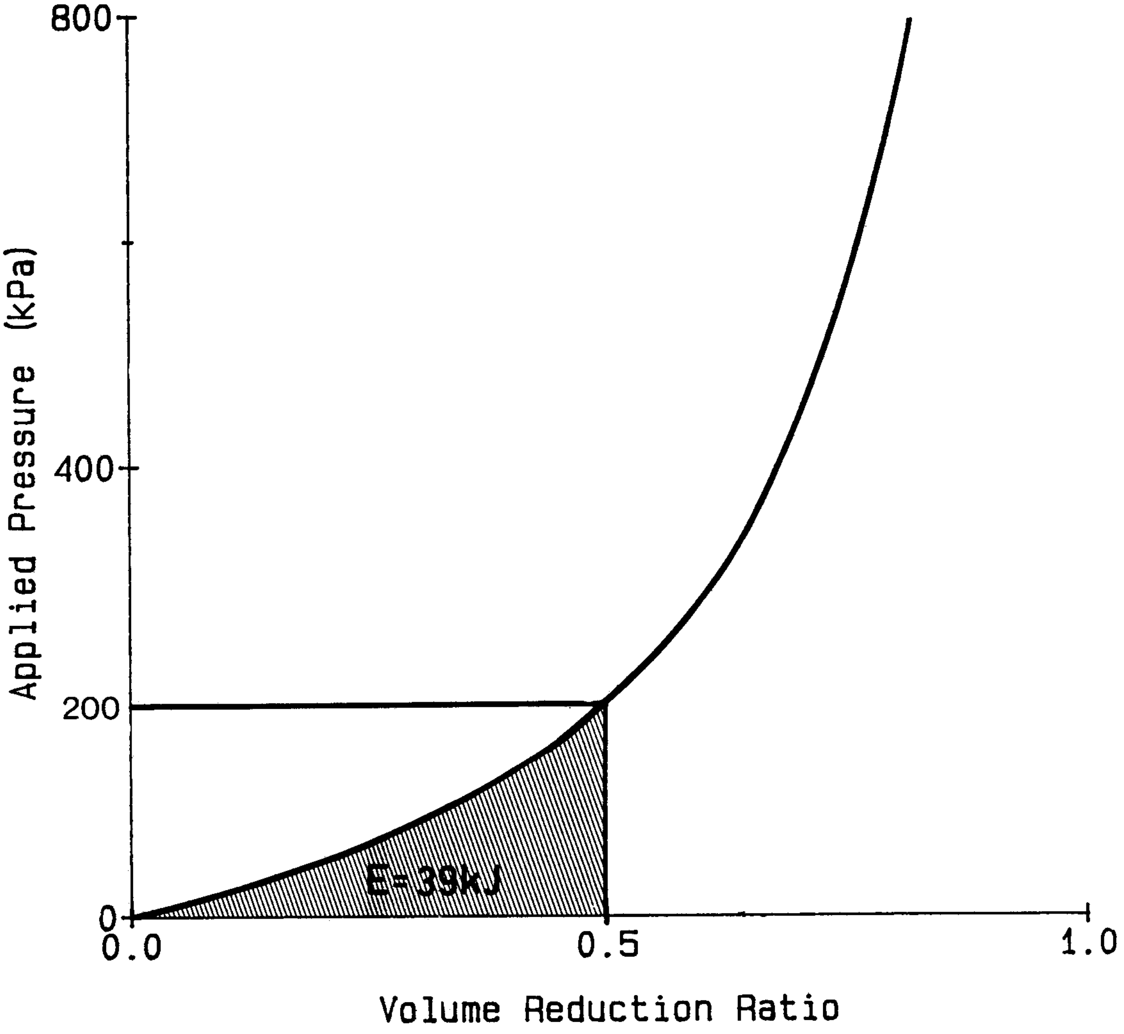


Figure 3. Typical compaction curve for a nonelastic material like woody biomass.

- **Compaction Energy** (E) required to compact a unit volume of biomass is expressed in joules (J). It is equal to the integral of P x d(VRR).

  $E = \int P \times d(VRR)$

  E is represented by the cross hatched area under the VRR versus P curve (Figure 3).

  In our example 39 kJ are required to compact 1 m^3 of material to half its original volume. Similarly to the applied pressure, the energy required grows exponentially with the degree of compaction. To compact the material to one quarter of its original volume, 127 kJ would be required.

III. NEED FOR BIOMASS COMPACTION EQUIPMENT IN CANADA

A - Forest Biomass Characterization

Forest biomass usable for energy, unlike traditional forest products, is not limited to the debarked stem portion of the tree; all parts of the tree above and below-ground can be used for energy. Forest energy biomass in Canada comes from many different sources: (Figure 4).

- mill by-products
- logging by-products
- non-commercial stands
- merchantable surplus
- energy plantation
- fuel wood from private woodlots

Figure 4. A sample of forest biomass products.

Mill by-products or residues are the biomass not utilized by the mill (sawmill, pulpmill, plywood mill, etc...) in the manufacture of its primary product(s). They include: bark, sawdust, shavings, trim-ends, edgings, peeler cores and chips.

Logging by-products are the trees or portion of trees that are by-passed or abandoned during the harvest of a forest for conventional forest products. Logging by-products include residues like tops and branches (slash) and residuals trees which are too small, defective or of undesirable species. This type of material can be found on the cut area or at the primary landing. With the gradual introduction of full tree harvesting and delimbing at roadside or at central landings, more and more of the logging by-products will be piled in a centralized location and consequently be more easily available as a source of energy.

Non-commercial stands are stands that do not contain enough material of sufficient quality to harvest them economically for conventional forest products. They include stands in need of cleaning or thinning, over-mature stands, stands of dead timber, or non-commercial species stands.

Merchantable-surplus are stands available for harvest as part of the annual allowable cut but are not harvested owing to economic or other reasons.

Energy plantation are forest planted with fast-growing species and harvested primarily for their energy value. Private woodlots are generally small privately owned forest harvested on a small scale basis for wood fuel.

The amount of forest energy biomass available in Canada from each of those sources is shown in Table 1.

Table 1. Availability of forest energy biomass in Canada. (Source: Pottie 1985)

Source	million o.d. t/year
Mill by-product	15.8
Logging by-product	24.1
Non-commercial stands	38.6
Merchantable surplus	33.3
Energy plantations	7.9
Fuel wood from private woodlots	3.2
Total	122.9

Of all those sources mill bi-products produce the cheapest energy because they are usually close to a conversion plant, they are clean and often processed into a form acceptable for direct burning. For these reasons compaction of mill by-products does not present major advantages. On the other hand the other major sources of forest biomass energy remain mostly unutilized because of their physical characteristics and location. Much of the volume of biomass is from logging by-products, non-commercial stands and energy plantations and can typically be described as small trees, branches or tops, slab, whole trees and stumps scattered over a wide area, or piled at roadside, and located at large distances from a conversion plant. In the last several years inventories have produced data on the volumes of biomass in Canada. Very little Canadian information is available that describes the physical characteristics of the biomass as it is found on the logging site; yet several of those characteristics, like the bulk density and the solid volume factor (SVF) are of major importance because they influence the economics of transporting, processing and storing the biomass. The physical characteristics of various biomass forms presented in Table 2 are borrowed from Swedish and US studies (no Canadian data were found). Table 2 points out the wide variation in bulk density and SVF between different forest biomass forms. In addition, large variations exist within each form, depending on the trees species, age, moisture content, origin, method of harvesting etc... The highest SVF is achieved with piled round logs; chips usually have a SVF between 40-50%; tree sections (sections of trees with limbs attached) have a SVF of 25-30% when loosely piled; slash, limbs and tops and small trees from precommercial thinning have the lowest SVF (20-25%).

Table 2. Physical characteristics of biomass forms.

Material description	Moisture content %	Bulk green density (kg/m³)	SVF	Reference
Round Wood				
Pulpwood, softwood	50	500-550	60-65	Danielsson 1983
Tree Sections				
Softwood	50	249	31	Larsson 1982
Birch	50	235-285	25-30	Danielsson 1983
Softwood	50	200-250	25-30	Danielsson 1983
Softwood	40	180-210	25-30	Danielsson 1983
Small Trees				
Pre-commercial thinning		175-200	20-22	Danielsson 1977
Logging Slash				
Green limbs and tops	56	212	21	Carlsson 1981
Slash	-	130-170	-	Larsson 1980
Chips				
Green pine	47	265	45	Hassan 1976
Aspen	45	221		Hensel 1976
Hardwood (all tree chips)		384		Haygreen 1981
Yellow pine (stem and bark)		240		Haygreen 1981

B - Need for Compaction

A major problem in making use of the available biomass energy is to harvest, process and transport the biomass economically to a place of conversion. At the present time the most common scenario is to chip (or comminute by other means) the material in the woods and truck it to the conversion plant (Figure 5-a). An alternative is to transport the raw material to a central location for chipping and conversion (Figure 5-b). Blakeney (1983) showed that this second alternative is, in most cases, more expensive than the first owing to the high cost of handling, loading and transporting the raw material to the central location. The introduction of compaction might reverse that conclusion. An analysis of the advantages and disadvantages of alternative one (chipping in the woods) points out where compaction would be of greatest value. Chips have the advantage of being homogenous, easy to handle and denser than the raw material they are made from; they can also be burned in conventional conversion systems after minor modifications. However chipping, like most other mechanical operations, is not done most efficiently in the woods; a stationary chipper in a central yard has a higher production than a mobile chipper specially if the material chipped is properly prepared. As an example Danielsson (1977) suggested that by baling the material before chipping, the productivity of a chipper is increased by a factor of 10 as compared to chipping unprepared material. Also, chips stored in large piles deteriorate with time; fungi growth can decrease the quality of fuel chips and, under some conditions, internal chip pile temperature can raise and cause spontaneous combustion., There is very little air circulation through the chip pile and chips will not dry while in storage, their moisture content might even increase if the pile is exposed to rain and humidity.

By compacting and preparing the raw biomass into manageable units, the chipping (or other comminution) operation can be delayed or even eliminated and most of the disadvantages of chipping in the woods (listed above) would disappear.

Compaction could be done in the woods during or just after the harvesting (or collection) phase so that all subsequent phases of the operation can benefit from the increase in density and uniformity of the material (Figure 5-c). An alternative combining compaction and comminution at the logging site could also be considered (Figure 5-d). A third scenario illustrated in Figure 5-e and proposed by Jones (1981a) consists in compacting the material at the logging site and bypassing the comminution phase altogether by burning or gasifying directly the compacted material (bales). Jones proposes two alternatives to feed the bales into the combustion unit using traveling grates (Figure 6).

Densification is another type of compaction presently used. As shown in Figure 5-f densification is performed after a comminution phase and before combustion to increase the handling, storage and combustion efficiency of the fuel.

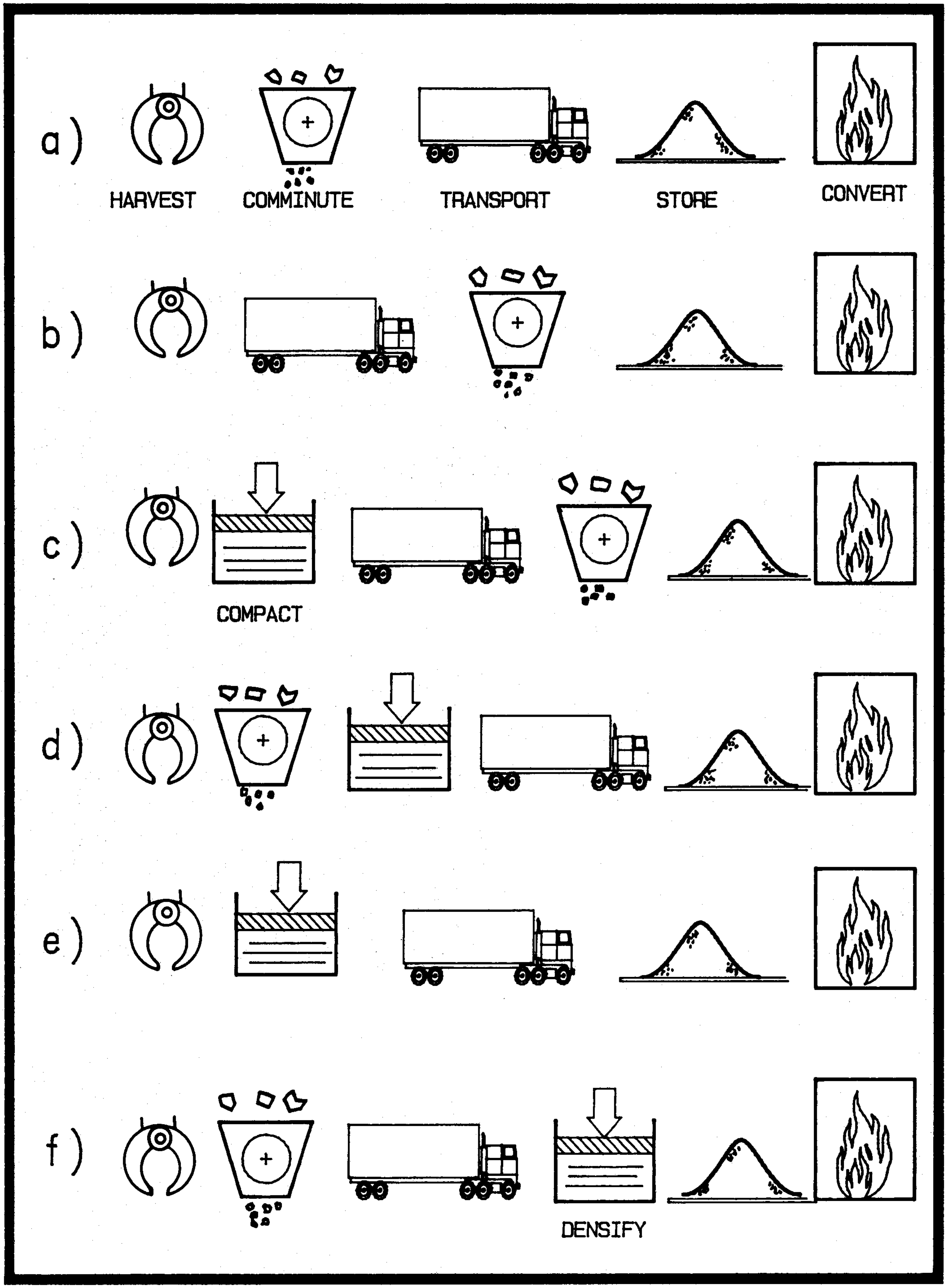
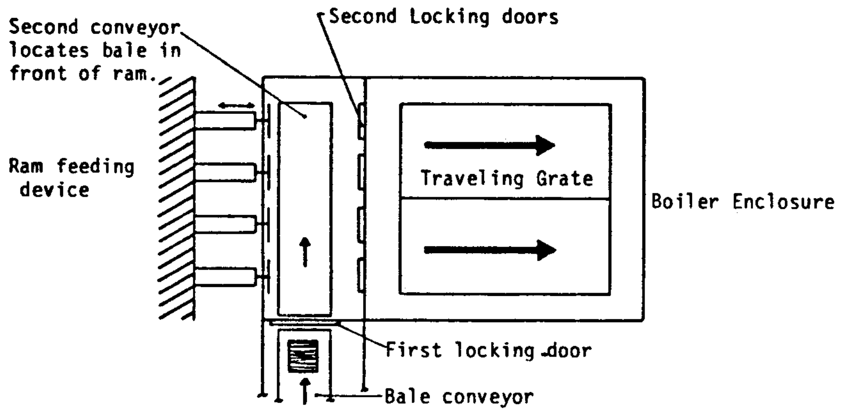
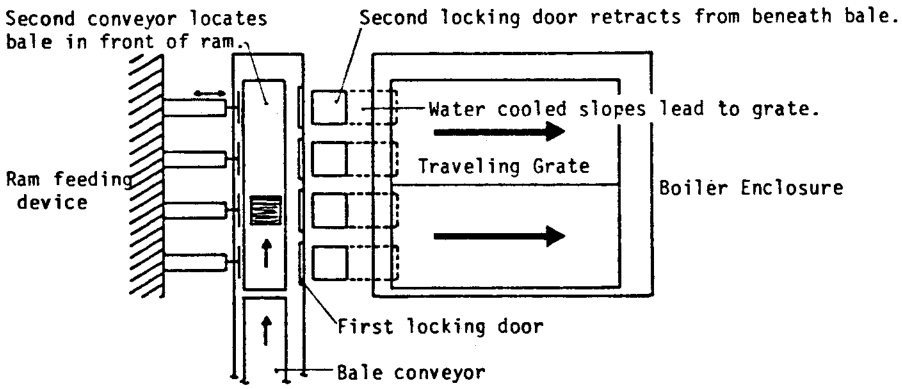


Figure 5. Biomass processing and conversion systems excluding or including a compaction phase.



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.



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.

Figure 6. Possible feed systems for burning whole bales. (Jones 1981b)

C - Economic Considerations

The optimum economic level of compaction can only be determined precisely on a case by case basis when the characteristics of the handling, transport and conversion equipment used, as well as the type of material handled are given. In an approximate approach we can assume that truck transport will be the determining factor in the analysis and that as long as the product is uniform, handling and storage can be done efficiently. Truck transportation costs are minimum when the truck can be loaded to its maximum payload capacity before the maximum volume capacity of its cargo space is reached. We assume that the biomass will be transported in a three axles semi-trailer van with a tandem axle-tractor (total of 6 axles) and that the hauling rig will operate within the regulations governing size and weights of truck trailer combinations on public roads in the province of Quebec. The characteristics of a truck-trailer combination meeting this description are listed below (source: Silverside 1985).

- allowable total weight .... 57 500 kg
- truck and trailer weight .... 24 500 kg
- legal load limit .... 33 000 kg
- trailer van volume .... 112.2 m^3
- average bulk density at the legal load limit .... 294 kg/m^3

In order to optimize hauling, the bulk density of the material should therefore be 294 kg/m^3 or greater. This figure is in agreement with data, published by (Danielsson 1983) for Sweden, showing that the density needed for a full load on a modified roundwood vehicle was 290 to 330 kg/m^3.

When comparing this optimal level of compaction with the actual bulk densities presented previously in Table 2 it can be seen that logging slash, tops, branches and small trees from precommercial thinning have a bulk density between half and two thirds of the level required for optimum transport; bulk densities for chips are also usually below the optimum and in many cases chip compaction would reduce transport costs.

IV. EXPERIMENTAL STUDIES ON WOODY BIOMASS COMPACTION

Several experiments have been carried out to determine the compressive characteristics of woody biomass and are reported in the literature. While these experiments are limited, they still lead to important conclusions.

A - Compaction of Green Pine Branches and Tops (Danielsson 1977)

1) **Experimental procedure**

The experimental equipment consisted of a compaction box 90 cm long by 60 cm wide and 100 cm high. The material was loaded through the top opening and manually pre-compacted. The box was then covered with a lid (lid area 0.54 m^2). The compaction force was applied to the lid with a hydraulic cylinder to a maximum force of 600 kN resulting in a maximum pressure in excess of 1000 kPa. The front panel of the compaction box could be removed to examine the compacted material and take measurements.

2) **Biomass characteristics before final compaction**

The green pine branches and tops had the following characteristics after having been manually pre-compacted inside the box:

- Moisture content - MC% ..... = 54%
- Green bulk density - d(bulk) = 206 kg/m^3 (green)
- Solid density - d(solid) ... = 500 kg/m^3 (green)
  = 382 o.d. kg/m^3 (oven dry)
- Solid Volume Factor - SVF = 41%

Because of the manual pre-compaction, the solid volume factor (SVF) of the material was higher than normal. The SVF of similar slash left in a pile would normally be between 20 to 30%.

3) **Compaction parameters**

The compaction curve in Figure 7 shows how the volume reduction ratio (VRR) varied while pressure was applied to the material described above. An applied compaction pressure of 219 kPa reduced the volume of the material by half (VRR = 0.5). The energy required to achieve this reduction was 25.2 kJ/m^3 equivalent to 120 J/kg of green material.

4) **Biomass characteristics after compaction**

The material had the following characteristics after having been compacted to a volume reduction ratio (VRR) of 0.5.

- Moisture content (assumed unchanged) - MC% ... = 54%
- Green bulk density - d(bulk) .... = 412 kg/m^3 (green)
- Solid density (assumed unchanged) - d(solid).. = 500 kg/m^3 (green)
- Solid Volume Factor - SVF .... = 82%

5) **Results summary**

Green pine branches and tops with 54% MC can be compacted to a bulk density of 412 kg/m^3 (green) and a solid volume factor of 82% by applying a pressure of 219 kPa. The process requires 120 J/kg of green material.

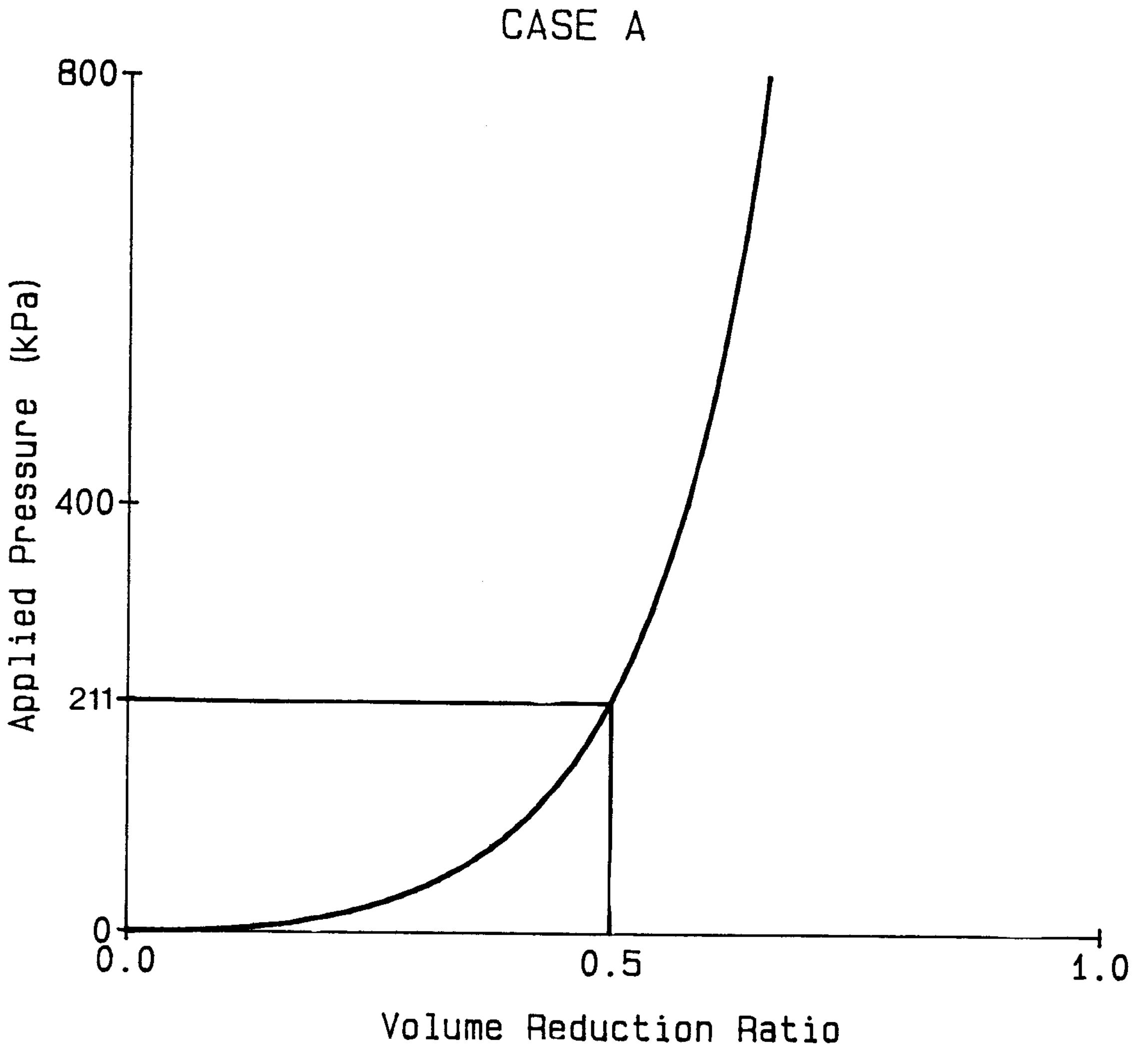


Figure 7. Compaction curve for green pine branches and tops. (Danielsson 1977)

B - Compaction of Dry Pine Branches and Tops (Danielsson 1977)

1) **Experimental procedure**

The procedure used was the same as described before for green pine branches and tops.

2) **Biomass characteristics before final compaction**

The dry pine branches and tops had tne following characteristics after having been manually pre-compacted inside the box:

- Moisture content - MC% .... = 20%
- Bulk density - d(bulk) .... = 136 kg/m³ (air dried)
- Solid density - d(solid) .... = 429 kg/m³ (air dried)
  = 404 o.d. kg/m³ (oven dry)
- Solid Volume Factor - SVF .... = 32%

As noted before because of the pre-compaction the SVF was higher than that of piled slash.

3) **Compaction parameters**

The compaction curve in Figure 8 shows how the volume reduction ratio (VRR) varied while pressure was applied to the material. An applied compaction pressure of 10 kPa reduced the volume of the material by half (VRR = 0.5). The energy required to achieve this reduction was 1.7 kJ/m³ equivalent to 12.4 J/kg.

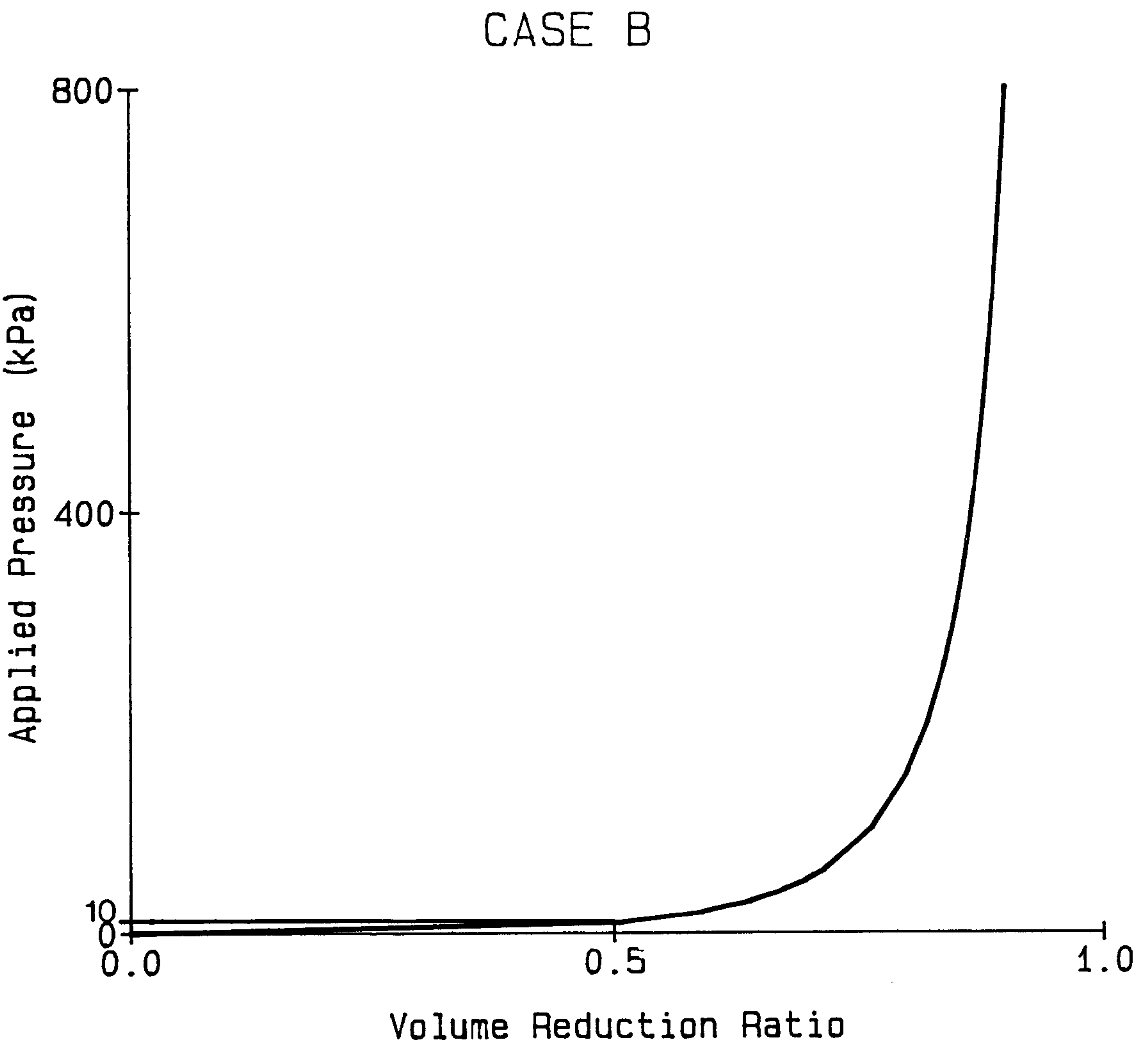


Figure 8. Compaction curve for dry pine branches and tops. (Danielsson 1977)

4) **Biomass characteristics after compaction**

The material had the following characteristics after having been compacted to a volume reduction ratio (VRR) of 0.5.

- Moisture content (assumed unchanged) - MC% = 20%
- Bulk density - d(bulk) .... = 272 kg/m³ (air dried)
- Solid density (assumed unchanged) d(solid) = 428 kg/m³ (air dried)
- Solid Volume Factor - SVF .... = 64%

5) **Results summary**

Dry pine branches and tops with 20% MC can be compacted to a bulk density of 272 kg/m³ and a solid volume factor of 64% by applying a pressure of 10 kPa. The process requires 12.4 J/kg of material.

C - <u>Compaction of Unscreened Green Pine Chips</u> (Hassan 1976)

1) **Experimental procedure**

Chips samples weighing about 8.2 kg were loaded in a 30 x 20 x 23 cm (internal dimensions) container. External pressure up to 600 kPa was applied to the top of the container by means of a 267-kN universal testing machine. The change in chip depth in the container versus applied pressure was recorded.

2) **Chips characteristics before compaction**

The unscreened green pine chips had the following characteristics after being loaded in the container:

- Moisture content - MC% .... = 47%
- Green bulk density - d(bulk) .... = 265 kg/m³ (green)
- Solid density - d(solid) .... ≃ 400 kg/m³ (oven dry) (assumed)
  ≃ 588 kg/m³ (green) (calculated)
- Solid Volume Factor - SVF .... = 45%

3) **Compaction parameters**

The compaction curve in Figure 9 shows how the volume reduction ratio (VRR) varied while pressure was applied to the chips. An applied compaction pressure of 268 kPa reduced the volume of chips by half (VRR = 0.5). The energy required to achieve this reduction was 25.1 kJ/m³, equivalent to 95 J/kg of green material.

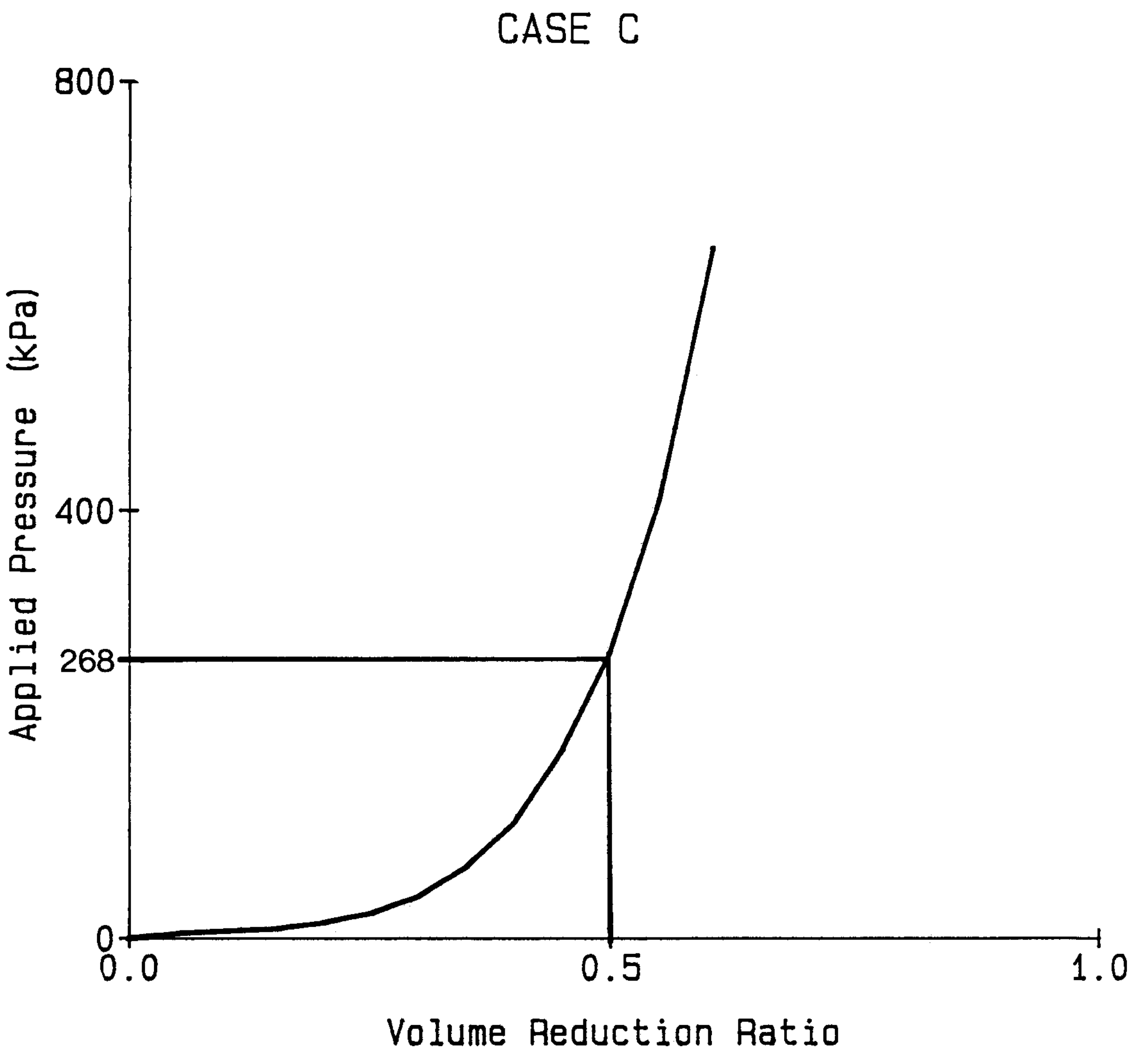


Figure 9. Compaction curve for unscreened green pine chips. (Hassan 1976)

4) **Chips characteristics after compaction**

After compaction to a volume reduction ratio (VRR) of 0.5 and with pressure maintained, the chips had the following characteristics:

- Moisture content (assumed unchanged) - MC% = 47%
- Green bulk density - d(bulk) .... = 530 kg/m³ (green)
- Solid density (assumed unchanged) - d(solid) = 588 kg/m³ (green)
- Solid Volume Factor - SVF .... = 90%

It was noted that when pressure was released some amount of spring back took place and as a result the bulk density and SVF were lower.

5) **Result summary**

Green pine unscreened chips with 47% MC can be compacted to a bulk density of 530 kg/m³ (green) and a SVF of 90% by applying a pressure of 268 kPa. The process requires 95 J/kg of green chips.

D - Compaction of Green Spruce Logging Slash (Jones 1981a)

1) **Experimental procedure**

The equipment used was the VPI baler (see description in Chapter V). The size of the compacting chamber was 1 x 1 x 0.91 m. Compression forces and bale volumes were measured at the end of the compression cycle.

2) **Characteristics of slash before compaction**

Before compaction the green spruce logging slash had the following characteristics:

- Bulk density - d(bulk) = 80 kg/m³ (oven dry)
- Solid density - d(solid) = 380 kg/m³ (oven dry)
- Solid Volume Factor - SVF = 21%

3) **Compaction parameters**

The applied pressure to reduce the volume the material volume by half was 343 kPa. (Jones 1981a) assumed that the applied pressure grew linearly with the VRR (Figure 10) and as a result he calculated that the required baling energy was 94 kJ/m³ or 1180 J/kg of oven dry material; assuming 50% MC this is equivalent to 590 J/kg of green material. As demonstrated in the previous examples it appears that assuming that applied pressure and VRR leads to an over-estimate for the energy and is conservative.

4) **Characteristics of the material after compaction**

As a result of baling and reduction of the volume by half the bulk density and SVF are increased; solid density is unchanged.

d(bulk) = 160 kg/m³ (oven dry)
d(solid) = 380 kg/m³ (oven dry)
SVF = 42%

5) **Result summary**

Green spruce logging slash can be compacted to a bulk density of 380 kg/m³ (oven dry) and a SVF of 42% by applying a pressure of 343 kPa. The process requires about 590 J/kg of green material. The energy figure is conservative.

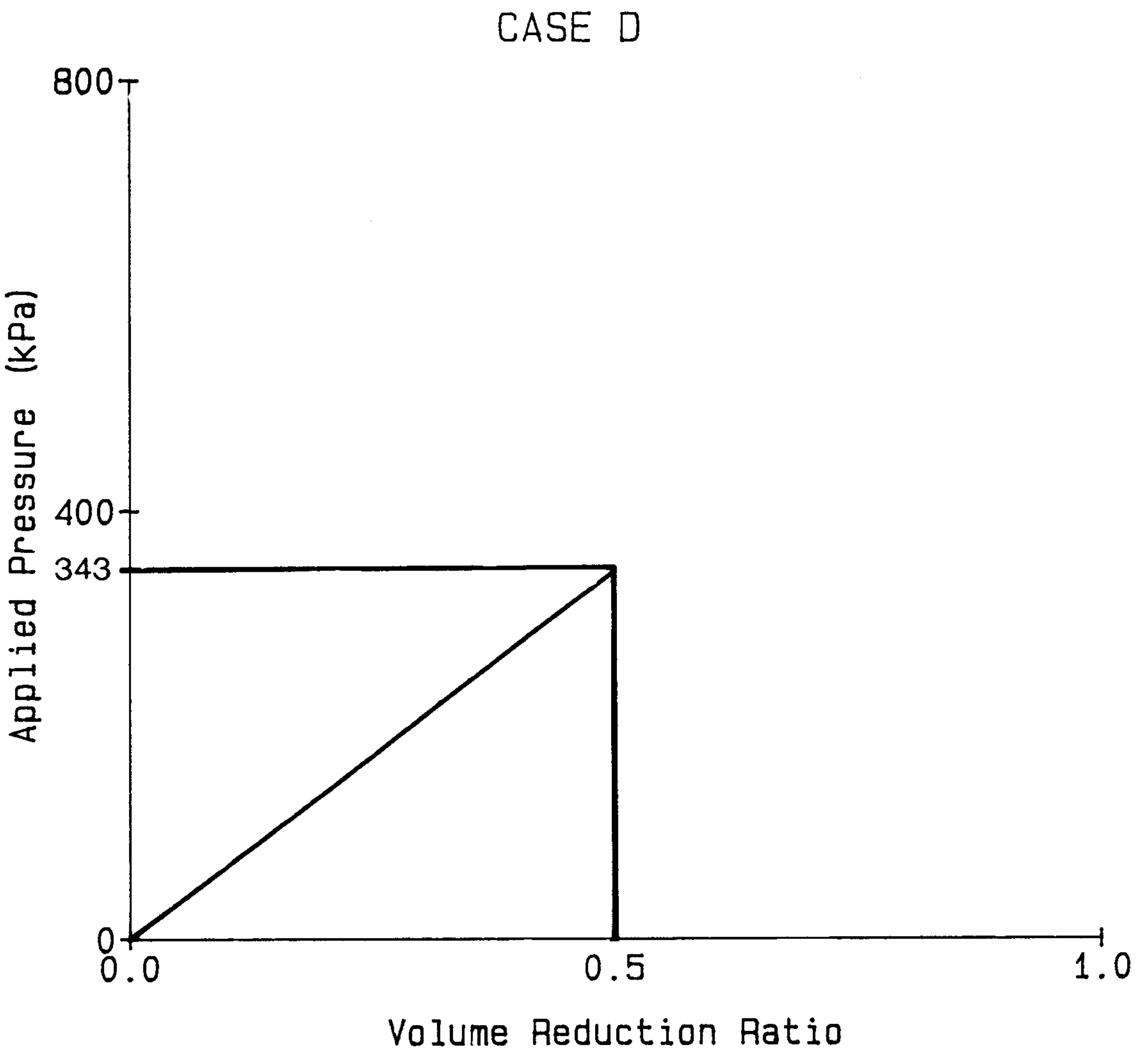


Figure 10. Assumed compaction curve for green spruce logging slash. (Jones 1981a)

E - Conclusions from Experiments

The compaction curves for green pine tops and branches (Case A) and green pine chips (Case C) are surprisingly very similar. Within the conditions of the experiments it took about the same pressure and same amount of energy to compact slash or chips to similar volume reduction ratios (VRR). Green spruce logging slash (Case D) can also be compacted to a similar VRR with an applied pressure of the same order of magnitude.

Pressure requirements are small in the initial phase of compaction but grow exponentially for VRR greater than 0.5.

The experiments reported by Danielsson show the difference between green and dry slash. Energy and pressure requirements to compact dry pine slash are very significantly lower that those to compact green material; it is hypothesized that dry slash yields by breaking when pressure is applied.

V. COMPACTION EQUIPMENTS

A - Generalities

The major portion of this study involved the investigation of existing pieces of equipment suitable for compacting various forms of woody biomass. Machines specifically designed to handle woody material are still very few and generally in early stages of development; on the other hand other industries like agriculture, recycling and waste handling industries have extensive experience with compaction. In order to benefit from this experience the state-of-the-art review included all equipments whether they were or were not designed for woody biomass. A computerized data bank was developed to catalog the pieces of compaction equipment found. At the present time 55 pieces of equipment were identified and are listed in the Milestone I report for this project (Guimier 1985). The data base program is implemented on an HP-150 computer and uses D-Base II software; the data bank will be edited and updated as new equipments come up on the market.

The state-of-the-art review identified five major types of compaction systems. They are:

- baling
- compacting into containers
- on-truck compaction
- bundling
- densification

Baling involves the compaction of the feed-stock into a compression chamber and produces regularly shaped handling units which are significantly denser than the original product. The bales can be square or round.

Compacting into containers uses a press or a tamper to compact material inside a large container. The container can be used for transport or removed after compaction like in the case of module builders.

On-truck compaction consists of compressing the material directly on the truck; on-truck compaction is generally tied to the loading phase.

Bundling is simply grouping together pieces of material to form a larger handling unit. As opposed to baling, bundling may or may not involve compaction.

In preparation for densification the material is first comminuted into a fine product. Densification is the compaction of this finer material into a dense and homogeneous form.

In each one of those five classes specific pieces of equipment were identified and their working principle described. Any test results which have been published on the use of a particular machine for woody biomass compaction are also presented in this chapter.

B - Baling

Baling has long been practiced in both the agricultural and the recycling industry as a method of preparing material for transport, handling and storage. At the present time however there are no commercially available balers for forest biomass. The two basic baler types are the so called round baler and square baler.

1) **Round baler**

Round balers are normally used in agriculture. They have been tried to compact forest biomass only on an experimental basis. A round baler is usually a mobile machine and has a pick up drum that feeds the material between compression rollers into the rounding chamber. The chamber is fully encircled by a series of belts; belt tightening and slack-taking devices on the baler allows the volume of the rounding chamber to vary from zero up to the maximum volume of the bale cylinder. As a new bale is started, a core is formed between the rollers and the moving belts (Figure 11). Baling continues by rotating this core inside the rounding chamber and wrapping additional layers of material around it so as to form a large cylindrical bale. When the bale reaches its maximum size it is tied with wires or straps. The back of the rounding chamber then opens and the bale is ejected.

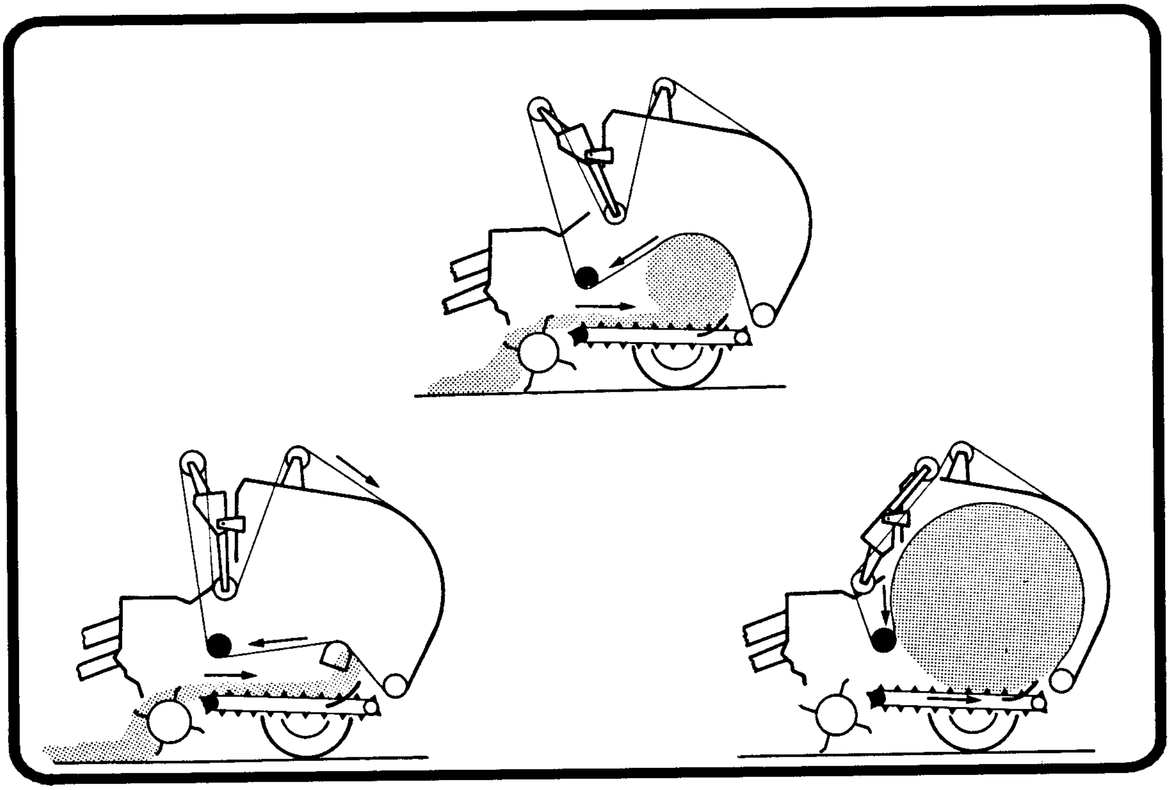


Figure 11. Round baler principle.

Fridley (1981) reports the results of an experimental test of a modified Vermeer 605F hay baler used for biomass baling. During that experiment small trees, branches, tops and hardwood brush were rolled into nine round bales. The bales measured from 1.22 m to 1.83 m in diameter, were 2.4 m long, weighed from 409 kg to 1516 kg and had a bulk density ranging from 144 to 338 kg/m³. The baler, which had been only slightly modified for this application, worked well. New bales were difficult to get started; an adequate core had to form inside the chamber before the baler became self feeding. The first bales were formed from material which was fed parallel to the axis of bale rotation; later, material up to 10 mm in diameter fed into the machine at right angle to the axis of bale rotation was successfully processed. The material bent and broke to conform to the bale being formed. This later technique required more power however. Fridley found that the belts on the baler contained the material adequately but they remained the most susceptible part of the machine. A positively driven full width belt or fewer wider belts were suggested to make the machine more suitable to woody biomass baling.

Internal heating of the bales was monitored. The highest internal temperature observed was 60°C. Further tests would be required to determine whether spontaneous combustion could be a problem.

The energy required to form bales of material fed parallel to the axis of bale rotation was recorded for two bales (Table 3).

Table 3. Energy required to round bale material parallel to the axis of bale rotation. (Fridley 1981)

Bale No	Mass (kg)	Dia. (m)	Length (m)	o.d. Density kg/m³	Baling density kg/m³	time hrs	Energy kWh/t
1	654	1.37	2.4	182	151	0.41	0.83
2	1083	1.83	2.5	164	136	0.82	1.18

A self-propelled forest biomass harvester incorporating a round baler is shown in Figure 13.

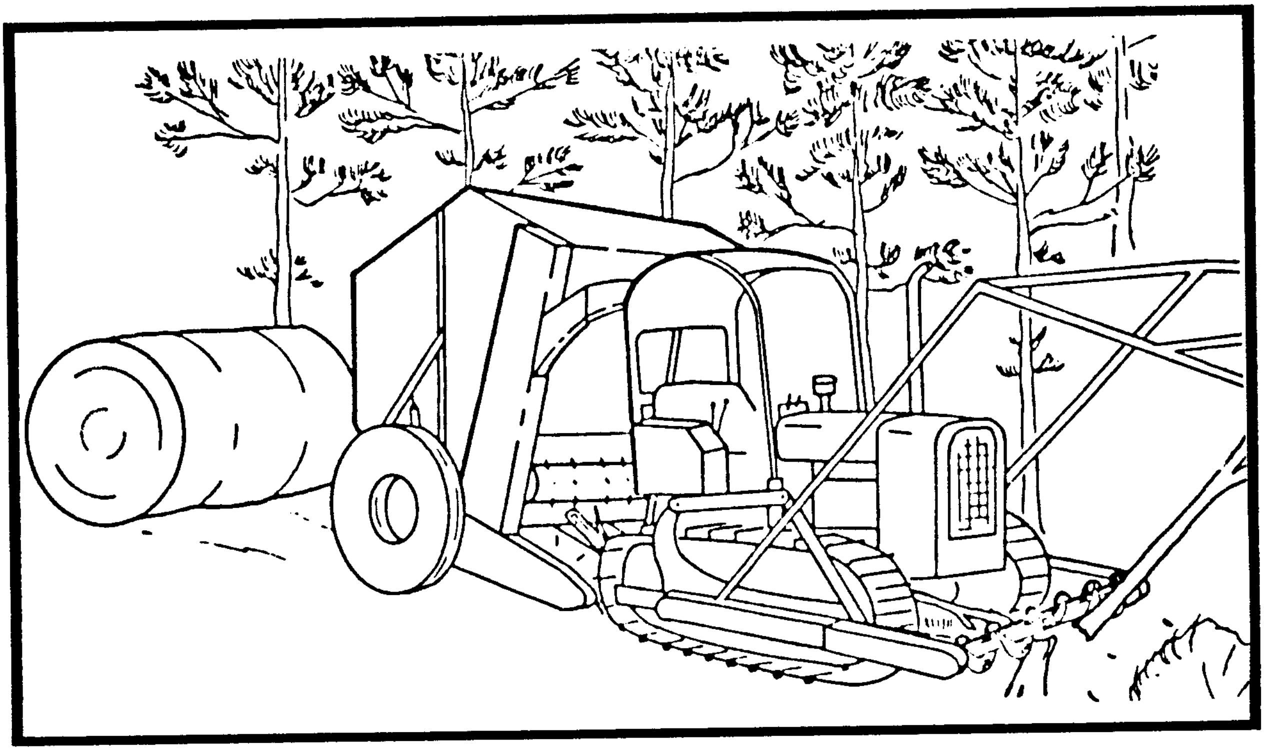


Figure 12. Proposed self-propelled forest biomass harvester incorporating a round baler. (Fridley 1981)

2) **Square baler**

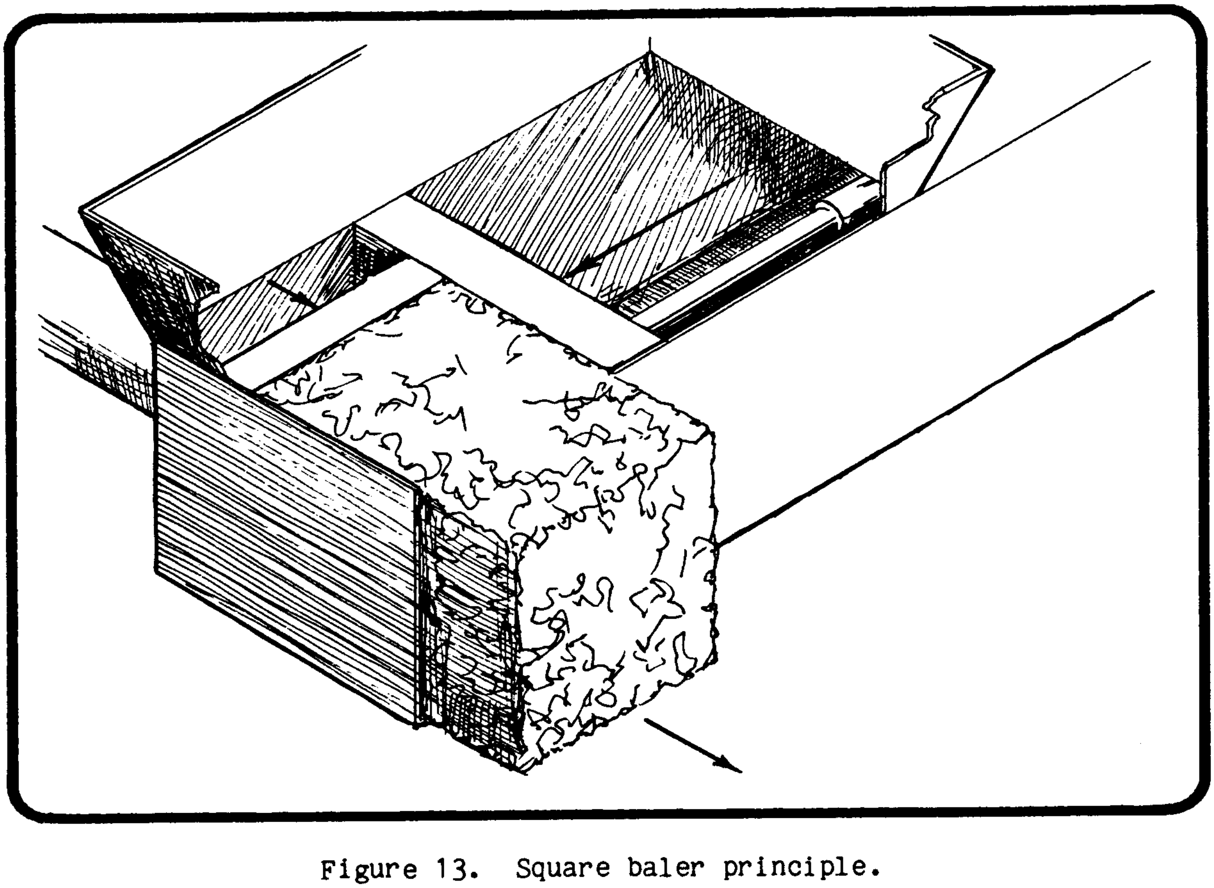


Figure 13. Square baler principle.

Square balers are by far the most popular types of compaction equipment today. Many different types of mobile square balers are used in agriculture to bale hay, straw, peanut hulls or other bulky materials; one such baler was modified and led to the prototype VPI baler (see VPI baler). Square balers are commonly used in the waste processing and recycling industries and are usually stationary. Scrap metal balers and car flatteners usually produce pressures much in excess of those needed to compact woody biomass; cardboard and paper balers correspond more closely to what is required for baling forest material. Fast (1982) reports on tests using three different scrap metal and paper balers to bale prunings from almond orchards and scrub oak. The material was up to 10 cm in diametre and up to 4 m long, with a moisture content estimated at 35%. The two scrap metal balers could apply ram face pressures of 9600 kPa and 5500 kPa which was found to be much more than necessary (Figure 14). Compaction resulted in considerable material damage due to the high compressive forces. The bales retained their shape during ejection and removal without the use of strapping material; the bales were strapped on the ground because they did expand with time. The paper baler could apply up to 2700 kPa ram face pressure; the machine required at least 10 strokes to complete a bale owing to the difficulty of feeding the scrub oak into the relatively small hopper. The bales were tied with the automatic tying system either with 11 gage round wire or polyester strapping material (Figure 15). The expanded density reportedly exceed 400 kg/m³.

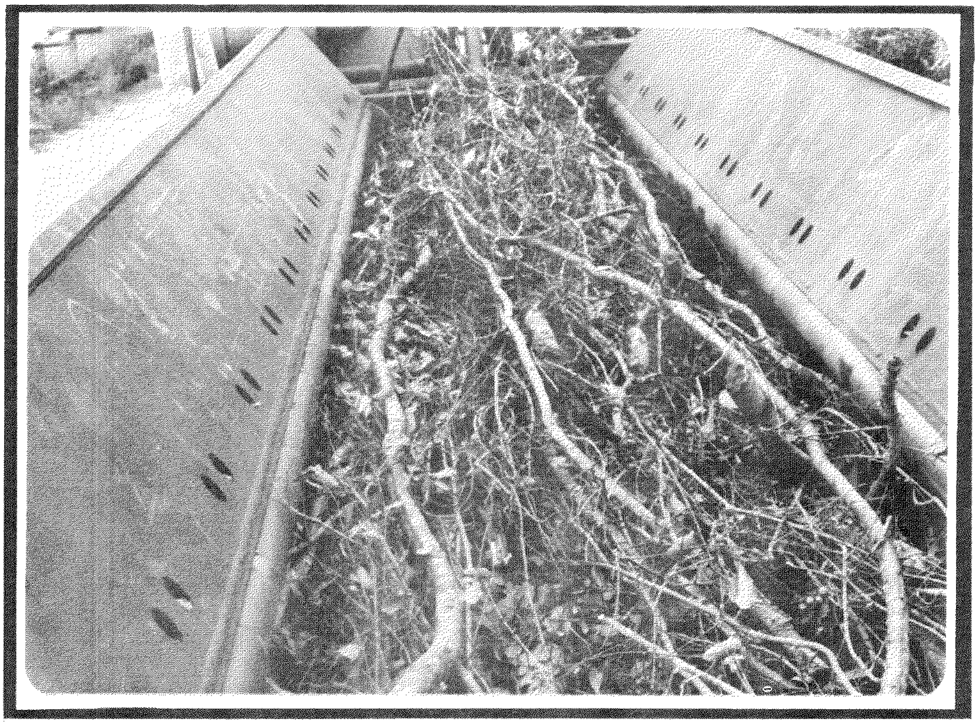


Figure 14. Scrub oak before baling in a folding box type portable scrap baler. (Photo courtesy Harris Press Inc.)

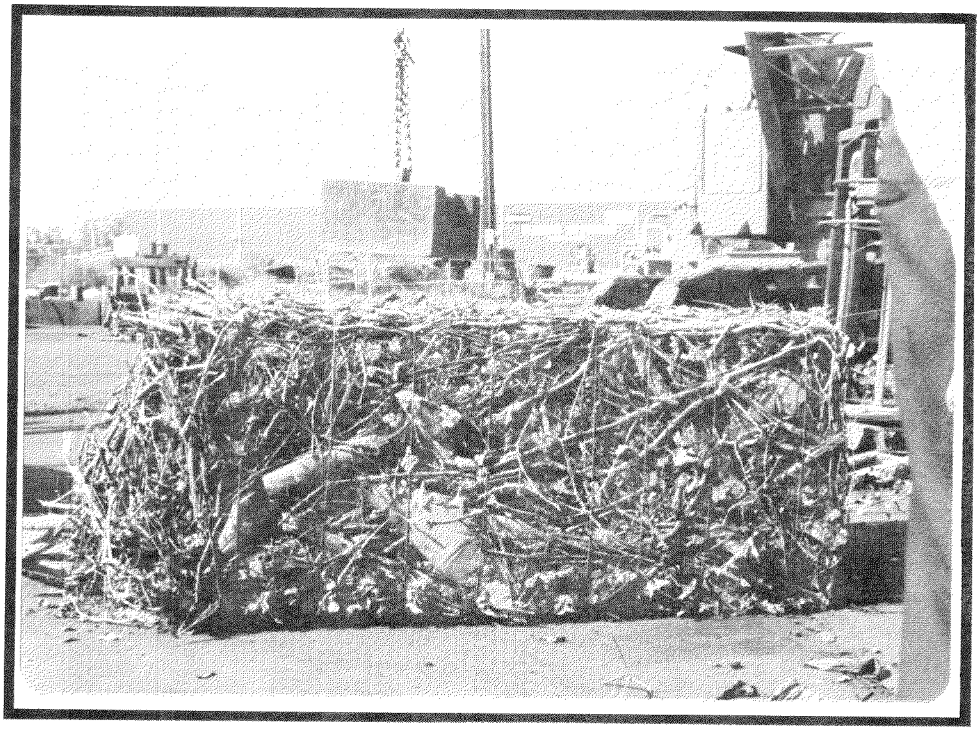


Figure 15. Scrub oak bale produced in paper baler.
(Photo courtesy Harris Press Inc.)

3) **VPI Square baler**

A prototype baler has been developed at the Virginia Polytechnic Institute (VPI) and State University specifically to handle long, small diameter forest biomass (Walbridge 1981). An artistic representation of the VPI baler is shown in Figure 16.

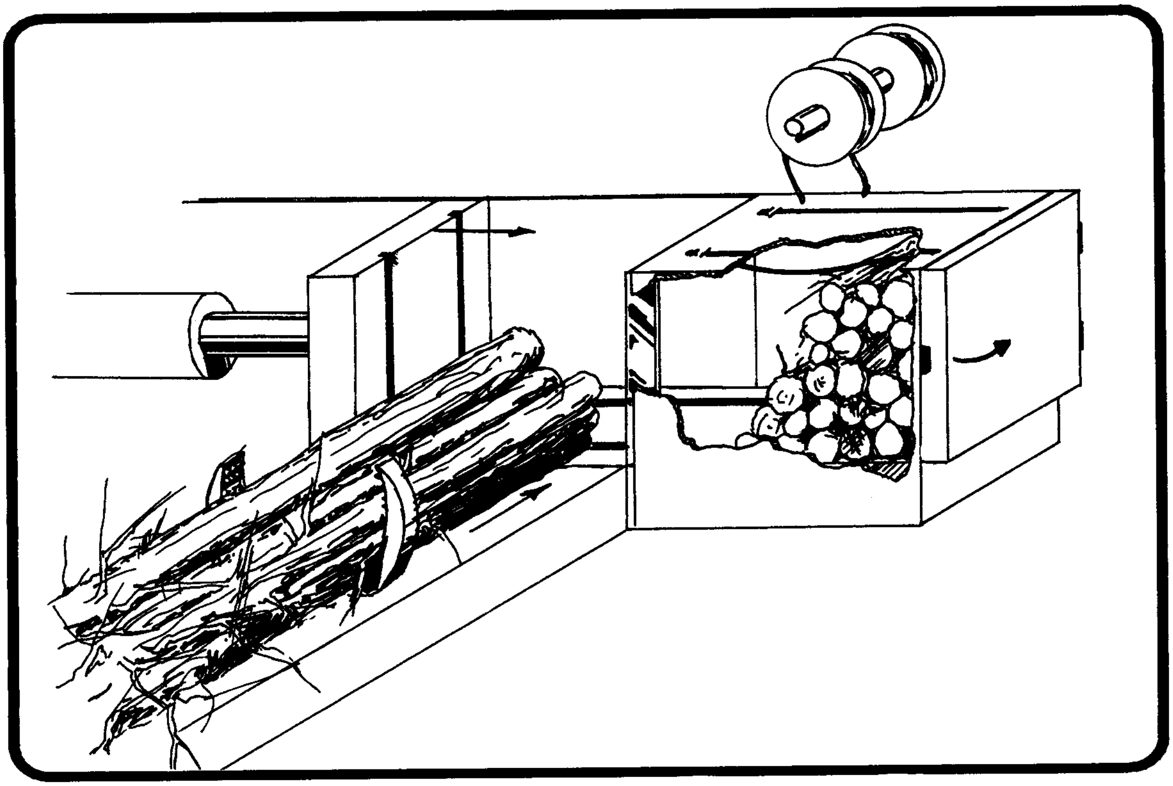


Figure 16. VPI baler principle.

A loader (not shown) places the feedstock into an inverted grapple on the feeder carriage. The grapple closes pre-compressing bulkier material, slides along the feeder carriage and inserts the feedstock butt first through the infeed door until the stems contact the far wall of the infeed chamber. The compacting plunger is then advanced until the stems are held between the shearing knife and the plunger. The inverted grapple is then released, moved back on the carriage, and closed again. The plunger completes its stroke, shearing the material and compacting it into the chamber. The plunger is then retracted. The cycle is repeated until the compaction chamber is full. The bale is tied with steel wire fed through grooves in the plunger and slots in the compacting chamber floor and top. The chamber outfeed door is then opened and the bale is pushed out by the next bale being compacted. When the bale has been removed, the door is closed and the baling process repeats.

The VPI baler produces bales 80 cm wide (length of the sheared pieces), 110 to 140 cm long (length of the compression chamber) and 90 cm high (height of the chamber). This results in a bale of 1 m^3 bulk volume or less.

Experiments show that the VPI baler can result in bale solid volume factors (SVF) of 50 to 80% (Table 4). This is higher than the SVF for loose logging residue (20-30%) and the SVF for chips or hog fuel (35-50%).

Table 4. Characteristics of bales produced by the VPI baler.

Reference	Bale characteristics				
	Size (cm)	Volume m^3	Weight kg	Bulk density kg/m^3	SVF
(Walbridge 1981)	76x91x110	0.76	455-682	600-980	-
(Schiess 1983)	80x90x140	1.00	427-700	505-658	70-80%

The VPI baler unit is powered by a 74 kW diesel engine driving a 190 L/min hydraulic pump operating at 13 800 kPa. No published data were found on the specific energy required to produce a bale.

Following testing of the VPI baler in the North Western U.S.A., several design modifications were suggested for a "second generation" baler. Schiess (1981) proposed:

- that the baler should be mounted on a highway legal trailer or be self-propelled on a tracked undercarriage;
- that the inverted grapple infeed should be replaced with a knuckleboom loader mounted on the baler. The loader would charge the chamber by pushing material loaded on a chute into the baler. The loader would also load bales onto trucks;
- a specially designed grapple that would efficiently precompact material before insertion into the chamber and also handle bales with a minimum of deformation and damage to the bale be incorporated;
- that the plunger cylinder(s) be modified with oversized pistons to allow a more rapid return stroke;
- an automatic tying mechanism;
- a top infeed to allow processing of small sized material;
- a bale size more suitable for loading and hauling on standard 244 cm (8 ft) wide trucks, e.g. 122 cm x 91 cm x 230 cm (4' x 3' x 7.5'). The bale weight would be increased to approximately 1130 kg (2500 lbs) which would also speed the load/unload elements in the haul cycle.

A drawing of the proposed square baler design is shown in Figure 17.

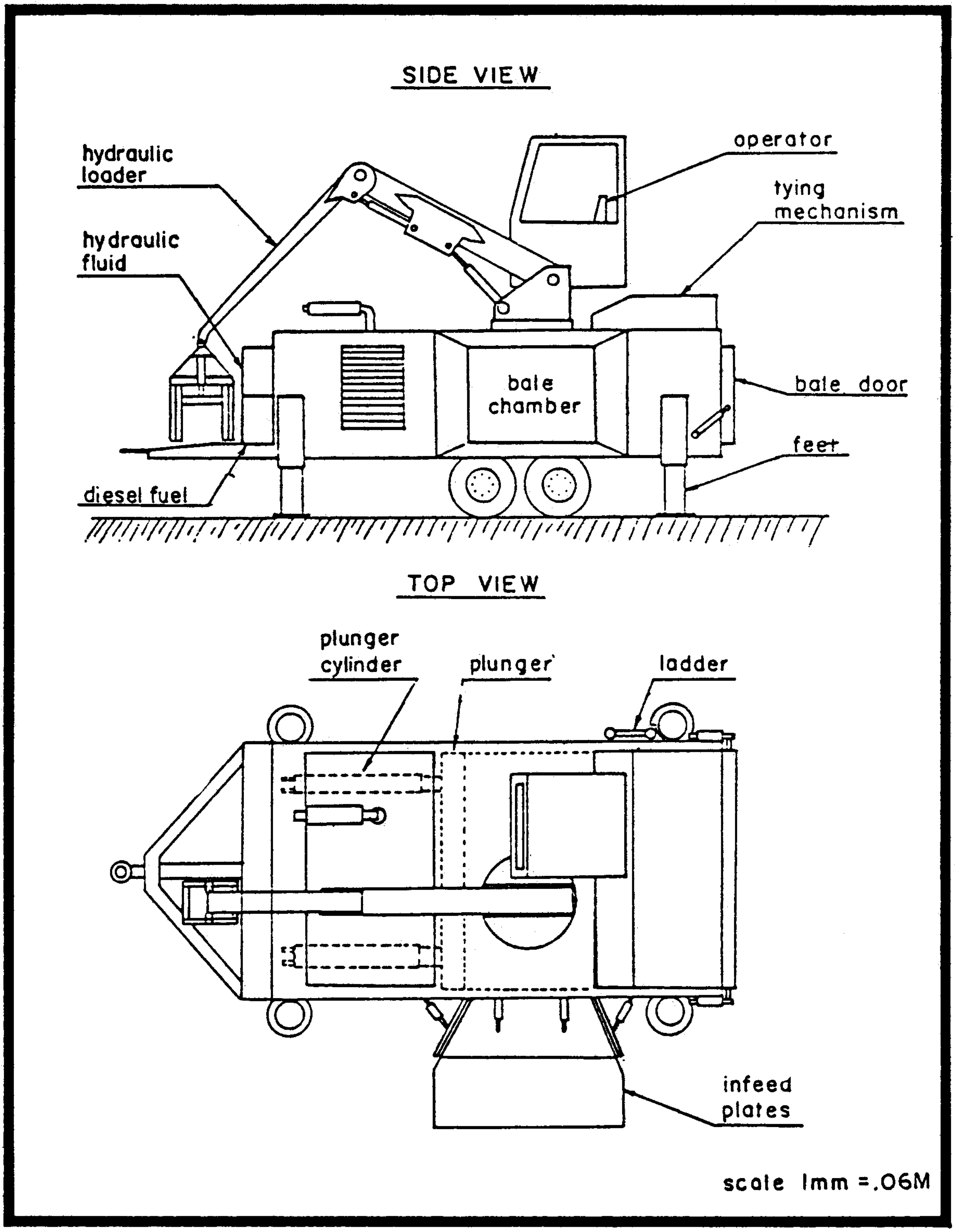


Figure 17. Proposal for a "second generation" baler. (Schiess 1981)

C - Compaction Into Containers

Two types of compactors are classified under this heading 1) Garbage compactors 2) Module builders.

1) **Garbage compactors**

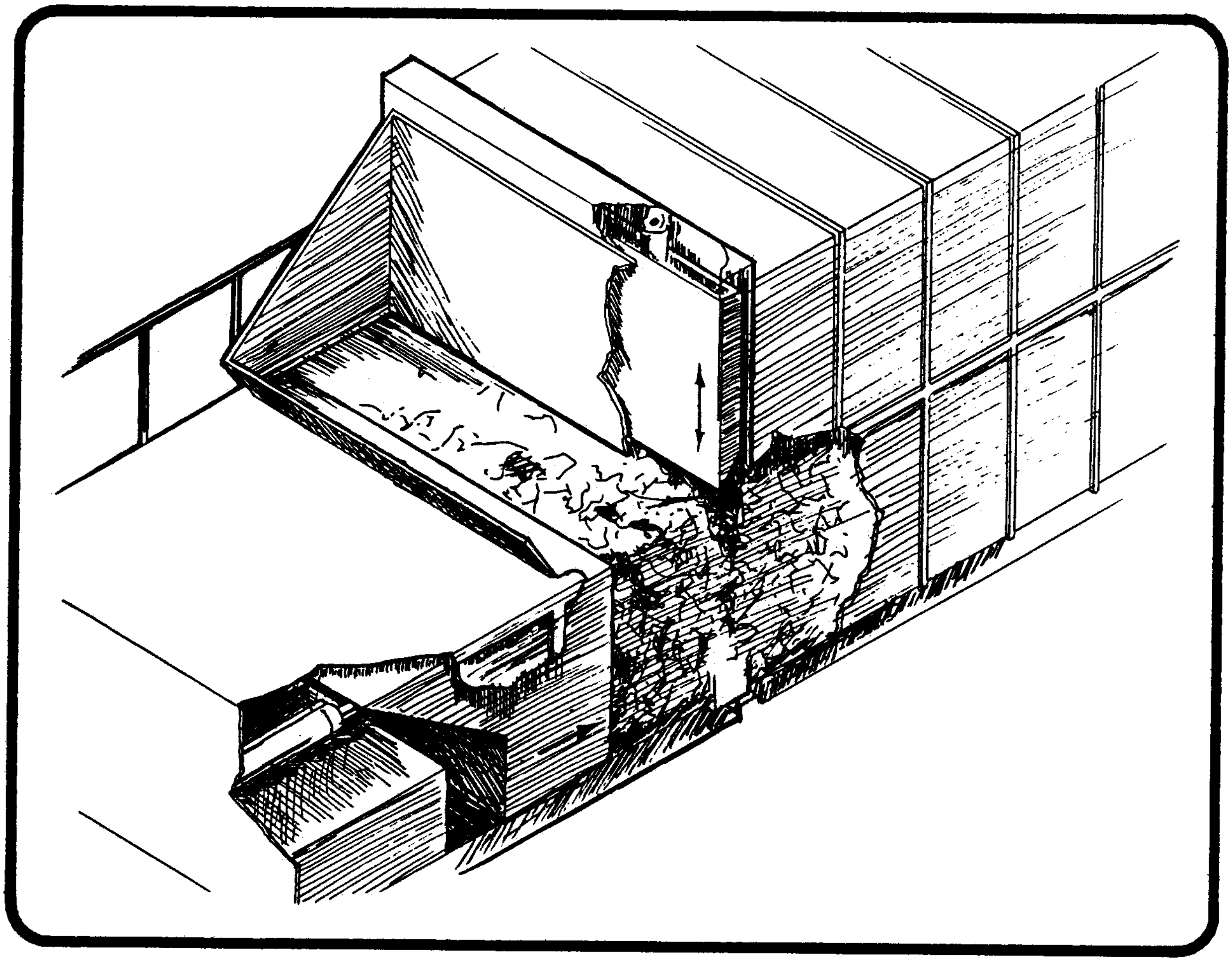


Figure 18. Garbage compactor combined with a container.

The compaction of garbage into a container is commonly performed in places where the concentration of population and the garbage volume produced warrant the initial purchase or rental cost of the equipment. Typical users are apartment blocks, schools and small industries. The equipment consists of a compactor and a container (Figure 18).

The compactor is fixed whereas the container is removable and is used to transport the waste to the dumping site. During the loading phase the container is attached to the compacting press and the material is dumped into the compacting chamber. When the compacting chamber is full, the piston is activated and the material is pushed against a vertical gate which is then lifted, allowing the material to be compacted inside the container. The piston is backed off, the gate is lowered and the compacting chamber is then ready to accept another charge. When the container is full it is disconnected from the compactor and loaded onto a truck for transport.

Makelä (1975) reports on a test of this type of equipment in Finland. The objective of the study was to develop methods and equipment to collect and transport logging residues economically from the cutting area to the point of utilization. In a preliminary experiment, branch raw material was compressed into a transport container of 21 m³ capacity by a waste press manufactured by Autolava Oy. The compactor had a 1.2 m³ compaction chamber; the piston was 1.35 m wide by 0.9 m high and had a 1 m stroke. A 150 mm diameter cylinder produced a 28 tonnes push resulting in a 226 kPa face pressure. The compactor was powered by a 7.5 kW electric motor. The compaction cycle took 42 seconds.

Table 5. Compaction of logging slash with a compactor-container system. (from Mäkelä 1975)

	Pine	Spruce
Uncompacted		
Green bulk weight (kg/m³)	138	124
Dry bulk weight	69	62
Moisture content MC%	50%	50%
Compacted		
Green bulk weight (kg/m³)	357	315
Volume Reduction Ratio (VRR)	0.62	0.61

As seen in Table 5, by using the compactor the volume of the slash material could be reduced by more than half. The bulk density was increased to above 300 kg/m³ which is greater than the bulk density for green chips. A compactor-container appear to be a feasible solution for handling logging slash. The system should be modified so that it can work more efficiently.

2) **Module builder**

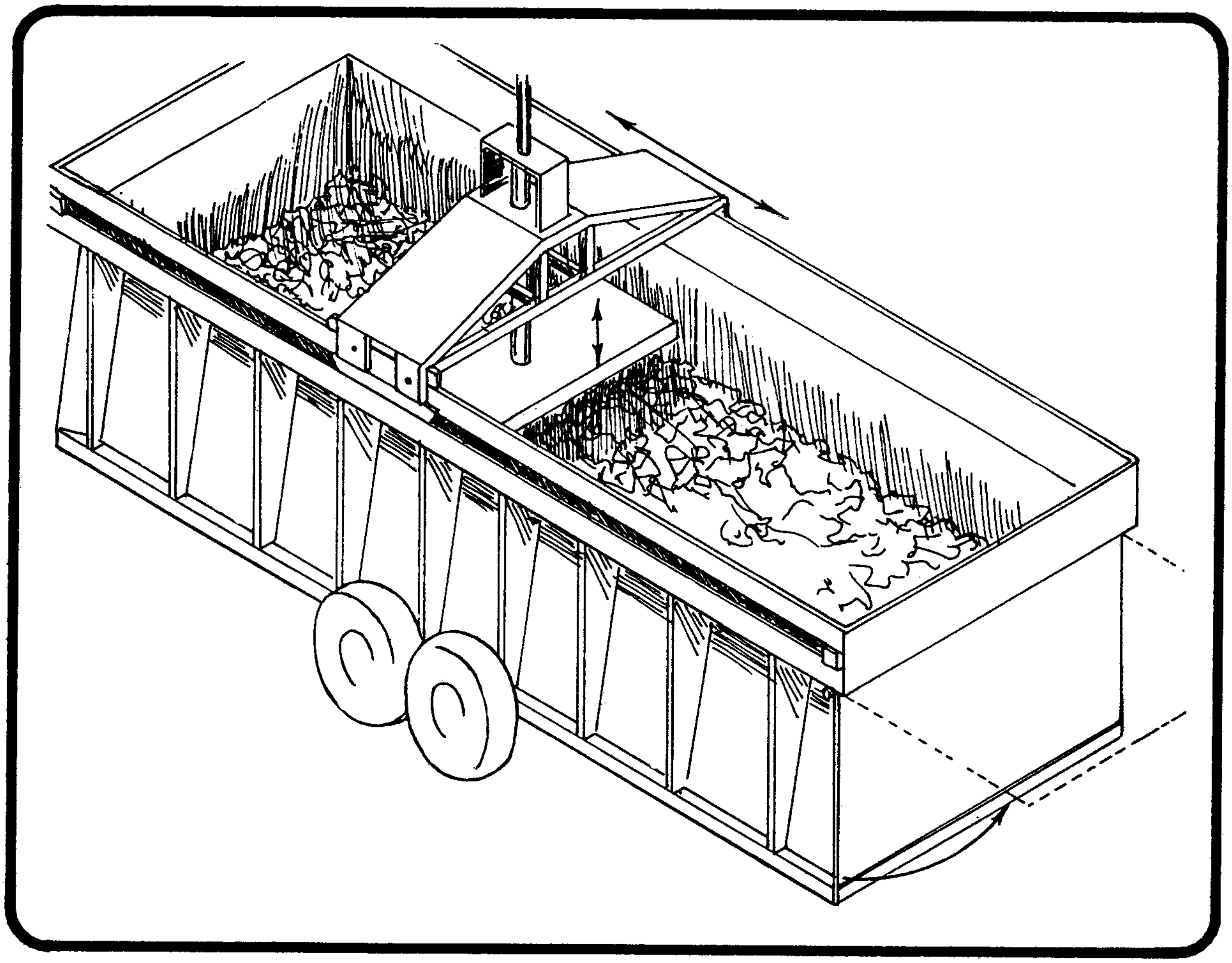


Figure 19. Module builder principle.

A module builder as shown in Figure 19 comprises a mobile open-bottom rectangular frame structure into which material can be loaded. A compacting tamper is mounted on a crosswise truss and is hydraulically driven back and forth on two tracks along the length of the module builder. In addition to compacting the material the tamper also serves to position and level the material. The material is loaded and compacted layer upon layer. When the module builder is full the frame structure is raised by the cylinders mounted on the wheel assemblies; the rear panel is open and the whole module builder is towed away from the compacted module of material. The module is then picked up at a later time by a specially constructed module handler carrier or by a regular loader. Module builders are used in agriculture to compress straw, hay or seed cotton into high density stacks. The system has also been tried to create modules of almond tree prunings (Jenkins 1983) and logging slash (Miles, n.d.).

A cotton module builder manufactured by CMC of Livermore, California reinforced with 1.9 cm thick plywood was used for the logging slash compaction test. The module builder had an operating weight of 5490 kg and was towed by a prime mover which also supplied the hydraulic power. The tamper could push down with a maximum force of 37 810 N. Logging residue compacted had a maximum diameter of 26 cm. The modules obtained were 98 m long, 2.2 m wide and up to 2.1 m high. The green bulk density of the compacted module was 192 kg/m³. Miles (n.d.) suggested that the modules thus produced could be transported to a central location for grinding and chipping; he also proposes design modification so that the equipment could be made stronger and better adapted to the processing of logging slash.

D - Truck Compaction

Truck transportation of bulky material like woody biomass is an expensive portion of the entire biomass collection and transformation processes. Trucks, like most other transportation systems, have gross weight and bulk volume limitations. Minimum trucking cost per tonne are achieved when the truck can be loaded to its maximum gross weight before the maximum bulk volume is reached. This is usually not the case when transporting woody biomass with bulk densities of 300 kg/m³ or less and a SVF below 30%. To alleviate this problem the baling or bundling systems described previously can be used to compact the material before loading. Another approach is to compact the material in the truck after it is loaded. Several truck compaction devices have been developed (mainly in Sweden). These devices can be classified into systems which are permanently mounted on the trucks and systems which are independent from the truck and are removed during the transport phase.

1) Truck mounted compactors

Truck mounted compactors are devices permanently mounted on trucks to compact the material once or several times during the loading phase and to serve as load binders during transport. They consist of a compaction beam pinned at the end of a telescopic stake; once the load needs compacting the beam is rotated onto the load and latched to the top of the opposite stake (Figure 20-a). The hydraulic cylinders in the stakes pull the beam down and compress the material. The beam is then raised and flipped to its original position to allow additional loading. After the last compaction, the beam is left in place to press the material down during transport. An alternate but similar system uses half cantilevered beams at the top of the stakes and compacts half of the load from either side (Figure 20-b).

The compactor shown in Figure 20-a was evaluated by Carlsson (1981) for the transport of green limbs and tops. A truck-trailer combination was used for the test; compaction equipment was used only on the trailer. The maximum truck capacity was 40 m³; the trailer could be loaded with 73 m³ of bulk material and was rigged with two sets of compactors capable of applying a total downward force of 48 tonnes. Weight and density measurements were recorded for uncompacted material in the truck and similar material compacted in the trailer. Results are given in Table 6.

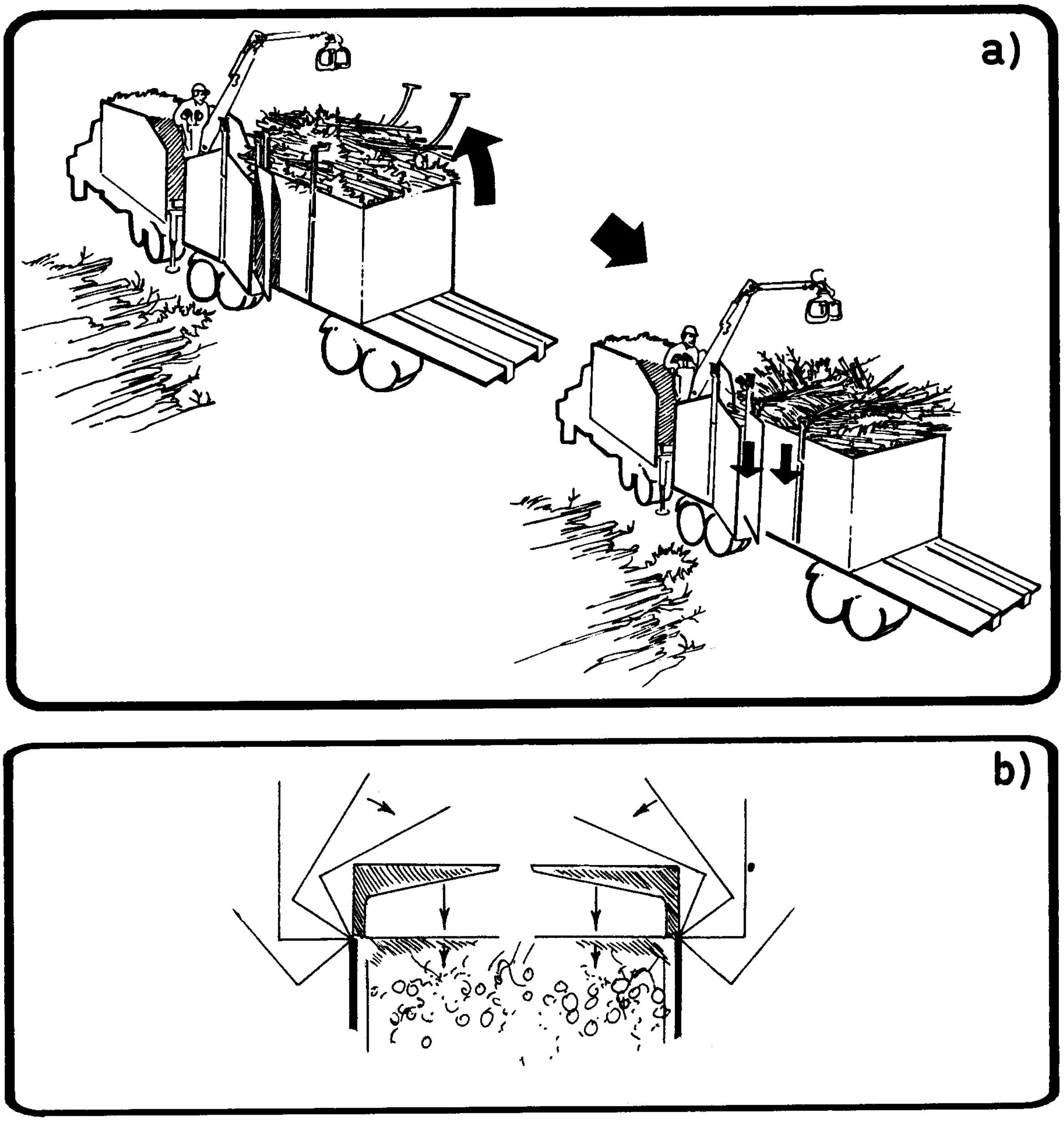


Figure 20. Truck mounted compactor principle.

Table 6. Compaction results using truck-mounted compactors. (Carlsson 1981)

Material characteristics	Uncompacted (truck)	Compacted (trailer)
Moisture content (%)	56	56
Bulk green density (kg/m³)	212	278
Solid green density (kg/m³)	996	996
Solid volume factor (%)	21.2	27.8

The on-truck compactor increased the solid volume factor from 21.2% to 27.8%. This corresponds to an increase of 31% in the weight transported. Similar tests with dry material showed greater increases.

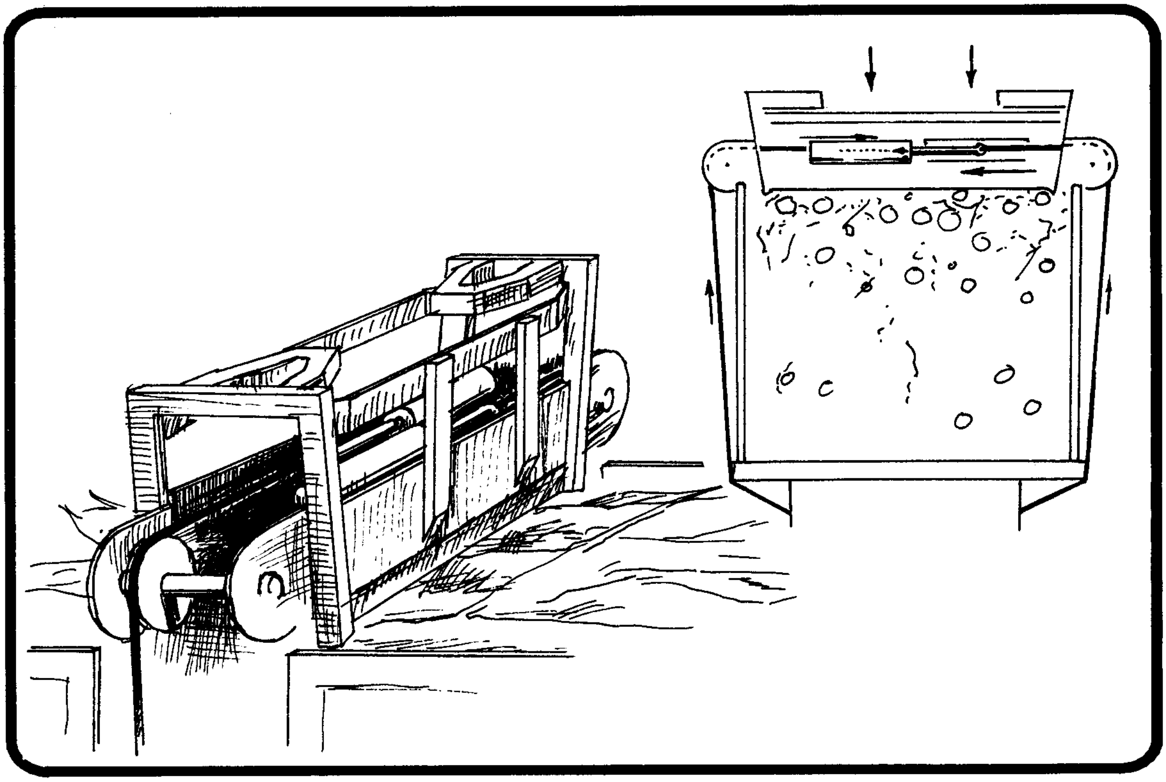


Figure 21. Detachable truck-compactor principle.

2) **Detachable truck-compactors**

The detachable truck compactor shown in Figure 21 is a prototype developed in Sweden. It consists of a main compacting beam that is placed, by the loader, across the truck load to be compacted. Hanging at both ends of the main beam are two tie down cables which are manually, temporarily secured to the side of the truck platform. Hydraulic cylinders located inside the main beam are activated by an external power supply (i.e. the loader) and pull on the tie down cables. The main beam is thus forced down and the load is compressed. Straps are then thrown over the load and permanently secured on either side to restrain the material during transport. The pull in the truck-compactor cable is relaxed and the compactor is removed from the load.

Larsson (1982) reported on compaction experiments using this type of equipment. A truck-trailer with a capacity of 99 m^3 was first loaded to its maximum with tree sections and weighed. The load was then compacted and additional tree-sections were added to complete the load; the new load weight was recorded. The compactor could apply a load of 38 tonnes. Results from the experiment are summarized in Table 7.

Table 7. Compaction results using a detachable truck compactor. (Larsson 1982)

Material Characteristics	Uncompacted	Compacted
Moisture content (%)	50	50
Bulk green density (kg/m^3)	249	294
Solid green density (kg/m^3)	792	792
Solid Volume Factor (%)	31.2	37.2

The solid volume factor (SVF) of the tree sections increased from 31.2% before compaction to 37.2% after. This corresponds to an 18% increase in the load weight transported. When comparing these results with those obtained with the truck mounted compactor (previous section) it should be noted that the SVF of tree sections is higher than that of loose slash owing to the heavy log portion of the tree sections; also tree sections are more difficult to compress than slash.

3) **Garbage truck**

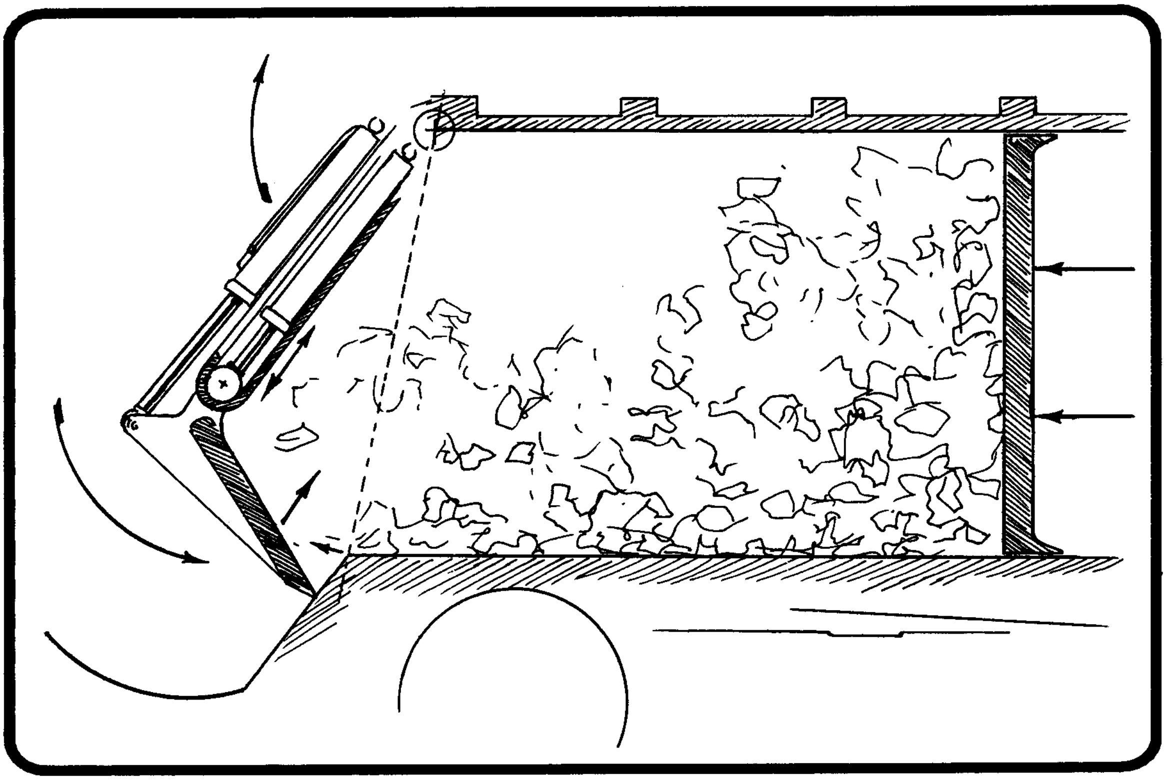


Figure 22. Garbage truck principle.

Garbage collection trucks come in a variety of sizes and configurations. Basically they consist of a compactor and a container mounted on a truck. Depending on the location of the compactor the truck can be a rear, top or side loader type. Once the container is full the truck is driven to a disposal site; the rear of the container completely opens and the refuse is pushed out.

A rear loader type garbage truck was tried in Sweden for the compaction of logging slash (Carlsson 1980). Branches and tops were loaded into the compaction system with a grapple loader, compressed into the 15.7 m^3 capacity truck, weighed, unloaded and measured. Some of the loads were tied with banding to retain more of the compression.

The results from the series of five tests are given in Table 8.

Table 8. Compaction of logging slash with a rear loader garbage truck. (Carlsson 1980)

Material characteristics	Location				
	1	2	3	4	5
Weight (kg)	3135	3735	3100	3580	3295
Before compaction					
- Bulk green density (kg/m^3)	129	158	157	169	170
Compacted in truck					
- Volume (m^3)	15.7	15.7	15.7	15.7	15.7
- Bulk green density (kg/m^3)	200	238	197	228	210
- Volume Reduction Ratio (VRR)	0.36	0.34	0.20	0.26	0.19
Out of truck (no band)					
- Volume (m^3)	20.5	22.5	23.5	-	21.1
- Bulk green density (kg/m^3)	153	166	132	-	156
- Volume Reduction Ratio (VRR)	0.16	0.05	-0.19	-	-0.09
Out of truck (banded)					
- Volume (m^3)	18.4	-	-	17.9	-
- Bulk green density (kg/m^3)	170	-	-	200	-
- Volume Reduction Ration (VRR)	0.24	-	-	0.16	-

The bulk density of the material varied greatly between the different location depending on tree species, ages, branches sizes etc...; compaction made the bulk density more uniform and generally increased it above 200 kg/m³. Most of the increase in density was lost as the material was expelled from the truck and sprung back to its original shape; in some cases the expelled material was bulkier than before compaction. Tying the material with bands helped maintain the compaction after unloading. Carlsson suggested that modification would be needed to the equipment to reach the desired densities of 300-350 kg/m³.

E - Bundling

Bundling consists in grouping together and restraining pieces of biomass (branches, logs) to form a unit that can be more efficiently handled and stored. As opposed to baling, bundling does not necessarily include compaction and the units formed can be of non-uniform dimensions.

1) **Bundling of logging residues**

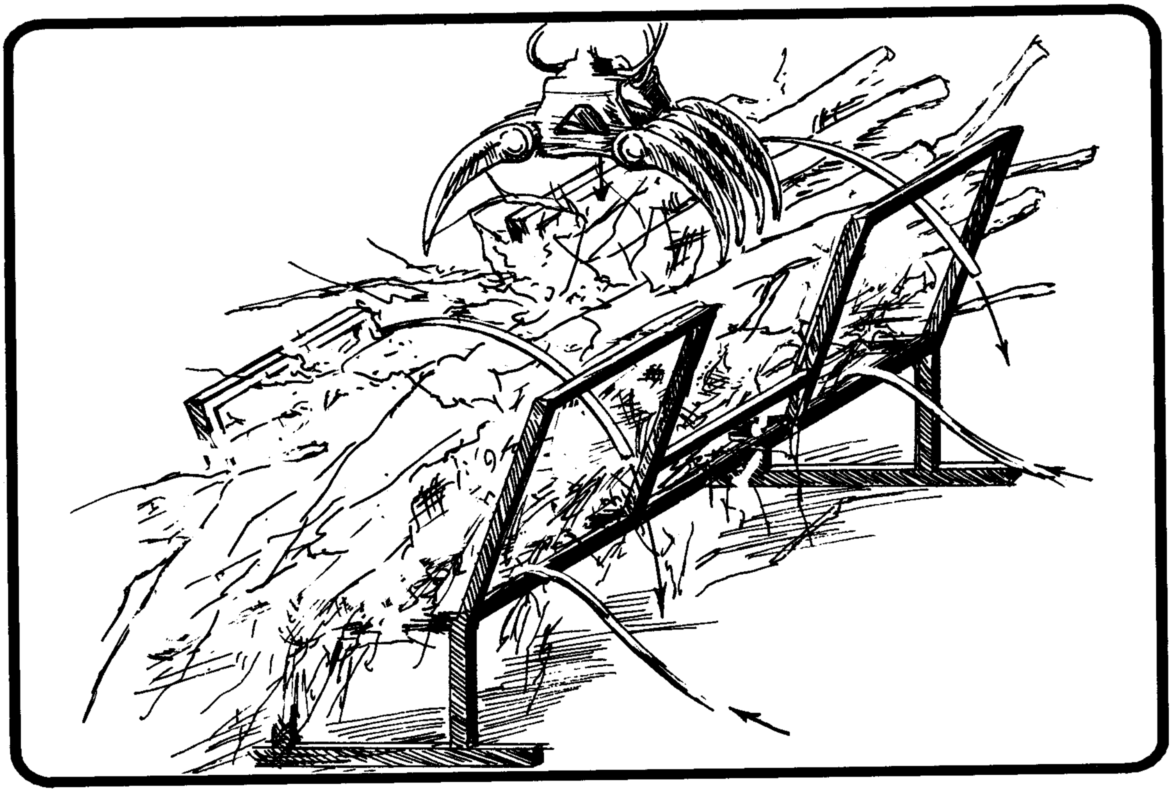


Figure 23. Logging residue bundling.

Experiments with logging residue bundling have been reported by Danielsson (1977). The objectives were to produce a bundle of residue roughly similar to a sawlog in size and shape so that all the existing logging equipment used to handle sawlogs could also be used for the handling of residues. The logging residues were placed in a bundling cradle with a boom loader. Two or four straps were manually tied around the bundle leaving a tie-free zone in the middle for grapple handling. The best results were obtained with small trees from pre-commercial thinning which were easily tied in packages of 10 to 20 trees and could sustain rough handling. Bundles of short logging residues like branches and tops lacked the strength and integrity to stand up to repeated handling and rapidly fell apart. Table 9 summarizes data obtained with two loads of twelve bundles each from pre-commercial thinning.

Table 9. Bundling of material from pre-commercial thinning. (Danielsson 1977).

Bundle Characteristics	Load 1	Load 2
Average weight (kg)	165	210
Trees/bundle	15	17
Average bundle dia.(cm)	42	45
Bulk volume (m^3)		
- before bundling	0.950	1.075
- after bundling	0.608	0.758
Bulk density (kg/m^3)		
- before bundling	175	200
- after bundling	270	280
Solid volume factor (%)		
- before bundling	20	22
- after bundling	31	32

Because a grapple was used to place the material on the cradle, bundling resulted in an increase in the Solid Volume Factor (SVF) of the material. Bulk density was increased by 40 to 50% and reach a maximum of 280 kg/m^3. Danielsson (1983) suggested that a bulk density of at least 300 kg/m^3 would be necessary to utilize logging vehicles at their optimum. A SVF of 30% was obtained for bundles of small trees from pre-commercial thinnings; this figure compares with 35 to 50% for chips and hog fuel and 50 to 80% for baled material.

2) **Kramaren bundler**

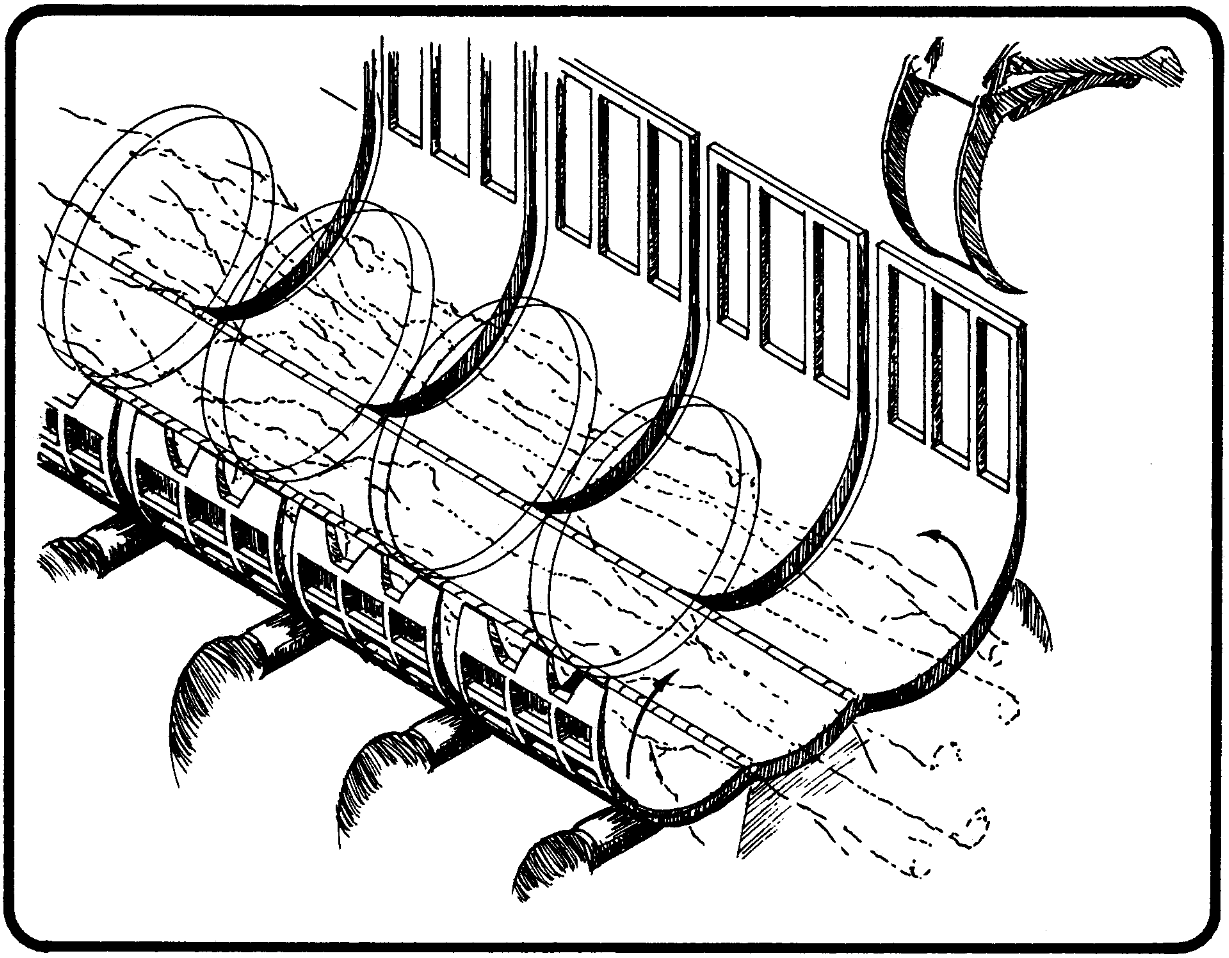


Figure 24. Kramaren bundler.

The Kramaren bundler was developed in Sweden in 1978; tests are reported by Hansen (1978) and Carlsson (1980). The Kramaren bundler is mounted on a forwarder (Figure 24); it consists of a loading boom and a compaction cradle. The material to be compacted and/or bundled is placed inside the cradle with the boom and grapple; the cradle closes on the material and compresses it. A band may be fastened around the bundle to keep it compressed and in one piece. The bundle is then removed from the cradle with the boom and grapple.

Small trees, consisting mainly of spruce, were compacted with the Kramaren and then loaded on trucks. The experiment compared the density of the truck loads in three cases:

Case 1: Material is loaded onto the truck as is (uncompacted)
Case 2: Material is squeezed with the Kramaren (but not tied in bundles) and then loaded onto the truck
Case 3: Material is squeezed with the Kramaren, tied in bundles then loaded onto the truck.

The results are given in Table 10.

Table 10. Results of experiments with Kramaren bundler.
(from Carlsson 1980)

	Case 1 Uncompacted	Case 2 Compacted & not tied	Case 3 Compacted and tied
Material characteristics			
- Average length (m)	3.7	3.7	4.1
- Average diameter (cm)	5.3	5.6	6.3
- Average stem volume (m^3)	0.012	0.014	0.018
Density loaded on truck (kg/m^3) (green)	242	279	323
Solid wood density (kg/m^3) (green)	831	831	831
Solid Volume Factor (SVF)	29%	34%	39%
Volume Reduction Ratio (VRR)	N/A	0.13	0.25

3) **Slyman**

The Slyman is a piece of equipment for compressing small-sized wood; tops, branches and trees, from energy plantation into bundles 3 m long and 50 cm in diameter. The Slyman was developed in Sweden by Lillevrå Sågverk AB. Its working principle is illustrated in Figure 25. The trees placed on the deck at A are moved to deck J by the feed rollers B and are cut to length by the cutter D. Pusher C transfers the material through the rollers E and into the open grapple F1. Once F1 is full it is closed and rotates to F2. Ram H pushes the material out of the grapple and bands are tied around the bundle by I. The finished bundle ends up on deck K. Söderberg (1984) describes the results of the development, construction and testing of the first Slyman prototype.

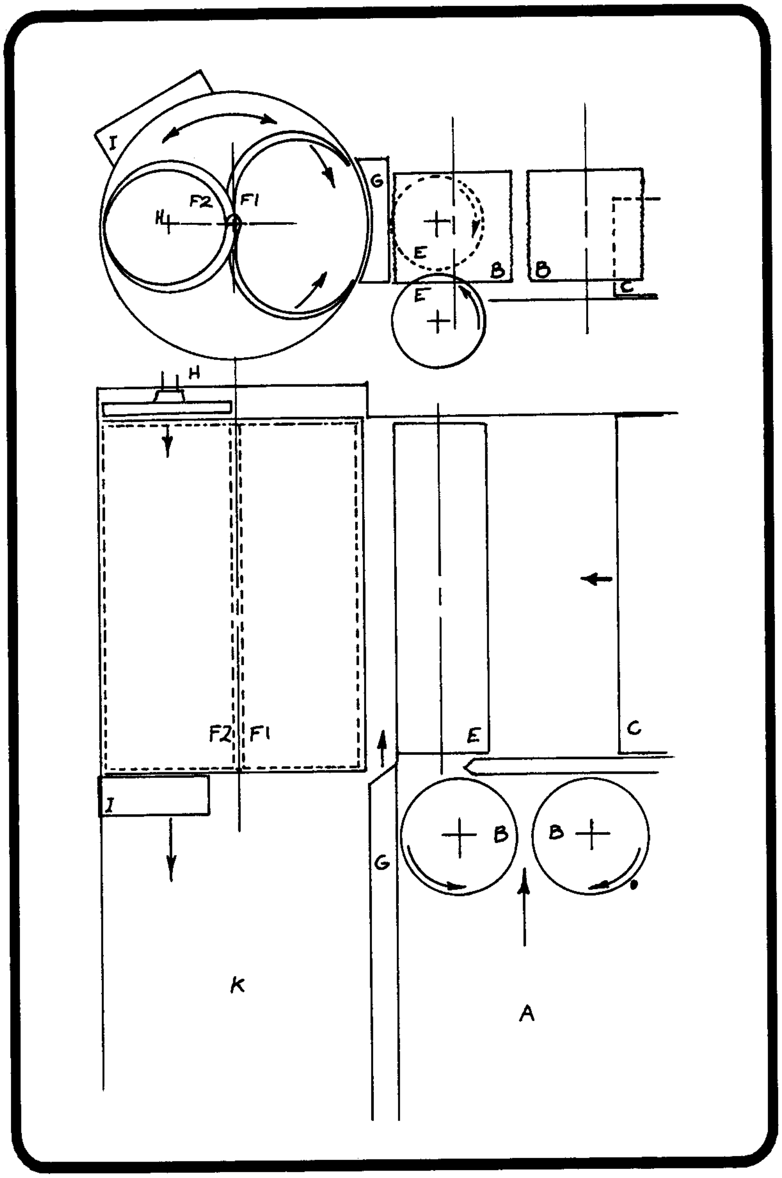


Figure 25. Slyman principle.

The report concludes that:

- obtained bundles are homogeneous (same size at both ends, same size apart from raw material etc.);
- the bundles are easy to handle and durable through several operations;
- the preset conditions for bundling capacity are reached and even exceeded (34-43 bundles per productive hour measured in time studies);
- the capacity can probably be increased after further development of the machine;
- compressing to 32% solid volume can be obtained in piles of bundled material;
- further development is needed to get a well functioning machine to test for a longer time under practical conditions.

4) **Fagoting**

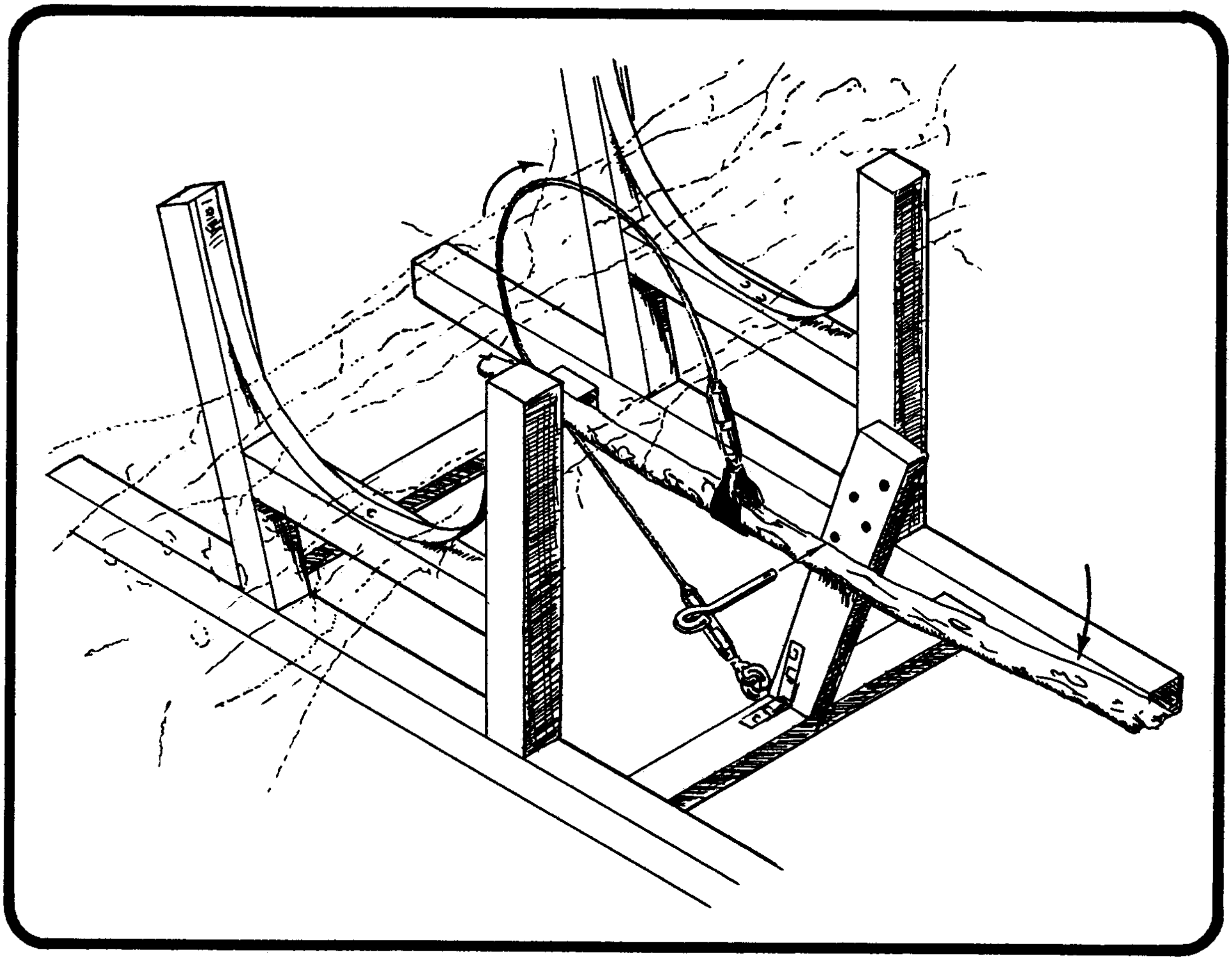


Figure 26. Implement used to make fagots.

At the time when people relied almost exclusively on forest products for energy and manual labor for harvesting it, special techniques and equipments were developed to prepare wood fuel. An old technique, rarely being used nowadays, is the utilization of the implement shown in Figure 26 for the making of fagots. This implement was used to manually assemble, compress and tie together branches and twigs smaller than 5 cm in diametre (any wood larger than 5 cm was cut into fire logs). The branches were cut to a maximum length of 1 m and placed in the cradle; small twigs, constituting excellent kindling, were placed in the middle of the fagot. The lever and cable system were used to compress the bundle and hold it in place while a tie was wrapped around and secured. The tie could consist of a length of stringy woody material but more often a piece of steel wire was used. Fagots were piled near the place of utilization where they could be left to dry for several years. Figure 27 shows a fagot manufactured with the above system; its size can be assessed in relation to the man holding it.

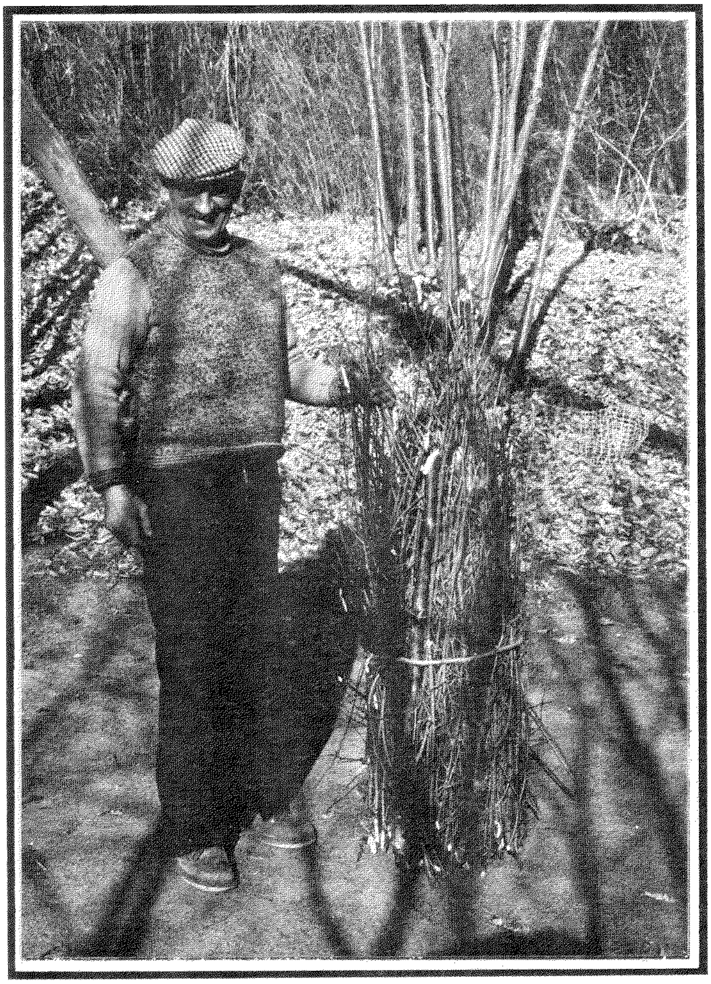


Figure 27. Fagot manually assembled using the implement shown in Figure 26. (Photo courtesy J. Renaudin)

5) **Firewood bundling**

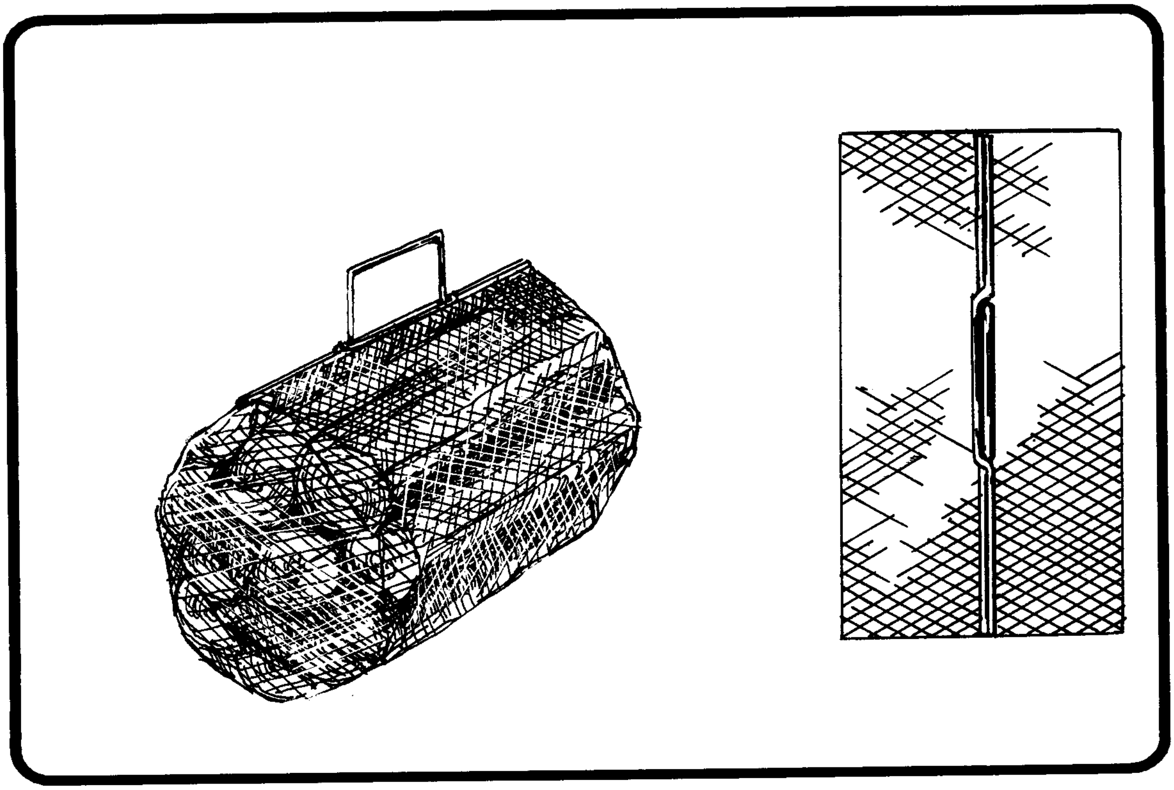


Figure 28. Firewood bundled in a net bag.

Firewood is generally commercialized in loose form and in amounts that will last the consumer the entire heating season. In urban areas, firewood is also delivered in smaller units that can be carried by the consumer. Firewood bundles can be formed by banding, boxing or bagging in specially made net bags. These firewood bundles are convenient unit for handling and selling to the small-scale urban consumer who only uses firewood occasionally for atmosphere and not for space heating.

Net bags have become popular in recent years as a method for bundling firewood (Figure 28). The wood is usually bundled (bagged) and stored in the bags for drying. For this reason the bags must be made of a material that will not deteriorate from sunlight and can withstand handling even after 1-2 years of sun-exposed storage. One problem with storing and drying the firewood in the bag is that the firewood will shrink as it dries and the bags will not be completely full after seasoning.

The per-unit cost for bundled firewood will usually be higher than for unbundled firewood.

F - Wood Densification

Wood densification is a process in which the raw materials are subjected to high pressures and temperatures to form a product with an increased basic density (oven-dry weight per unit of solid volume). The product will usually also be of uniform shape and size.

Wood is a cellular material. Studies have shown that the density of the material that constitutes the cell walls of wood fibers is approximately the same for all species or about 1540 kg/m^3 (Mullins 1981). Most wood is much lighter because of the air spaces in the cellular structure. The densification processes crush the cells through high pressures and create a denser product. Densities achieved are normally between 600 and 1300 kg/m^3 depending on the product. In general, during the densification process:

- the raw material is subjected to high pressure with a special compacting mechanism;
- high temperatures generally result from the friction between the feedstock and the machine during compaction and extrusion;
- the combination of heat and pressure causes a restructure of the material;
- and the lignin present in the wood softens as a result of high temperature and allows the woody material to take a new (smaller) form.

Since there is no chemical transformation of the product during the process and no addition to the basic woody material, the basic heating value per oven dry ton of densified fuel is equal to that of the original biomass fuel.

Densification presents several advantages:

- because densified biomass fuels are of low moisture content and high bulk density they can be shipped and handled at substantial cost savings as compared to low density high moisture biomass fuels;

- the more uniform size and moisture contents reduces feed problem and combustion upsets in burners. Densified biomass can be burned in most coal fired combustors using existing fuel feeding methods. Fuel feed rate, combustion air and exhaust gas flow rates should be adjusted for optimum combustion of the new fuel;

- lower sulfur content of biomass fuel does not impose a need for sulfur removing flue gas scrubbers;

- lower moisture content of densified fuels results in a higher combustion efficiency and higher heating value than for regular biomass. It should be noted however that this is as a result of drying and not of densifying.

The main disadvantage of densification is the cost associated with the various phases of the process. Case by case cost analysis is necessary to determine if densification is economically viable.

A variety of shapes and sizes of densified wood products are made; they can be classified into four categories:

- logs typically resemble roundwood logs and are about 300 mm long by 50 to 100 mm in diametre;
- pellets, range in diametre from 6 mm to 12 mm and are 10 to 20 mm long;
- cubes, range from 20 to 50 mm on each side;
- briquettes have an effective diametre in the range of 20 mm to 50 mm.

Most of the products which are currently available disintegrate with moisture. With the exception of the densified fuels using petroleum products as additives only the logs produced on an experimental basis at B.C. Research have proved to be water stable (Simons 1983). The B.C. Research process uses a special screw type densifier and, as opposed to most other processes, requires a feed stock with a moisture content of at least 30%. Most other processes require the feed stock to have between 10% to 25% moisture.

The full densification process includes several stages. First the biomass material is screened to remove contaminants; then the product is pulverized in a hammer or ball mill; the fine product is dried and is ready for densification. Wood densification equipment can be grouped into the four following categories based on their basis operating principle:

- ram extrusion
- rotating screw
- rotary type
- counter-rotating rollers

1) **Ram extrusion**

Ram extrusion machines use a piston to push the material being densified through a die. The ram is driven by a crankshaft and a large fly wheel evens out the cyclic load. The feedstock is delivered down into the compacting chamber by a feed screw when the ram is in its retracted position. On the forward stroke the ram forces the material into the tapered die against previously compacted material. The densified product is formed by adding discrete segments of material which adhere to one another to form a solid product. The compaction pressure can be increased by reducing the gap between the two halves of the split die and thus reducing its cross section.

Ram extrusion machines normally produce logs 50 to 100 mm in diameter and about 300 mm long. An optional cut-off device can be added on the output side of the machine to section the logs into briquettes 20 to 50 mm long.

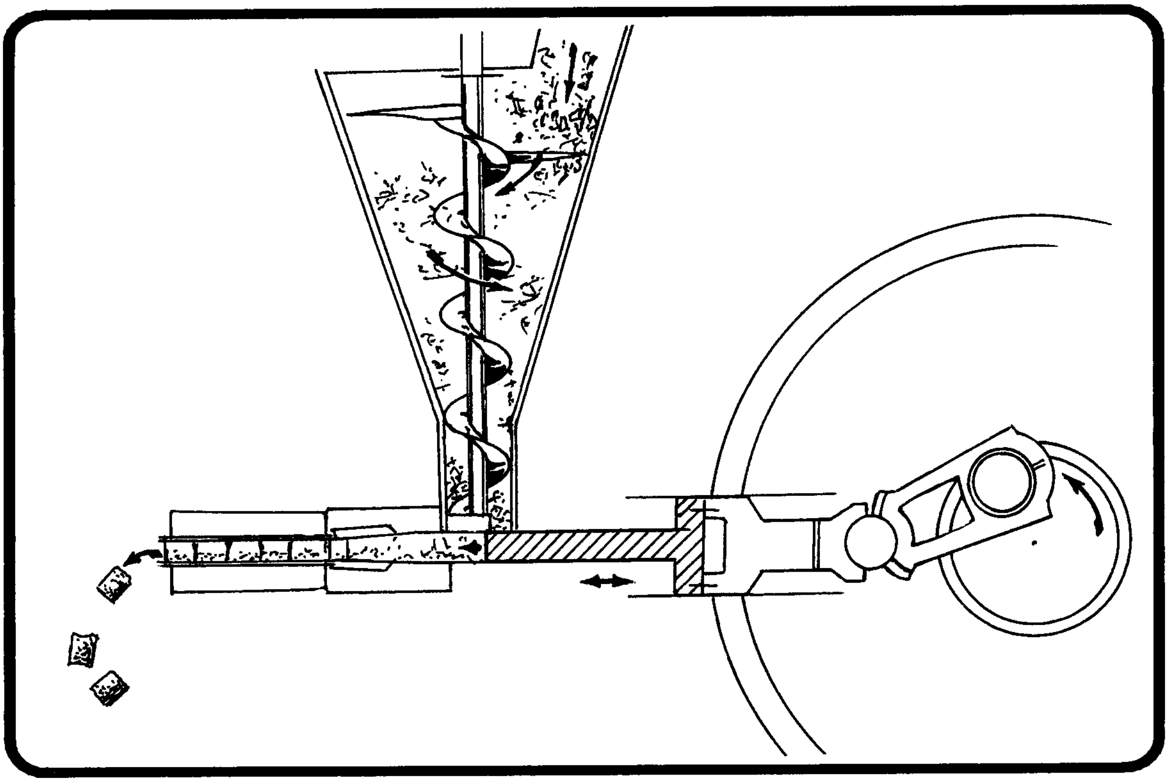


Figure 29. Ram extruder principle.

Table 11 gives the characteristics, production and power consumption for several commercially available ram extruders.

Table 11. Operating characteristics of ram extruders. (Arola 1983)

Machine name	Fred Hausmann	SPM Group	Spanex	Eco Briquet	Desmi
Motor					
type	electric	electric	electric	electric*	electric*
power (kW)	18-125	45-100	7-18	30	50
Feedstock					
. material	biomass	biomass	biomass	biomass	biomass
. size (mm)	10 max	20 max	pulverized	-	-
. moisture content	12% max	10-15%	-	-	-
Densified product					
. type	logs/briquettes	logs/briquettes	briquettes	briquettes	briquettes
. diameter (mm)	40-100	75-100	40-60	60	-
. length (mm)	25-300	10-300	25-50	-	-
. bulk density(kg/m^3)	-	480-580	-	-	-
. moisture content	10%	10%	-	-	-
Production					
tonnes/hour	0.3-3.0	0.8-2.8	0.2-0.5	0.8-1.2	1.5-2.0
Power					
kWh/tonne	74-37	56-35	56-32	24-37	25-33

* diesel if portable unit.

2) **Rotary screw**

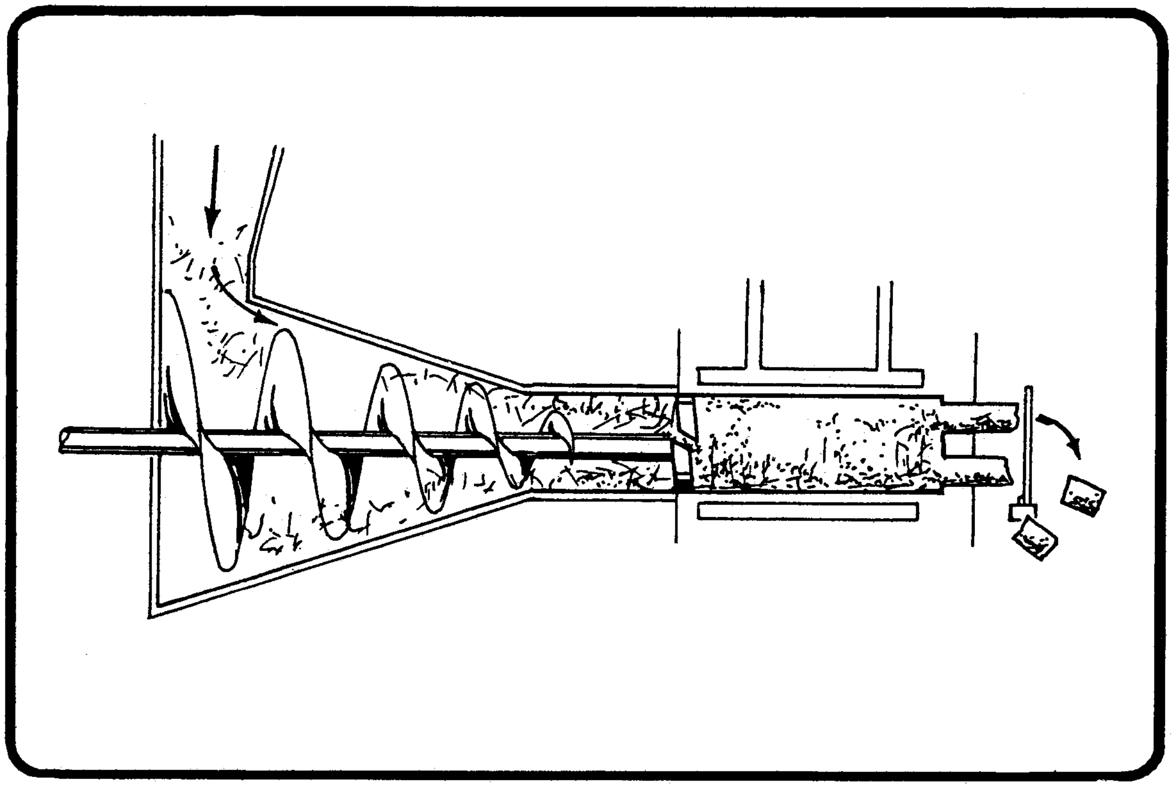


Figure 30. Rotary screw extruder principle.

Basically a rotary screw densifier consists of an auger continuously pushing material through a die. The loose feedstock is fed into a hopper at the head of the compacting auger. The auger can be tapered as shown in Figure 30 in which case the material is compacted along the entire length of the auger and maximum pressure and temperature occur at the small end of the auger. A straight auger merely pushes the material through the die and high pressure and temperature develop in the tapered die by friction. The extrusion die can have a single or multiple holes to form logs, briquettes or pellets. A cooling and decompressing chamber is necessary on the outfeed of the die to achieve cohesive strength. Some rotary screw densifiers use heated dies to reduce the power required to extrude the log and yet still achieve bounding of the particules.

Table 12 gives the characteristics, production and power consumption for several commercially available rotary screw extruders.

Table 12. Operating characteristics of rotary screw extruders. (Arola 1983)

Machine name	Mod-Log (Tiaga Ind.)	Reydco (Model TO-90)	Bonnot Lumberjack	BC Research
<u>Motor</u>				
type	electric	electric	electric	-
power (kW)	75	55	7	-
<u>Feedstock</u>				
. material	Wood residue	biomass	50-50 mix of wax and biomass	Wood residue
. size (mm)	10 max	6 max	3 max	pulverized
. moisture content	10%	6-8%	10% max	30% min
<u>Densified product</u>				
. type	logs/ briquettes	logs	logs water stable	logs water stable
. diameter (mm)	98/25	90	100	-
. length (mm)	300/25-75	300	406	-
. bulk density(kg/m³)	640	760	-	-
. moisture content	3.5-5%	4.5%	-	20%
<u>Production</u>				
tonnes/hour	0.7-0.9	0.7	3.3-3.8	-
<u>Power</u>				
kWh/tonne	90-80	80	2.2-1.9	-

3) **Rotary**

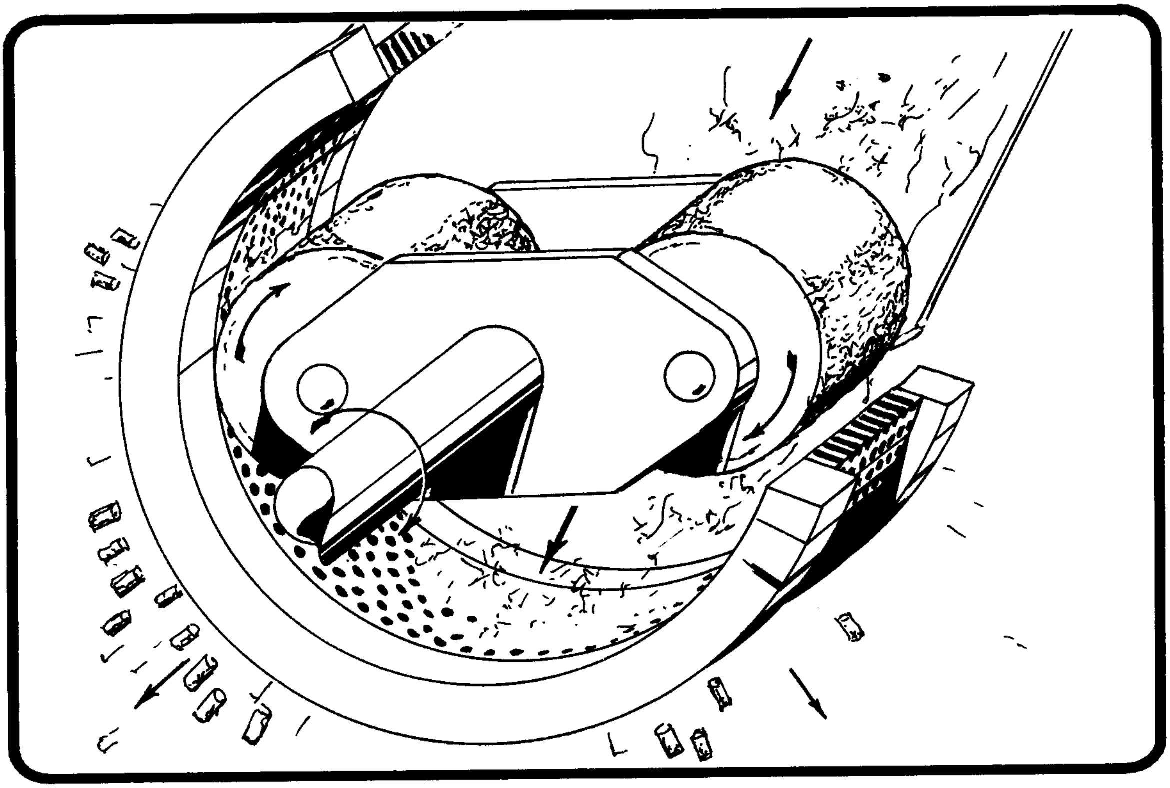


Figure 31. Rotary extruder principle.

A rotary type densifier consists of a rotating die ring through which material is forced by one or more rollers. As the die rotates the material is squeezed by the rollers and gets extruded through perforation in the rotating die. Scrappers inside the assembly distribute the feedstock evenly in the die. A stationary cutting knife in the external periphery of the ring cuts the extruded product to the desired length. Enough pressure and heat is generated in the process to ensure bonding of the particles. As opposed to the ram extruder a rotary extruder is a continuous process. It is very commonly used and can produce pellets and cubes of various sizes and shapes by changing the rotating die.

Table 13 gives the characteristics, production and power consumption for several commercially available rotary extruders.

Table 13. Operating characteristics of rotary extruders. (Arola 1983)

Machine name	California Pellet Mill Co. Model 250	Columbia fuel densifier	Koppers	Landers Machine Co.	Papalube Corporation	SPM Group	Matador
<u>Motor</u>							
type	electric	diesel	electric	electric	electric/ diesel	diesel	electrical
power (kW)	180	170	2-220	220-590	110	150	160-250
<u>Feedstock</u>							
. material	biomass	biomass	biomass	biomass	biomass	biomass	wood waste
. size (mm)	5 max	76 max	8-10	-	32 or larger	25 or larger	-
. moisture content	18-25%	-	17-20%	-	10-20%	18% max	-
<u>Densified product</u>							
. type	pellets	cubes	pellets	pellets	cubes	cubes	pellets
. diameter (mm)	6-10	6 square	6-20	-	32 square	32 square	15 dia.
. length (mm)	1.5 x dia.	50-75	2 x dia.	-	50-75	25-75	-
. bulk density(kg/m^3)	560-640	720-800	-	-	450-690	400-575	600-800
. moisture content	8-12%	15% max	-	-	11-18%	10%	-
<u>Production</u>							
tonnes/hour	2.7-6.4	14 max	0.06-12	22	7-9	4-5	2-8
<u>Power</u>							
kWh/tonne	67-29	12	40-19	27	15-12	40-27	33-44

4) **Counter-rotating rollers**

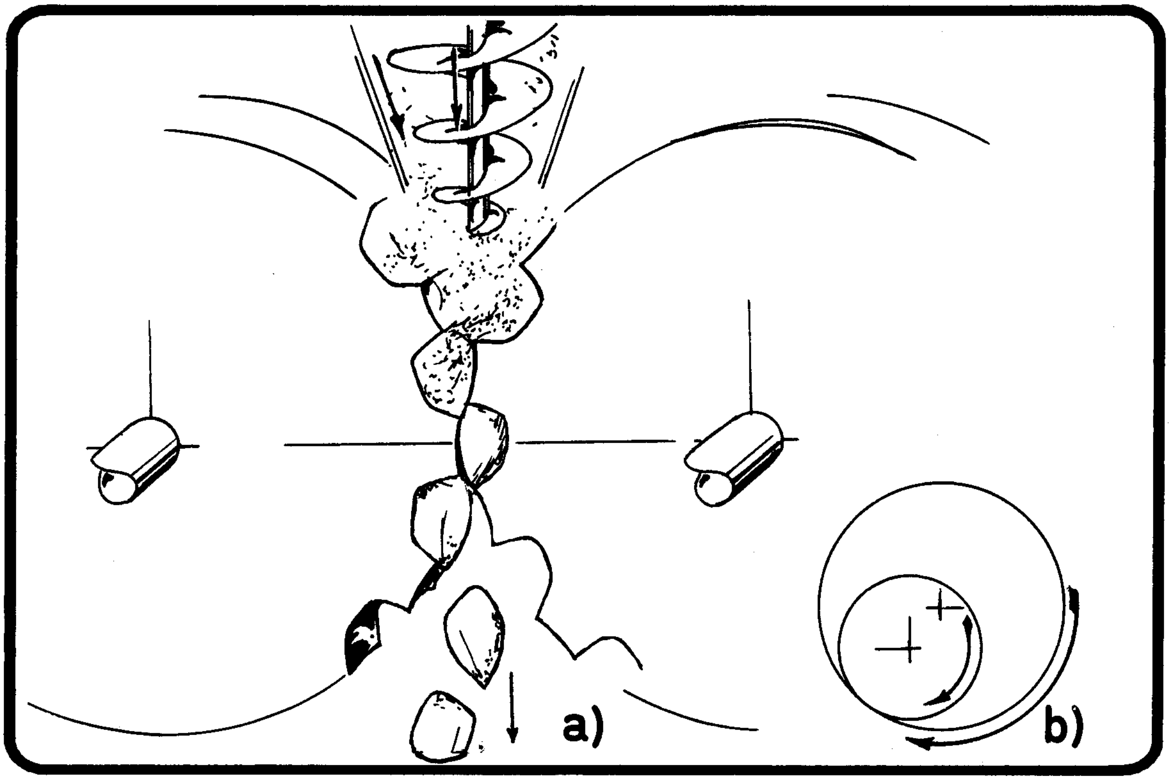


Figure 32. Counter-rotating roller densifier principle.

This type of densifier uses two rollers counter-rotating on parallel shafts to compact the feedstock. The feedstock is delivered down to the two rollers by a vertical feed-screw. Pockets, machined into the rollers surfaces, fill with material as the rollers turn. As the rotation continues the two rollers mesh and the feedstock is squeezed inside the closing pockets. Further rotation opens the pockets and the briquettes fall off. A variation of this principle uses a small roller meshing in the inside of a larger roller (Figure 32-b). Counter-rotation roller densifiers require the least energy of the four methods. Very little heat is generated in this process and it may be necessary to heat the feedstock or add binders to achieve particle cohesion.

Table 14 gives the characteristics, production and power consumption for the Ferro-Tech roll briquettor.

Table 14. Operating characteristics of a counter-rotating roller extruder. (Arola 1983)

Machine name	Ferro-Tech
<u>Motor</u>	
type	electric
power (kW)	100 (Model WP-150)
<u>Feedstock</u>	
. material	wood residue
. size (mm)	12 max
. moisture content	5-15%
<u>Densified product</u>	
. type	briquettes
. diameter (mm)	depends on rollers
. length (mm)	depends on rollers
. bulk density (kg/m^3)	640-720
. moisture content	-
<u>Production</u>	
tonnes/hour	5-7
<u>Power</u>	
kWh/tonne	19-14

VI. DISCUSSION AND RECOMMENDATIONS

In Canada one of the biggest potential application of compaction equipment is the processing of logging residues at roadside. The equipment should be portable and capable of handling tops and branches resulting from mechanical delimbing and small trees from pre-commercial thinning or from energy plantations. This study did not find any forest biomass compaction experiment carried out in Canada; it also pointed out how little was known about the physical characteristics of forest biomass material. For lack of better information U.S. and Swedish data were used. Basic research could be carried out in Canada to better characterize its forest energy sources.

The state-of-the-art review showed that compaction technology has evolved into sophisticated machines in several industries outside forestry, such as agriculture, recycling and waste disposal. The application of this technology to the compaction of woody biomass however is still in its infancy with the exception of fuel densification equipment which is used to produce commercial wood fuels like densified wood logs or pellets. Most of the equipments used for forest biomass compaction are either prototypes, or pre-commercial units and which are seldom used on a production basis. It is remarkable that many pieces of equipment used by the other industries, have been tried at some point for the compaction of woody material. Among these are:

- the round agricultural baler
- the square baler (paper or scrap metal presses)
- the garbage truck
- the garbage container-compactor
- the cotton module builder

All these machines succeeded in compacting forest biomass with various degrees of success; most would require substantial modifications before they could be used in the forest on a production basis. Typically, the machine would have to be beefed up to process woody material. The round baler is an innovative and simple idea but it appear to be too weak for logging slash type material and its principle does not lead to the desired level of density for the bales. A square baler can have the strength and power to compress woody material to a sufficient degree of compaction; a technical difficulty is to feed bulky and long material into the compaction chamber. A possible solution is the feed system developed for the VPI baler. Garbage truck and garbage container-compactor systems compact and retain the material within a large container which constitute a convenient package during transport; two draw-backs for those systems are 1) the container has to be large and heavy and imposes a weight penalty onto the transport; 2) that once unpacked out of the container the material will regain some of its original bulkiness and become hard to manage in subsequent phases. The cotton module builder principle is an attractive possibility for forest biomass compaction; it is simple and produces units that can be efficiently handled providing the modules keep their integrity under repeated handling. Experience with the module building of woody biomass is still very limited; the preliminary results appear to be satisfactory enough to justify a test with this type of equipment under Canadian conditions.

The prototypes specifically developed to handle woody biomass are of three major types:

- balers and bundlers
- on-truck compactors
- densifiers

The VPI baler is the baler that has been most extensively tested with forest biomass. The results achieved with the present prototype are promising; the "second generation" VPI baler proposed by Schiess (1981) appears to have much merits and could prove to be suited to Canadian needs. It would be of interest to follow its development and test it under Canadian conditions when available. Various on-truck compaction equipment have been developed in Sweden mostly to compact tree-sections. They reduce the density of the material during transport but do not resolve the problems of handling and storage of the material once unloaded. Therefore, their potential for use for woody biomass is limited. Densification is by and large a process that is best done at a fixed central location. Although it could be attempted to densify woody biomass right at the logging site, the high energy and complexity of the equipment required by such a process would make it technically difficult and might prove to be economically impractical.

It therefore appears that the module builder and the square baler like the VPI baler have the greatest potential of applicability for processing logging slash or thinning material at roadside. Testing existing prototypes of those two systems under Canadian conditions would appear to be the next logical step in an investigation of the use of compaction equipment in woody biomass harvesting. Such tests would be designed to test the existing prototypes from a technical point of view and would also generate data to verify that compaction is economically viable.

The ultimate objective of a biomass collection, processing and conversion system is to minimize the cost of the energy produced from the biomass. While traditional biomass processing systems are primarily designed to produce the best fuel for a particular conversion system, this might not lead to the most cost efficient solution if the ideal fuel imposes an expensive preparation process.

While there are two major reasons for processing biomass;

1) to increase its handling and transporting efficiency
2) to prepare it as a fuel

the second reason has usually over-shadowed the first and priority has generally been to prepare the best fuel.

Compacting biomass, on the other hand, would mainly be done for the first reason. Since bales cannot readily be burned in existing furnaces they are not considered desirable fuel forms. Jones (1981) suggests that burning whole bales is technically possible; research could be started to improve conversion systems capable of handling whole bales or module sections. Furnaces handling bales would more than likely have lower efficiencies than those burning chips but the overall cost efficiency of a harvesting, processing and conversion system that would not require a comminution phase could be higher than presently used systems.

The compaction and comminution combination could also prove to be the most efficient alternative. Therefore forest biomass compaction experiments should include the testing and the comminution of compacted material.

Summary of Recommendations

Future research on forest biomass compaction could:

- develop basic data on the physical properties of Canadian forest biomass forms;
- test existing prototypes of the module builder and VPI square baler under Canadian conditions;
- design a conversion system capable of handling uncomminuted, compacted biomass material;
- investigate the overall economics of a biomass harvesting system using compaction;
- test the effect of compaction on the efficiency of comminution equipment.

VII. LITERATURE CITED

Arola, Rodger A.; J. Mullen; and Edsel D. Matson. 1983. A review of equipment for preparing and comminuting forest biomass for energy conversion processes. North Central Forest Experiment Station, Houghton, Michigan. IEA CPC3 Stage III. Nov. 1983. 125 p.

Blakeney, K.J. 1983. Guidelines for assessing profitably of chipping forest biomass at field and central locations. Forestal International Limited. Vancouver. 126 p. + app.

Carlsson T.; R. Hansen; and M. Larsson. 1980. Lastbilstransport av stubbar, träd, träddelar och hyggesavfall - resultat av studier 1977-79. [Trucking of stumps, full trees, tree sections and logging residue - study results 1977-79]. Skogsarbeten Redogörelse N° 1, 1980. 36 p.

Carlsson, Torbjörn. 1981. Vidaretransport av komprimerade hyggesrester. [Hauling of compacted slash]. Report 1981-02-20. Forskningsstiftelsen Skogsarbeten. Sweden.

Danielsson, Bengt-Olof. 1983. Harvesting and transportation of small whole trees in Sweden. American Society of Agricultural Engineers. Paper N° 83-1599. 17 p.

Danielsson, Bengt-Olof; Jörgen Marks; and Hans-Olof Säll. 1977. Komprimering av klena träd och träddelar. [Compressing small trees & tree components]. Report N° 119-1977. Dept. of Operational Efficiency. Royal College of Forestry. Garpenberg, Sweden.

Fast, Walter D. 1982. Woody biomass baling tests. Harris Press and Shear, Inc. Cordele Georgia. Unpublished. 9 p. plus illustrations.

Fridley, J.; and T.H. Burhard. 1981. Densifying forest biomass into large round bales. American Society of Agricultural Engineers. Paper N° 81-1599. 21 p.

Guimier, Daniel Y. 1985. Evaluation of forest biomass compaction systems - Milestone I report. Forest Engineering Research Institute of Canada. Pointe Claire, Canada. Interim report. April 1985. 83 p.

Hansen, Rolf. 1978. Lastbilstransporter av okvistat klenvirke. [Hauling of unlimbed smallwood]. Report 178-09-05. Forskningsstiftelsen Skogsarbeten. Sweden.

Hassan, Awatif El-Domiaty. 1976. Compaction of wood chips - Energy cost. American Society of Agricultural Engineers. Paper N° 76-1568. Chicago, Ill. 17p.

Haygreen, John G. 1981. Potential for compression drying of green wood chip fuel. Forest Products Journal. Vol. 31, N° 8. August 1981.

Jenkins, B. M. 1983. Module systems applied to biomass. American Society of Agricultural Engineers. Paper N° 83-3553. 20 p.

Jones, K.C. and Associates. 1981a. A review of energy requirements to comminute woody biomass. ENFOR Project P-28, FERIC Special Report N° SR-14. Canadian Forestry Service, Environment Canada. Ottawa, Ont.

Jones, K.C. and Associates. 1981b. Field tests to develop energy saving wood comminution techniques. ENFOR Project P-28. FERIC Special Report N° SR-15. Canadian Forestry Service, Environment Canada, Ottawa, Ont.

Larsson, Magnus. 1980. Development of transportation systems for logging residues, stumps and trees in Sweden. Paper presented at the International Forestry meeting in Jönköping, Sweden. Sept. 29-Oct. 2, 1980. N° 3, 1980.

Larsson, Magnus; and Berndt Norden. 1982. Komprimering av träddelar från slutavverkning med en separat utrustning. [Compacting of tree sections from clear cutting with separate equipment]. Report 1982-10-01. Forskningsstiftelsen Skogsarbeten. Sweden.

Mäkelä, Markku. 1975. Oksaraaka-aineen kasaus ja kuljetus. [Bunching and transportation of branch raw material]. Folia Forestalia N° 237. Metsantutkimuslaitos, Institutum Forestale Fenniae. Helsinki, Finland.

Miles, John A. n.d. A new method to recover logging residues for energy. University of California. Davis. 5 p.

Mullins, E.J.; and T.S. McKnight. 1981. Canadian woods: their properties and uses. 3rd edition. Toronto: Univ. of Toronto Press. 389 p.

Pottie, M.; and D.Y. Guimier. 1985. Preparation of forest biomass for optimal conversion. Forest Engineering Institute of Canada. Pointe Claire, Canada. IEA/FE/CPC3. In print.

Schiess, Peter; and Keith Yonaka. 1983. Baling: A new concept in residue handling. College of Forest Resources - Univ. of Washington. Presentation at the First Technical Conference on Timber Harvesting in the Central Rockies. 26 p.

Simons Resource Consultants, B.H. Levelton & Assoc. Ltd. 1983. A comparative assessment of forest biomass conversion to energy forms. Phase I: Proven or near-proven technology. Volume III: Data book of unit processes for fuel preparation and handling. ENFOR Project C-258. Energy, Mines and Resources, Ottawa, Ont.

Söderberg, Lena. 1984. SLYMAN - Komprimerings och buntnings aggregat. [SLYMAN - Compaction and bunching equipment]. Interforest AB. 12 p. + app.

Walbridge, T.A.; and W.B. Stuart. 1981. An alternative to whole tree chipping for the recovery of logging residues. Proceedings of the International Conference "Harvesting and Utilization of Wood for Energy Purposes" Elmia, Jönköping Sweden. Sept. 20-30, 1980 (in proceedings).