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DENSIFYING FOREST BIOMASS
INTO LARGE ROUND BALES

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Thomas H Burkhardt
Major professor

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DENSIFYING FOREST BIOMASS
INTO LARGE ROUND BALES

By

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ABSTRACT

DENSIFYING FOREST BIOMASS INTO LARGE ROUND BALES

By

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A large round-bale hay baler was modified to examine the concept of baling forest biomass in large round bales. The baler was used to form nine bales similar to large round bales common in agriculture. Material baled, feed orientation, and baler belt tension were varied to observe their effects on the baling process and bale density. Torque and power required to drive the baler were measured while forming two bales. The energy required for these two bales was determined to be 0.83 and 1.18 kW-hr/t. The average torque was found to be 34.1 and 41.4 N-m.

The bales formed were all 2.14 m long and had diameters from 1.22 to 1.83 m. The bales ranged in mass from 409 to 1516 kg for densities of 142 to 338 kg/m^3. Once formed, the bales were observed for internal, self-heating. Three reached temperatures of 60°C. The remaining bales did not become warm.

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1.0 INTRODUCTION

1.1 Benefits of Compaction

Baling is a means of densifying a material for transportation and/or storage prior to subsequent use or processing. Compaction densifies the bulk material so a given mass is contained in a smaller volume for handling, transporting, and storage. In many operations, particularly transportation and storage, capacity can be increased by densifying or compacting the material being handled since space may be a limiting factor.

The harvesting and handling of forest materials includes at least some processing which is conducted at or near the growing location (i.e., the stump). Harvest consists of cutting or shearing at the stump. Stems may be processed by operations such as bucking (cutting into pieces), limbing, and chipping. The material is then transported some short distance (less than 2 km) to a landing or loading site where additional processing often occurs. This processing can be additional bucking, limbing, chipping, marking, and loading. The product of these operations is then transported to a manufacturing/processing plant (sawmill, pulpmill, burner, etc.). The above sequence applies in a general sense to all forest harvest operations. The produce could be sawlogs, peeler logs, pulpwood, whole tree chips, or fuel.

The current practices of handling logs and wood chips are relatively efficient. However, as the forest industry moves into an era of more complete utilization of biomass, these same handling practices may not be appropriate. Handling, transportation and storage of currently underutilized forest biomass will likely require innovative new concepts. Forest biomass is the quantity of living biological material in the forest, the only portion of which is currently well utilized is the main tree stems down to a diameter of about 10 cm. The efficiency of the transporting and processing of these materials may be increased by handling these materials in bulk and compacting or densifying them. Accumulation and compaction of material during the initial collection provides increased payloads which lead to increased efficiency of the collection and transportation operations and improves space utilization during storage.

1.2 The Potential for Round-bale Balers

Baling is a means of compacting a loose or bulky material. Baling also provides unitized packages which can be handled more easily than loose material. Baling hay is a common agricultural practice. Technology in hay baling has been well developed in the United States.

The use of round-bale balers for collection of forest biomass is interesting for several reasons. Round-bale balers are relatively uncomplicated pieces of equipment. The mechanical motions are continuous, not reciprocating. Material being baled is rolled up inside the baler. The bale is rotated within the baler and new material is drawn in much like laundry into an old-fashioned wringer; the material being baled tends to feed itself into the baler. Compaction takes place in the bale due to external squeezing from belts, chains, or rollers, and also from the weight of the bale being formed.

Round-bale balers make large single bales so a large mass of material can be picked up, moved, and otherwise handled at one time by one person with conventional uncomplicated equipment. Ease of handling is the main reason farmers have turned to large bales for harvesting and handling hay. Harvesting forest biomass with large round-bale balers also has the potential of having very low energy costs compared with other harvesting and handling schemes, such as chipping in the woods.

Handling material in large round bales may be an alternative to chipping in the woods or may prove to be appropriate prior to chipping in any application where chipping currently is done or being considered. If material is baled prior to chipping, chipper efficiency alone might be increased enough to justify baling. Baling also may prove to be desirable to combust or gasify the material. Likely applications of round bales in forest product handling are outlined in Table 1-1.

Table 1-1. Applications for round bales in forestry.

	Specific application	Current practice
Silvicultural treatments	Vegetative control	Chemical applications
	Thinning	Leave in woods, leave limbs and tops, chip
	Pruning	Leave in woods
Harvest	Short rotation forestry	Whole tree chipping
	Limbs and tops	Chip, pile, burn, scatter
Urban forestry	Pruning	Chip, pile, burn, chip limbs
	Tree removal	
	Right-of-way clearing	

1.3 Objectives of the Investigation

An investigation was conducted to evaluate the technical feasibility of the new concept of collecting and handling forest biomass material in large round bales formed with a machine similar to large round-bale hay balers commonly used in agriculture. The objectives were 1) to observe the round-bale baling process, the baler requirements, and the bales of forest biomass formed and 2) to evaluate the concept feasibility and provide machine design information necessary for implementation of the concept in a prototype system.

2.0 REVIEW OF RELATED RESEARCH

2.1 Hay Baling

Hay balers have been a part of American agriculture for over one hundred years (Kepner, 1978). Balers were first operated only as stationary machines before pick-up mechanisms were added to make field machines. Incorporation of the automatic twine and wire-tie mechanisms provided the conventional rectangular baler in use today.

Large round-bale balers similar to the one shown in Figure 2-1 first became available in 1972 and grew quickly in popularity (Kepner, 1978). However, these machines were not the first machines to form round bales. Machines which formed small round bales with a mass of 18 to 36 kg (40 to 80 lbs) were marketed by Allis Chalmers Co. during the 1940's and 50's (Rider, 1976). The fact that the round bales were more weather resistant than conventional bales and farmers' desires to reduce the labor requirements of hay baling led to the development and extensive use of large round baling systems during the 1970's.

2.1.1. Comparison of Round-bale Balers with Conventional Balers

A conventional rectangular bale is formed by compressing hay in an enclosed bale chamber. A plunger is driven by a crank and pitman and reciprocates approximately 80 times per minute. When the plunger is retracted, hay is forced into the chamber through an opening in front of the plunger. As the plunger moves forward, any hay partially inside the chamber is sheared off at the opening. The plunger compresses the new

(a)

(b)

Figure 2-1. Baling hay with a round-bale hay baler.

charge of hay until the newly compressed hay and the previously formed bale are moved along the chamber, the sides of which converge toward the outlet end. The plunger then retracts and the cycle is repeated. When a bale of sufficient length is formed, the tying mechanism is activated, the bale is tied, and a new bale is begun.

The force on the plunger while compressing the hay is caused by the friction of the bale moving through the converging chamber. Work is done to 1) compress the hay, 2) shear any material in the chamber opening, and 3) slide the bales out of the converging chamber.

Typically, a baler is pulled with a tractor. A pick-up unit lifts hay from the ground and directs it into the chamber opening. The finished bales are ejected onto the ground or to some type of loading mechanism.

Rectangular bales are tied with either two or three wires or twines. Two-wire/twine bales are generally about 40 x 46 x 100 cm with a mass of 23 to 36 kg; three-wire/twine bales are about 42 x 58 x 120 cm with a mass of 57 to 68 kg. The three-wire bales are most popular where hay is handled commercially and transported long distances.

The large round-bale machines operate on an entirely different principle (Kepner, 1978). Hay is picked up and rolled to form the bale. Some commercial machines roll the hay directly on the ground, but more commonly, the bale is formed completely off the ground. In the latter balers, the bale is enclosed in belts, chains and slats, or rollers. The bale diameter increases as more and more hay is rolled up in the bale. The hay is compressed by the weight of the bale being formed and also by the baler mechanism resisting the diameter growth of the bale as it is formed. Some machines compress the hay beginning with the initial core while others only compress the bale by adding hay after a full diameter is reached. Typical large round bales of hay are 1 to 2 m in diameter and 1 to 1.8 m long with a mass of up to about 1300 kg.

Large round hay bales generally are not suitable for long distance transportation. The round shape of the bale results in inefficient loading on the vehicle. Usually, round bales are moved only two times--once from the field to the storage location and again to where the hay is fed.

Baling hay in round bales was compared with baling hay in conventional rectangular bales by Renoll (1976). He reported that round bales have a density of about 75 percent of that for rectangular bales--104.1 kg/m^3 compared to 137.8 kg/m^3. The baling capacity for the large round baler was reported to be 5.4 t/hr compared to 4.7 t/hr for rectangular bales. Renoll concluded that large round-bale systems had lower total costs than conventional bale systems for producing, harvesting, storing and feeding hay.

2.1.2 Tractor Power Requirements for Round-bale Balers

A review of five manufacturers' sales literature for nine different balers was done to determine the recommended minimum tractor power. Large round-bale machines require tractors of about 30 to 52 kW (40 to 70 hp). The tractor power required increases with the size of the bale which the machine will form. The minimum recommended tractor power, according to one manufacturer's representative, is determined by field testing under ideal conditions. Ideal conditions are operating conditions where the maximum possible fraction of the tractor power is used to drive the baler and minimum power is necessary to propel the tractor and baler across the field. These conditions are characterized by flat terrain, dry ground, and high per hectare yields.

If the machine capacities specified by manufacturers are combined with the recommended tractor power, an energy requirement of between 3.3 and 8.3 kW-hr/t (4 to 10 hp-hr/ton) is suggested. This energy requirement assumes that the tractor is operating at full rated power and includes power necessary to propel the tractor and baler. Thus, the 3.3 to 8.3 kW-hr/t computed energy requirement is higher than the actual energy required for baling alone.

In a series of publications evaluating large round-bale balers (PAMI 1977 - 1979), average energy requirements to bale alfalfa were found to range between 1.11 and 2.44 kW-hr/t for the large round-bale balers compared to 0.70 to 1.02 kW-hr/t for small square-bale balers. The energy requirements for the round-bale balers were found through field testing. The source of information on square-bale balers was not given. Similar publications, in the same series, evaluating small square-bale balers report average energy requirements to bale alfalfa between 1.0 and 1.42 kW-hr/t for small square-bale balers. An explanation for the difference in energy requirements between large round-bale balers and small square-bale balers was not found in the literature. The difference is surprising because of the shearing of stems and friction in the bale chamber for square-bale balers; there is however, friction on the ends of the round-bale baler chamber. Information on energy requirements for large square-bale balers was not found.

2.2 Wood Chip Densification

Studies were conducted (Hassan, 1977, 1978) to determine if wood chips could be compacted for storage and shipping. The average wet bulk density of a load of loose green chips was reported to be 272 - 384 kg/m^3. Handling of this material would be facilitated by increasing the density of the material. The denser material would be containerized and therefore would not require enclosed vans for transportation. Hassan (1977) concluded that 385 J/kg were needed for a 50 percent reduction of the chip volume.

Hassan (1978) monitored the temperature of baled and loose chips for 236 days. The moisture content of the green chips was reported to be 89 percent on a dry basis or 47 percent on a wet basis. An uncompacted, containerized mass of chips lost more than 50 percent of its moisture while no moisture was lost in the containerized, compacted chips. An increase in moisture content of about 20 percent was reported for loose, uncompacted chips simulating a stockpile. Hassan concluded that "containerization and compaction of wood chips neither damaged fibers nor altered the chip response to conventional pulping" and that "the temperature of the uncompacted chips was, in general, higher than the containerized compacted chips when stored outdoors under the same conditions." It was not concluded, in general, how much of a temperature difference could be expected.

2.3 Forest Biomass Baling

Baling logging residues has been under investigation at Virginia Polytechnic Institute and State University (VPI) since 1975 (Jolley, 1977). This investigation began with experiments using a conventional rectangular-bale type agricultural baler which had been modified by replacing the power take-off drive with a hydraulic system. The plunger was driven with a hydraulic cylinder and material was fed by hand. The plunger sheared material in the infeed opening and compacted the material in the chamber. The material baled was limbs and tops of varying diameters. The largest piece that could be sheared was about 100 mm in diameter.

A baler manufactured by International Baler was received by VPI in December of 1979 (Lane, 1980). The machine was described as being similar to a large industrial type garbage compactor with a capacity to form bales 0.61 m x 0.92 m x 1.22 m with a mass of 430 to 540 kg. The baler was mounted on a trailer approximately 1.2 m by 4 m and was powered by a GMC 353 engine. Research currently is being done in the areas of material feed into the baler and development of a tying system. The baler is being developed in an effort to reduce the cost of recovering logging residue by reducing the machinery investment to less than the investment required for mobile chipping equipment.

2.4 Christmas Tree Baling

In the spring of 1978, a number of Michigan Christmas tree growers met with members of the Michigan State University Agricultural Engineering Department to discuss initiating Christmas tree harvest research. The request led to the experimental use of a modified Vermeer large round-bale hay baler to form a bale of Christmas trees (Ledebuhr, 1979; Hansen, 1980).

In the fall of 1979, a special baler built by Vermeer Co. was delivered to Michigan State University. The baler was designed to form bales 2.5 m long and up to 1.8 m in diameter. Additional baler modifications were made in the Agricultural Engineering Department's research laboratory prior to forming several bales of Christmas trees and shipping bales to sales lots in New Orleans and Atlanta where the marketability of the baled Christmas trees was studied.

(a)

(b)

Figure 2-2. Baling Christmas trees with the modified baler.

Bales were formed containing about 50 trees which were up to 2.5 m tall. The trees were fed into the baler with opposing orientation such that the butts of the trees made up the ends of the bales (see Figure 2-2). Baling of Christmas trees was concluded to have potential for a significant improvement over current handling techniques, especially where labor availability is questionable (Hansen, 1980).

Some concern exists about the potential for damage of the trees due to heating within the bales. Temperatures in excess of 38°C (100°F) were measured on at least one bale but no trees in any bale were obviously damaged by the heating.

2.5 Other Densification Schemes

Densification schemes other than chipping have been tried in the forest industries; however, none have as yet been implemented with much success or on a scale which would compare with chipping. Forest residue and forest biomass materials generally have been handled or considered for handling only by chipping. In a general sense, most chipping systems are based on handling individual pieces of the material before the material is chipped.

A machine currently is being developed by the U.S. Forest Service to cut and chip a 2.4 m-wide swath while moving continuously through the woods (Koch, 1980). The machine has been developed to a prototype stage and has been tested in red alder (*Alnus rubra* Bong) stands near Seattle, Washington. The machine was built on the lower frame, undercarriage, and lengthened tracks of an FMC skidder and is powered by a 430 kW diesel engine. Ground speed is about 1.6 km/hr, for a harvesting rate of about 0.405 ha/hr. The complete machine has a mass of 33,000 kg (72,000 lbs). Koch's machine represents the most advanced mobile machinery for harvesting forest biomass or forest residue materials. The harvester would be used in conjunction with forwarders that move the chips to roadside; it does not have the capability of transporting the chips.

Another machine concept, which is under development at the Agricultural Engineering Department, University of Maine (Monico, 1979) would simultaneously fell and chip material with the cutting head, in contrast to the two separate functions being combined on one prime mover as done by Koch. The University of Maine machine would be boom-mounted in contrast to the swath-cutting concept of Koch.

Besides chipping, material can be densified into pieces or packages by cubing, pelletizing or any other consolidation scheme. Sawmill residue has been cubed successfully to form individual wafers as dense as 7,860 kg/m^3 (49 lb/ft^3) (Dobie, 1973). In general, consolidation is used to densify very fine material, such as sawdust, and chipping is used to densify larger bulky material, such as logging residue.

2.6 Heating Phenomena

Wood is a perishable raw material (Cowling, 1974). Losses in stored pulpwood chips are significant enough to attract interest in alternative methods of chip storage (Springer, 1978). Losses apparently are related to temperature increases within the piles (Hulme, 1976). Self-heating occurs in most outdoor chip piles and has in some cases resulted in spontaneous combustion of the chips (Zoch, 1976).

Whole-tree chips have a greater tendency to heat than clean, bark-free chips. Greater losses and higher temperatures for stored whole-tree aspen chips compared with clean-wood aspen chips were reported by Zoch (1976).

A similar potential for heating and spontaneous combustion exists with agricultural hay storage. Heating occurs in both chopped and baled hay (Bruhn, 1976). Since spontaneous combustion is a problem with both bales and chips of biological materials, the heating phenomenon is of some concern with regard to baling biomass.

2.7 Discussion of the Round Bale Concept and Related Research

The densification schemes discussed above demonstrate an interest in developing new ways of handling forest materials. Associated problems or potential problems are also pointed out. The cost of an operation is always a consideration in evaluation of an operation. Size and power requirements of equipment are major factors in the cost. Internal heating of stored biological materials such as baled hay or piled woodchips is also a problem.

The ability to form large round bales of woody material was demonstrated by baling Christmas trees. This led to the concept of using a large round-bale baler to bale forest materials. To examine this concept the investigation of baling forest materials with a large round-bale baler was performed.

2.7.1 Scope and Limitation of the Investigation

This study was a first look at the concept being investigated. Therefore, the study was designed to identify the important aspects of the process and to make observations and evaluation of as many of these aspects as possible. An in-depth study of any one aspect was not done; instead, the many observations of the process as a whole were combined to provide insight for the entire baling concept.

Relatively few bales were formed for this research. A large amount of time was required in preparation for and subsequent to formation of each bale. Frequently, more than one variable was changed from bale to bale. Generally, this was unintentional and caused by machine failures and characteristics of the material being baled.

2.7.2 Outline of the Investigation

Quantitative measurements were made to evaluate machine power requirements, bale composition, size and weight, and bale temperature for a period of time after the bale had been formed. The machine power requirements are useful in predicting the machine costs and performance, as well as for design of any future prototype machinery which might be built. The information about the bales is necessary to determine the desirability of the concept and also important in the design of future prototype balers and associated machinery.

Qualitative observations also were made to learn as much as possible about the concept of forming round bales. Specifically, qualitative observations were made to determine and understand any problems encountered and to determine the effects of material size, shape, and orientation on the bales and the baling process.

The investigation was done using equipment--a modified Vermeer large round-bale hay baler--already available to the Agricultural Engineering Department. The baler, which is discussed in detail in Section 3.2, had been set up to be hand-fed. All material was cut, collected, and fed to the baler by hand. Overall this was a labor-intensive handling process. However, the characteristics of the baling process and bales formed is believed to be independent of how the material was handled prior to baling. The material size, orientation for feeding, and any cutting or chopping prior to baling was variable and observed during the baling experiments.

3.0 GENERAL DESCRIPTION OF THE ROUND-BALE BALING MACHINE

3.1 Vermeer 605F Hay Baler

The experimental baler used for this study is the modified Vermeer 605F large round-bale hay baler shown in Figure 3-1. The model 605F is the largest Vermeer baler and a review of several manufacturers' promotional materials suggests that it makes the most dense bale of any of the large round-bale balers available. The Vermeer product literature gives the following specifications for the 605F.

Table 3-1. Specifications for the Vermeer 605F hay baler.

Weight	2020 kg
Length	4.32 m
Width	2.41 m
Height	2.64 m
Drive	540 or 1000 rpm PTO
Bale size	1.52 m wide up to 861 kg
Minimum tractor	45 kW (60 hp)

The hay, or other material to be baled, is fed into the baler and is rolled up into a cylindrical bale by a set of endless flat belts operating in parallel (Figure 3-2). As more material is added, the bale diameter increases and as the diameter increases more belt length is required to wrap around the bale. A series of idlers, which take up slack

Figure 3-1. The modified Vermeer 605F large round-bale baler.

(a)

(b)

Figure 3-2. Endless, parallel flat baler belts forming a bale.

(c)

Figure 3-2. (cont'd)

(d)

Figure 3-2. (cont'd)

(e)

Figure 3-2. (Cont'd)

in the belts, give up the necessary slack by moving against a force provided by springs and a hydraulic cylinder (Figure 3-3 and Figure 3-4).

3.2 Baler Modified for Forest Biomass Baling

The Vermeer 605F hay baler was modified initially by the Vermeer Co. for an MSU research project on baling for Christmas trees. The baler was built 5 m wide instead of the standard 2.4 m. Due to the larger size it was built 90° to the standard configuration so that the baler could be pulled on the highway with a truck or tractor.

During the Christmas tree project, the baler was modified further in the Agricultural Engineering research laboratory. The frame was reinforced by adding bracing and a wagon-type trailer tongue so as to handle the large weight and size of bales that were anticipated. The power-take-off drive was replaced with a hydraulic motor, and an air-cooled engine and hydraulic pump were mounted on the baler to supply all necessary power. With this arrangement, a tractor was not needed to operate the baler. Two flat conveyor belts were added to make the machine easy to hand-feed. These feed conveyors guided the material being baled into the throat of the baler.

While modifying the baler for Christmas tree baling, the hydraulic belt-tightening cylinder (Figure 3-4) was changed so that it could be used to keep the belts slack to prevent damaging the Christmas trees. However, to make dense bales of forest biomass, the belts needed to be tight. The control valve for the cylinder locked the cylinder in place when the valve was in the center position. Therefore, a relief valve was installed on the cylinder to provide controlled belt tension. With this arrangement, represented schematically in Figure 3-5, the cylinder could be extended or contracted using the control valve. When the

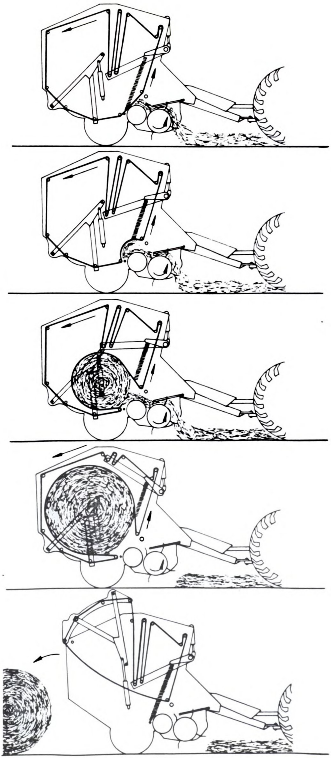

Figure 3-3. Schematic of round-bale hay baler operation

Figure 3-4. Hydraulic cylinder for maintaining belt tension.

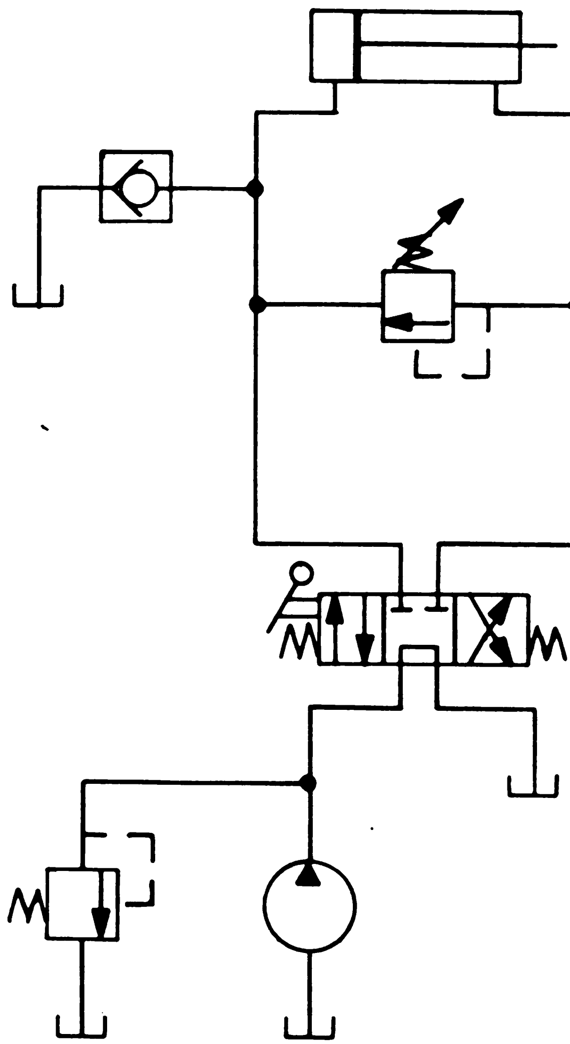

Figure 3-5. Hydraulic circuit for baler belt-tightening cylinder control.

control valve was in the center position, the cylinder could be extended only when the force on the cylinder caused a pressure large enough to open the relief valve and allow fluid to flow from the rod end to the piston end of the cylinder. As material was added and the bale increased in diameter, the cylinder was extended against the pressure determined by the relief valve setting.

In addition, the linkage on the tightening cylinder was changed to provide a greater mechanical advantage for the cylinder and thus a greater belt tension. For the bale diameter to grow a given amount, the cylinder also was forced to extend further. This provided flow across the cylinder relief valve greater than the flow with the original linkage, thus reducing the effect of leakage and increasing the control over the belt tension. The change in the linkage also limited the maximum bale diameter which could be obtained because the cylinder was fully extended when the bale diameter reached 1.5 m in diameter.

No other significant modifications were made to the baler. The basic operating principle of the 605F baler was not changed. The machine was only made larger, to some extent simpler, feed conveyers were added, and the belt-tightening cylinder was changed to provide a greater compressive force during the baling process.

4.0 EXPERIMENTAL PROCEDURES

Materials to be baled were cut by power saw and transported to the baler which was stationary during the baling process. No attempt was made to reduce the bulk of materials by excessive cutting. However, stems were cut so as to limit the stem diameter to minimize the risk of mechanical damage to the baler. For some bales, stems were also cut to facilitate orientation of the stems in the bales.

4.1 Bale Forming Process

The basic bale-forming procedure was the same for each bale made. The process consisted of feeding the material to be baled into the baler by positioning the material between two large feed belts which had been added during the modification of the machine for Christmas trees (Figure 4-1). Once the bale was full-size, twine was fed into the machine while it was running to wrap the twine around the bale (60 to 100 wraps). Then, the bale was ejected from the machine.

The operation required one machine operator and one to three people to feed material to the baler. Even with three people feeding the baler, it was difficult to keep a constant flow of material to the baler so the machine operator only ran the baler when there was material to be drawn in by the rotating bale.

A bale core had to be formed at the beginning of the baling process. The procedure used was to slacken the baler belts and hand-feed material into the bale chamber until sufficient material had been supplied so the baler could rotate it and form a core. The material was difficult to

Figure 4-1. Large feed belts, installed for Christmas tree baling, with material typical of forest biomass which was baled.

feed into the bale chamber at this stage and the minimum diameter necessary for this core was difficult to judge. Once the core was started sufficiently, the baler belts were tightened and the bale would tighten up and begin to rotate. From this point, the baler would accept essentially any material placed on the feed conveyor. The material to be baled was drawn into the baler as it became caught between the rotating bale and the baler belts. The baling process was remarkably smooth from the time the core was formed through the twine wrapping process. The bale was ejected by opening the rear gate of the baler and rolling the bale free of the baler. On several occasions the bale became stuck and had to be forced from the baler. Design modifications could correct the problem of bale sticking.

4.2 Bale Density

One primary part of the investigation was to determine the size and mass of the bales formed. After the bales were ejected, the diameter was measured by putting the bale on a flat surface and measuring from the support surface to a level straight edge which was placed on top of the bale. The diameters were measured at both ends and the middle of the bale. The length of the bales was measured in a similar fashion. Originally, the machine was built to form bales 2.4 m long and 1.8 m in diameter.

The bales were weighed by weighing a truck loaded with one bale and then measuring the tare weight of the truck immediately after the bale was unloaded. The bale weight was determined by subtracting the tare weight of the truck from the gross weight of the bale and truck combined. The weight data were then converted to mass. Bulk densities were calculated by dividing the mass of the bale by the cylindrical volume. All bales were weighed within 48 hours of the time they were made.

4.3 Material Orientation and Size

The material orientation for feeding was studied to observe any effects on the bales or baling process. Orientation must be controlled by any cutting and feeding system to be used in conjunction with or integral to a baling machine. Clearly, if material orientation has any effect on the baling process or bale characteristics, feeding mechanisms must be designed accordingly. Material orientation was kept consistent for any given bale and was recorded as being perpendicular, parallel, or random to the axis of bale rotation. Random orientation is best defined as most convenient for the persons feeding the material into the machine.

The length of the material (for a single bale) was either left uncut or all cut so no piece was longer than the 2.5 m bale length. The approximate range of lengths of the pieces put into each bale was recorded as was the diameter range. All length and diameter data were estimated during the baling process. Individual pieces were not measured, but exceptionally large pieces were observed more closely than the small and midrange size pieces. The feed angle was also not closely controlled--the people feeding the material simply made an effort to orient the material as instructed to keep orientation consistent.

4.4 Bale Heating

Some concern exists about the potential for spontaneous combustion in bales formed with green forest biomass material. The concern was a result of problems encountered in both baled hay and piled wood chips

(Section 2.5). All bales were observed for any external signs of heating such as steaming, warm to touch, or composting odor. Any bales showing any of these external signs were monitored more closely. A simple immersion type thermometer was adequate for periodically checking the temperature in the outer 200 mm of the bale.

The temperature deep within the bale was observed by the use of copper/constantan thermocouples. The thermocouples were embedded in electrical component potting compound inside 1/8 inch pipe couplings. The potting compound was electrically non-conductive and conducted heat quite well. The lead wires were threaded through a piece of 1/8 inch pipe. The pipe couplings with thermocouples were loosely threaded onto the pipe and inserted into holes which had been drilled into the bale. The pipe was then unscrewed from the coupling and pulled out of the bale leaving the coupling and thermocouple in the bale.

The thermocouples were connected to a Texas Instruments 24-point multi-riter chart recorder which had been previously set up by the Agricultural Engineering Department for periodic recording. The temperatures were recorded at least twice each day and could be recorded more frequently if large temperature variations were observed. The bales for which temperature observation were monitored had five thermocouples within them and one measuring the ambient temperature near the bale. Lead wire length was kept to a minimum by placing the recorder close to the bale and trimming excess wire. Based on comparisons near ambient temperature the accuracy of the temperatures observed was assumed to be easily within ± 3.0°C.

4.5 Bale Material Moisture Content

Bale moisture content data were taken so as to compare variation in bale density, bale heating, and moisture content. Dense bales and bales with a relatively large temperature rise after baling were expected to be those bales made from material with a high moisture content. An in-depth study was not to be done; rather, samples were taken from each bale to monitor large differences. The samples were taken by cutting a slice from the bale as shown in Figure 4-2. The individual pieces were sorted roughly by size. Samples consisting of several pieces of similar size, each sample between 10 and 30 g, were weighed and oven-dried at about 95°C for a period of about one week. Oven-dried samples were then weighed again after they had been allowed to cool to room temperature. The individual samples were roughly proportional, in mass, to the size distribution of pieces in the sample slice taken from the bale.

4.6 Energy Requirements

To compare baling in large round bales with other handling and processing schemes, energy requirements can be used to indicate relative costs of the operations. Processes requiring more energy will require either more power or more time. If more power is required, then larger, heavier, and more expensive machinery will be required. If more time is required to carry out an operation, then the labor and time-dependent machinery costs will be relatively greater. Power requirements and estimated productivity information for hay and forage are available in manufacturers' sales and product information literature and, in some instances, in scientific literature.

The energy requirements for baling forest biomass with the large round baler were estimated by measuring the torque and shaft speed

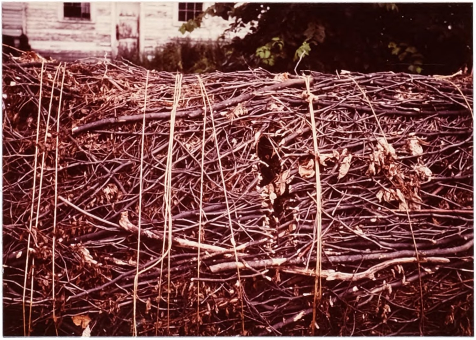

Figure 4-2. Bale with slice removed for moisture sampling.

supplied by the hydraulic motor used to power the machine. From this information, the average power input was calculated over the time required to make one bale and the work-per-unit mass of material being handled was determined. Work-per-unit mass of material is a number easily derived from power and productivity information for any machine. The energy requirements calculated for the baler were based upon the actual power delivered so they had to be multipled by an assumed drive train efficiency before being compared with empirical values for equipment which is currently in use.

The output voltage of a DC generator was used to measure the input shaft speed. The generator was manufactured by Barber Coleman Co., part number FYLM 73920-51. The particular generator used was borrowed from the Agricultural Engineering Department electronics laboratory. The output voltage was 10×10^{-6} V/RPM.

The hydraulic motor was used as a dynamometer to measure the shaft torque. A mathematical model was developed to describe output torque as a function of the pressure drop across the motor and the speed of the output shaft (Appendix I). Two electronic pressure transducers, which were obtained through the United States Department of Agriculture (USDA), were used to measure the pressure drop across the motor. The output of the transducers and the tachometer were recorded on paper printout using the Kaye Instruments RAMP data logger and scanner. The output was sampled and recorded every 7.5 seconds and the data were put on the College of Engineering Computer (Prime 750) for analysis and graphical presentation. The programs used are included in Appendix II. Any data points for which the calculated torque is below the minimum necessary to turn the input shaft or the motor speed is below 90 RPM are thrown out. The points thrown out occurred when the machine was stopped or nearly stopped to wait for more material or similar delay.

The computer programs calculated the operating time required to form the bale and the average power used over that period of time. These numbers were combined with the mass of the bale to determine the work-per-unit mass in kilowatt hours per kilogram. A graphical output was obtained and is included in Appendix I.

5.0 RESULTS

5.1 Summary of Bales Made

Material to be baled was obtained from three sources. The materials were: common prickly-ash (Rutaceae *Zanthoxylum americanum* Mill.); a composite of hardwoods and conifers; and red pine (Pinaceae *Pinus resinosa*). The common prickly-ash, obtained from a small private woodlot near Owosso, Michigan, was used to form four bales. The mixture of hardwood and conifer tree species, obtained on campus at MSU following a severe summer storm, was used to form three bales. The red pine was logging residue obtained near Ishpeming, Michigan. Two bales were made with red pine tops and limbs as they were produced with a Hahn Harvester limbing and bucking machine operated by a local logging contractor (Figure 5-1).

A total of nine bales were made with the modified baler and properties of these bales are given in Table 5-1. All of the bales were 2.4 m long. The bale diameters ranged from 1.22 m to 1.83 m and mass ranged from 409 kg to 1516 kg. Moisture content measurements were not made of every bale, but bales were made from both very green and very dry materials.

5.2 Density of Bales

The bulk density of the bales formed ranged from 143 kg/m^3 to 338 kg/m^3. The density of the bales is determined primarily by two factors--the density of the material being baled and the degree of compaction achieved by the baler. The baler does not actually compress the wood

(a)

(b)

Figure 5-1. Baling logging residue.

Table 5-1. Bale material, size and mass.

Bale	Material	Length m	Diameter m	Mass kg
1	Prickly-ash	2.14	1.22	409
2	Prickly-ash	2.14	1.37	654
3	Mix	2.14	1.53	1230
4	Mix	2.14	1.53	1062
5	Mix	2.14	1.53	1035
6	Prickly-ash	2.14	1.83	1053
7	Prickly-ash	2.14	1.40	690
8	Red pine	2.14	1.53	1516
9	Red pine	2.14	1.57	1407

Table 5-2. Factors affecting bale density.

Material	Bale	Feed orien-tation	Belt tension cylinder pressure x 100 kPa	Diameter m	Density kg/m^3	OD density kg/m^3
Prickly-ash	1	(a)	48	1.22	142	119
Prickly-ash	2	(a)	83	1.37	182	151
Prickly-ash	6	(a)	100-140	1.83	164	136
Prickly-ash	7	(b)	120-140	1.40	184	153
Mix	3	(a)	83	1.53	275	145
Mix	5	(c)	83	1.53	231	121
Mix	4	(b)	83-100	1.53	237	124
Red pine	9	(c)	83-120	1.57	296	---
Red pine	8	(a)	69	1.53	338	---

(a) Feed parallel to bale rotation
(b) Feed perpendicular to bale rotation
(c) Feed at angle to bale rotation

so the maximum density which could ever be achieved is limited by the density of the wood. Wood density was not measured, but is affected greatly by moisture content. Green density of red pine (*Pinus resinosa* Ait.) wood is given in the Textbook of Wood Technology (Panshin, 1980) as 784 kg/m^3 (49 lb/ft^3). Green density of quaking aspen (*Populus tremuloides*), a moderately light hardwood (which should serve as a guideline for the prickly-ash, which is not given) is 688 kg/m^3 (43 lb/ft^3). The degree of compaction achieved by the machine is affected by the basic machine design, belt tension, and material feed orientation. These factors will be discussed in Section 6.3.

Examination of Table 5-2 shows a tendency toward higher density bales for high belt tension and large diameter bales. The larger diameter bales probably have greater bulk densities due to having a lower proportion of low bulk density core material, which is used to start the bale without the belts tight. The greater bulk density for larger diameter bales may also be due to compression of the material as it is fed into the baler and drawn under the heavy, rotating bale. As the bale becomes larger it also becomes heavier and the bale compresses the new material.

Bale number 6 is the largest diameter bale formed. The belts were loosened late in the baling process of this bale for machine repairs. When the belts were loosened the bale expanded noticeably. This explains the low density and large diameter.

A difference in bulk density was observed for bales of different materials; however, this is believed to be due to moisture content more than due to the material dry wood density. An estimated oven-dry bulk density is also shown in Table 5-2.

5.3 Material Orientation

A pick-up and feed system would need to be designed in order to build a baler to efficiently bale specific forest materials. To provide information for design of a feed mechanism, the effects of material orientation on the baler were observed. Initially, material was fed into the baler with an orientation such that the main stems would lie parallel and would not have to wrap around the bale (Figure 5-2). The parallel orientation was achieved by cutting all pieces shorter than or only slightly longer than the bale itself. Material fed in this fashion seemed to bale quite nicely and was always contained very well by the baler belts. The only problem was that the material had to be cut and oriented on the feed conveyors.

Another feed orientation tried was to feed full length pieces (up to 10 m) lengthwise into the baler in such a manner that they would wrap around the baler (Figure 5-3). This feed orientation worked surprisingly well and resulted in a satisfactory bale. The only problem encountered was that on several occasions stems protruded between the belts (Figure 5-4) and either broke off or continued to ride on out through the back of the baler where they fell on the ground. Although the machine never completely jammed, a large stem, protruding through the belts, might not break and might get caught on one of the belt rollers.

A third orientation which was tried, was to feed the uncut pieces of various lengths at a slight angle of about 15 to 20 degrees to the in-feed. This orientation was intended to prevent pieces from protruding between the belts on the baler and yet allow baling of pieces not cut to the 2.5 m length. Only occasionally, a stem protruded between

(a)

(b)

Figure 5-2. Material orientation parallel to bale rotation.

(a)

(b)

Figure 5-3. Material orientation perpendicular to bale rotation.

(c)

(d)

Figure 5-3. (Cont'd)

(a)

(b)

Figure 5-4. Stem protruding between baler belts.

the belts with this feed orientation. Larger pieces, more likely to cause jamming, seemed to slip by the rollers instead of catching and breaking off. This was probably due to their protruding at an angle and not protruding as far as they did when fed straight in.

For two bales, the feed orientation was fairly random. In this case, the material was placed on the conveyors in the most convenient fashion. The random orientation produced results essentially the same as the angled orientation, both from the standpoint of how material appeared to be feeding into the baler and how well the baler seemed to handle the material.

Contrary to expectations, a material orientation did not seem to have noticeable effects on bale density. Highest density was expected for bales with all material fed parallel, either parallel to the axis of bale rotation or lengthwise parallel to wrap around the bale. Better space utilization near the ends of the bale occurs when material is wrapped around the bale. A tighter core is expected when material is baled parallel to the bale rotation. The third orientation tried, feeding material at a slight angle, was expected to result in material crossing at odd angles resulting in more void space. Any differences were not noticeable. More experiments would need to be performed to determine actual differences in density due to feed orientation. In the experiments done, bales seemed to form equally well, and equally tight with any of the orientations tried.

5.4 Bale Heating

All of the bales were observed for indications of internal heating. Thermocouples had been prepared as discussed in Section 4.4, but difficulties with installing these in the bales prevented this from being done for all but one bale. The bale, of prickly-ash stems, which was wired with thermocouples showed no external signs of heating and exhibited no increase in temperature within any portion of the bale.

Three of the bales--those made from wet, mixed materials obtained from MSU grounds--became quite warm. The bales were wet in both the sense of having green foliage and high wood moisture content and also being baled in a light rain. All three of the bales heated in a similar manner; steam and odors became noticeable 7 days after the bales were formed. The temperature was measured in the outer 200 mm of the bales using a dial type thermometer. Temperatures in this region were found to be as high as 60°C. The temperature did not remain this high for long and dropped to below 37°C within 14 days of when the bales were formed.

The remaining bales did not show signs of heating. There were no external signs of heating, and no measurable temperature increases in the outer 200 mm of the bales.

5.5 Energy Requirements

Energy input measurements were done on three of the bales. Due to mechanical problems with the printout on the RAMP data logger, data collection was incomplete for one bale. Power data were not analyzed for this bale, but were analyzed for the other two baling experiments as discussed in Section 4.6 and Appendices I and II. Average torque and power were computed by only including data which indicated the machine was operating. Total operating time was also found. Average torque, power and total operating time are actually estimates made by sampling torque and shaft speed every 7.5 seconds, the fastest sampling rate possible with the available equipment.

Peak torque and power were also found. Peak torque and power occurred at the same time and can be easily identified on the curves in Appendix I. These peaks seem to correspond to loads caused by stems protruding between the belts and catching on the belt sheaves. The peak torque for bale number 6 nearly stalled the machine. These peak torque and power values will be useful in the design of future prototype balers.

Total energy required is given in units of kW-hr/t. Energy required was computed from the average power input to the baler drive shaft, total operating time and mass of material processed.

Results of the energy requirement measurements are given in Table 5-3. These measurements were done on bales numbered 2 and 6 in Table 5-1.

Table 5-3. Energy requirements

Bale	Average torque N-m	Peak torque N-m	Average RPM	Average power kW	Peak power kW	Total operating time Hrs	Bale mass kg	Energy required kW-hr/t
2	34.1	110.	375	1.32	3.13	0.41	654	0.83
6	41.4	116.	352	1.52	3.13	0.82	1053	1.18

Torque, shaft speed and power were plotted over the duration of the baling process. These plots have been included in Appendix I as Figures A-1 and A-2. Plots were condensed by deleting any delay time occurring over the total time of the baling experiment.

Both of the two bales for which the power was measured were formed with material orientation parallel to the axis of bale rotation. When bales were made with feed orientation not parallel to the axis of bale rotation (see Section 5.3), the baler was very obviously working much harder. Quantitative data were not taken because the recording equipment was not suited for use in the woods. But, the hydraulic system pressure, at the pump, was noted as being nearly twice as high, causing noticeably lower rotational speeds with feed orientation not parallel to bale rotation as with orientation parallel to bale rotation. This indicates greater torque, which is expected when stems must bend or break to conform with the bale being formed.

6.0 SUMMARY AND CONCLUSIONS

Handling forest biomass or forest residue in large round bales using machinery similar in principle to the large, round-bale hay balers which are commonly used in North American agriculture is a new and different concept. Development of hay handling equipment has led to the extensive use of the large round hay bales. Popularity of the round bale is due largely to the capability of one person easily handling large volumes of hay. Popularity is also contributed to by the simplicity and energy efficiency of the balers used for making the round bales. These same factors contribute to the potential value of the round-bale machinery concept for use in forestry.

Nine bales were formed using green forest biomass; four were of hardwood brush; two of red pine tops and limbs; and three of hardwood and conifer, mixed in the form of small trees and small and large branches and tops. The bales were 2.44 m long and varied from 1.22 m to 1.83 m in diameter. The mass of the bales was between 409 and 1516 kg and bulk densities ranged from 144 to 338 kg/m^3.

The machine used to form the bales was a modified, oversized version of a Vermeer model 605F baler. The machine handled all of the material with surprising ease. At first, material was fed only parallel to the axis of bale rotation (parallel to the belt sheave-bearing shafts), but later longer material was fed into the machine oriented up to 90° to the bale rotation. Material up to 10 mm in diameter would wrap, bend, and break to conform to the bale being formed. The belts on the baler seemed to adequately contain the material and only occasionally a limb or other piece of material would protrude from the bale through the gaps between the belts. This occurrence could be reduced by using fewer, wider belts. Also, fewer belts would reduce the total amount of belt edges, which were the most susceptible part of the belt arrangement to damage. Possibly one full-width belt would be best to use since it should contain all the material and there would be no gaps for material to protrude through.

New bales were difficult to start at times. An adequate core had to be formed before the bale would begin to turn and the machine would self-feed. For the baler to start, the core had to have a diameter larger than the throat opening of the baler. If positively-driven belts were used, bales might start more easily by enabling the slackened belts to keep turning, thus encouraging the core to begin turning inside the baler. Once the bale core was formed the baling process went smoothly and was limited only by the rate at which material could be hand-fed to the baler.

Bales formed had good integrity (Figures 6-1 and 6-2) and would have been easy to handle with the right equipment. Even after four months of outside storage, the bales appeared to have this integrity (although each time a bale is handled it loses some integrity). It appears that if bales are wrapped with sufficient twine they could be handled several times (perhaps a dozen) over a period of several months. Equipment is commercially available for handling large round hay bales. This equipment is not sophisticated or complex and should in some instances work in forestry applications.

Figure 6-1. Bale number 3, 1240 kg.

Figure 6-2. Bales number 8 and 9, 1516 kg and 1407 kg.

Internal heating of the bales was anticipated to be a problem but no serious problem was encountered with any of the nine bales made. All bales were monitored (one with thermocouples) and the highest temperature observed was 60°C. In practice, care would have to be exercised and further tests would be necessary to determine if spontaneous combustion is an actual problem.

Baling forest biomass in some form is the most obvious alternative to in-the-woods chipping of these materials. The trend in agricultural hay handling has been toward large round bales for many of the same reasons which should be important in the choice of handling systems in the forest industries. Using a machine similar to a large round-bale agricultural baler to bale forest biomass appears to have potential.

7.0 RECOMMENDATIONS FOR FURTHER RESEARCH

An economic analysis of baling forest biomass with a large round-bale machine has not been done. The comparatively low cost equipment and low energy costs should make round bales competitive with both in-the-woods chipping and conventional shaped bales. The results of this investigation and an appropriate economic analysis would verify or disprove the competitive position and would provide the necessary understanding for decision making on further development of the concept. For this reason, an economic analysis of this concept should be done. This requires examination of the entire system, woods to conversion site. Important is the entire system cost--the cost of getting the biomass to the converted form (most likely energy in the form of steam or electricity).

Whole bale chipping or shredding should be explored. It is hypothesized that a system of in-woods baling of forest materials and processing the bales at the point of use would be more economical than in-the-woods chipping. Potential advantages of whole-bale processing include increased machine efficiency and reduced equipment investment. Schemes suggested for processing the bales include chipping, chopping or shredding the bales with machines similar to the agricultural tub grinders, or burning or gasifying complete bales. These ideas should be investigated in both the systems economics context and also through hardware development

For efficient use of the baling concept in forestry, bale handling schemes need to be developed. This includes any forwarding, temporary storage, loading, and transporting. Bale handling could influence the design of a baling machine. For example, if bale orientation, after being deposited by the baling machine, affects later handling (for loading or forwarding), orientation should be considered during the design of a baling machine. Material baled in large round bales would probably dry in the baled form if left in the woods. Handling schemes to take advantage of this would save the cost of transporting the water in the green material and might also increase the fuel value of the material by reducing the moisture content prior to utilization. However, the following must be determined: 1) how much and how fast the baled material will dry; 2) how bale properties, such as bale integrity and durability are affected by outdoor storage for this purpose; and 3) how the fuel value is affected by this storage.

Transportation of round bales is less efficient than transportation of rectangular bales of similar density. This is because of the inefficient space utilization of stacking cylindrical bales. Round bales could be reshaped, by compressing, into rectangular bales and stacking efficiency would be improved. To justify a process such as reshaping round bales, gains in transportation efficiency would need to exceed the cost of the process. Intermediate processing such as outdoor drying or bale reshaping need to be explored.

The actual baling process is well developed and works very well. To incorporate this process into forestry practices two refinements must be made. An effective material feeding system should be developed. In principle, the round baling machine is self-feeding. However, the material must be guided into the throat of the baler and the material must be fed aggressively into the baler at the beginning of each bale.

These do not appear to be major problems, but they must be solved. Use of spiked or cleated feed drums or conveyors and positively driven baling belts should be explored. The second recommended refinement is in the baler belts. In personal discussion, a Vermeer representative pointed out that the belts used in Vermeer balers have a tendency to shrink with use. This contrasts with most people's expectations, particularly when abusing the machine as suggested by baling forest biomass. After the nine bales were made the belts had not stretched or shrank. However, development of an improved belt system is necessary. Positively-driven belts and full-width belts have been mentioned. These concepts need to be explored further.

Sketches of two mobile baler concepts which could be developed to a prototype stage are shown in Figures 7-1 and 7-2. Each of these machines would bale material in bales similar to those made in this research. These machines would utilize the principles of the baler used for this research with refinements recommended in this paper.

Figure 7-1. Tractor-pulled machine to bale forest biomass.

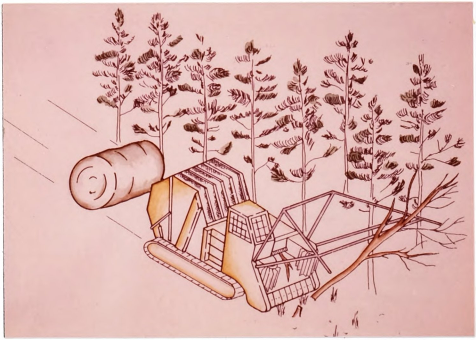

Figure 7-2. Self-propelled machine to bale forest biomass.

APPENDICES

APPENDIX I

TORQUE MEASUREMENT

Power input to the baler was measured by determining the torque and shaft speed of the hydraulic motor. The torque was determined indirectly by measuring the pressure on both the inlet and outlet of the motor. The following model was used to find the torque from the pressure.

The theoretical torque produced by a hydraulic motor is related to the pressure drop across the motor by

$$T_{TH} = \Delta P \times \frac{D}{2\pi}$$

where:

T_{TH} = theoretical torque

ΔP = pressure drop

D = displacement

with appropriate physical units.

The actual torque produced is equal to the theoretical torque less the frictional torque. Frictional torque is the torque, internal to the motor, which results in a pressure drop across the motor when run with no load. For the motor used on the baler, frictional torque was measured by recording the pressure drop for several shaft speeds while running the motor with no load. A linear regression was used to find the following equation for frictional torque for the particular motor used.

$$T_F = [(0.5386)S - 30.779] \frac{D}{2\pi}$$

where:

T_F = frictional torque

S = shaft speed in RPM

Torque delivered by the motor, T , to the baler is given by

$$T_A = T_{TH} - T_F$$

$$T_A = (\Delta P \times \frac{D}{2\pi}) - [(0.5386)S - 30.779]\frac{D}{2\pi}$$

The motor used had a displacement of 10.3 in^3, ΔP was measured in pounds per square inch, and S in RPM. This gives T_A in units of pound-inches. This is convertible to SI units of N-m using a conversion factor of 0.1129848 N-m/pound-inch.

The computer program Torque, listed in Appendix II, used this torque model to calculate motor torque for each sample data point. Motor power was calculated from the torque and speed of the motor shaft.

The program Average uses subroutine Smooth to delete any time for which the torque was zero or shaft speed was less than 90 RPM. The program then calculates average torque, shaft speed, and the total operating time. Average then graphs the torque and shaft speed for the duration of the bale-forming process with any delay time deleted. These graphs are presented in Figures A-1 and A-2. These plots indicate a tendency for torque to increase through the bale-forming process; this is probably a result of increasing end force on the rotating bale. Large peaks in torque seem to correspond to drops in shaft speed, indicating an under-powered system. The largest peaks correspond to near stalls which occurred in the baling experiments.

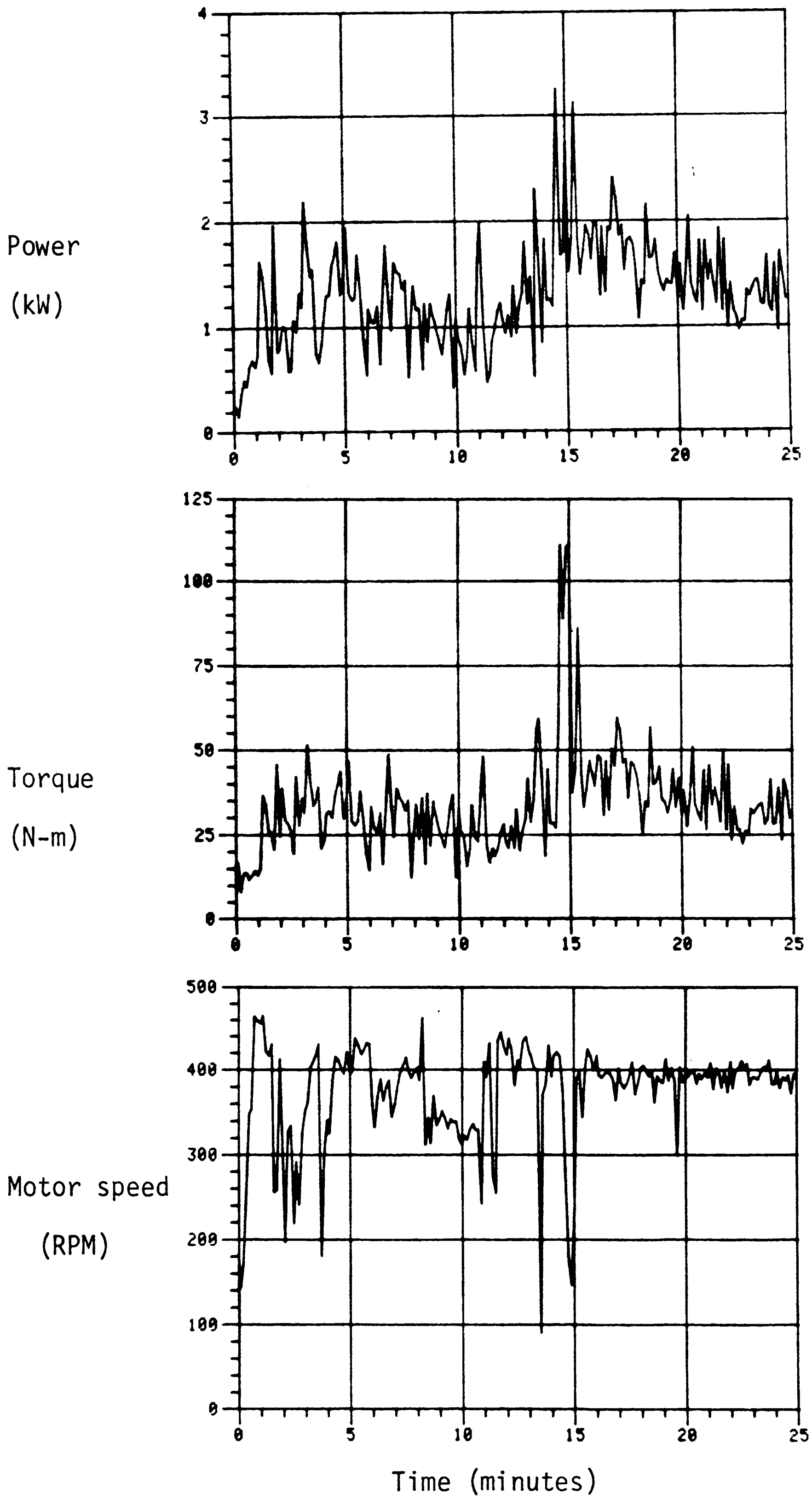

Figure A-1. Power input for bale 2.

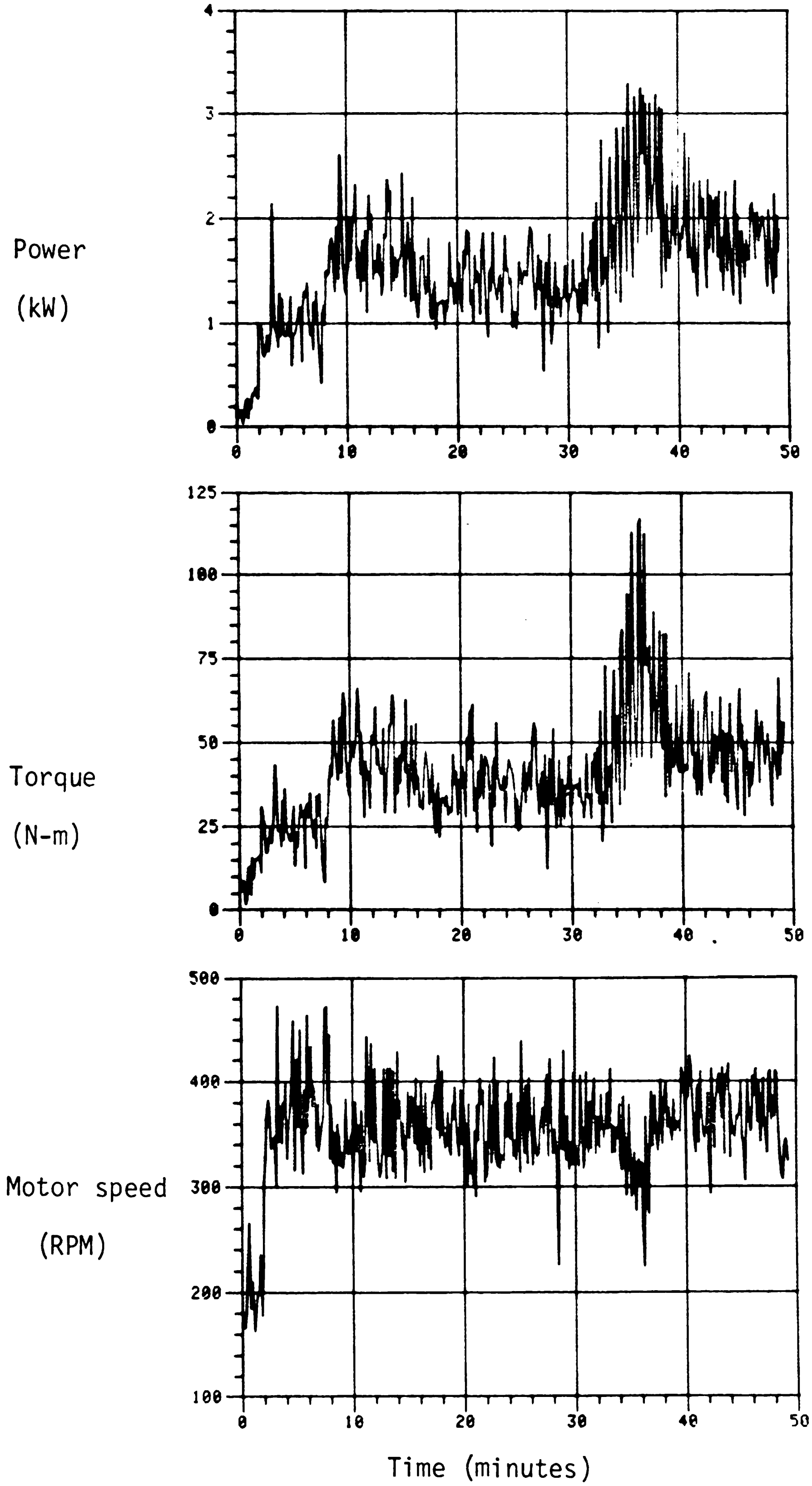

Figure A-2. Power input for bale 6

APPENDIX II

```
C     PROGRAM TO CALCULATE THE INPUT TORQUE, RPM, POWER, AND
C       PRESSURE FOR THE BALER
C
        REAL MV1,MV2,TORQ,TTH,HP
        INTEGER HR,MIN,SEC,MV0
        CALL SRCH$$(1,'TEMP6',5,11,ITYPE1,IERR2)
        CALL SRCH$$(2,'OUTB6',5,10,ITYPE2,IERR2)
        DISPL=10.3
   10   READ(15,*)HR,MIN,SEC,MV0,MV1,MV2
        RPM=MV0/10
        P1=(MV1-0.08)*154.0
        P2=(MV2-1.86)*310.0
        PDROP=P1-P2
        TTH=PDROP*DISPL/6.283
        TF=(RPM*0.5386-30.779)*DISPL/6.283
C     TF IS THE TORQUE TO OVERCOME THE INTERNAL FRICTION
C       OF THE MOTOR
        TORQ=TTH-TF
        HP=TORQ*RPM/63025.0
        WRITE(14,100)HR,MIN,SEC,RPM,PDROP,TTH,TORQ,HP
        IF(HR.LT.99)GO TO 10
        ENDFILE 14
        ENDFILE 15
  100   FORMAT(2X,I2,3X,I2,3X,I2,4X,I4,2X,F7.2,2X,F7.2,2X,
     *  F7.2,4X,F5.2)
   60   STOP
        END
```

```
CC      PROGRAM AVERAGE---JF 10/27/80
C         THIS PROGRAM USES A SUBROUTINE TO ELIMINATE ANY
C         * DELAY TIME IN THE BALER TESTS IT  THEN
CC      * CALCULATES THE AVERAGE TORQUE, SPEED, AND POWER  .
C         INPUT TO THE BALER
C       IT USES THE OUTPUT OF THE PROGRAM TORQUE.
        REAL PDROP(1000),TTH(1000),TORQ(1000),HP(1000),
       *,TIME(1000)RPMRL(1000)
        INTEGER RPM(1000),HR,MIN,SEC
        CALL SRCH$$(1,'OUTB6',6,11,ITYPE1,IERR2)
        HPTOT=0.0
        RTOT=0.0
        TTHTOT=0.0
        TTOT=0.0
        I=1
     10 READ(15,*)HR,MIN,SEC,RPM(I),PDROP(I),TTH(I),TORQ(I),
       * HP(I)
        I=I+1
        IF(HR.LT.99)GO TO 10
        CALL SMOOTH(I,RPM,TORQ,HP,TTH)
        I=I-1
        TSEC=I*7.5
        THR=TSEC/3600.0
        DO 200 J=1,I
        TORQ(J)=TORQ(J)*0.1129848
        TTH(J)=TTH(J)*0.1129848
        HP(J)=HP(J)*0.7456999
        TIME(J)=J*7.5/60.0
        RPMRL(J)=FLOAT(RPM(J))
        TTOT=TORQ(J)+TTOT
        TTHTOT=TTH(J)+TTHTOT
        RTOT=RPM(J)+RTOT
    200 HPTOT=HP(J)+HPTOT
        AVTOR=TTOT/FLOAT(I)
        AVTTH=TTHTOT/FLOAT(I)
        AVHP=HPTOT/FLOAT(I)
        AVRPM=RTOT/FLOAT(I)
        WRITE(1,100)AVTOR,AVTTH,AVHP,AVRPM,THR
        PAUSE
        CALL PLOTME(TIME,RPMRL,I)
        CALL PLOTME(TIME,TTH,I)
        CALL PLOTME(TIME,TORQ,I)
        CALL PLOTME(TIME,HP,I)
    100 FORMAT(6X,F10.5,3X,F10.5,3X,F10.5,3X,F10.5,3X,F10.5)
        ENDFILE 15
        STOP
        END
```

```
      SUBROUTINE SMOOTH(I,RPM,TORQ,HP,TTH)
      REAL TORQ(I),HP(I),TTH(I)
      INTEGER RPM(I)
      TMIN=0.0
      HPMIN=0.0
      RPMMIN=0.00
      K=0
      DO 200 J=1,I
      IF(TORQ(J).LE.TMIN)GO TO 200
      IF(HP(J).LE.HPMIN)GO TO 200
      IF(RPM(J).LE.RPMMIN)GO TO 200
      K=K+1
      TORQ(K)=TORQ(J)
      RPM(K)=RPM(J)
      HP(K)=HP(J)
      TTH(K)=TTH(J)
  200 CONTINUE
      I=K
      RETURN
      END
```

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