Assessment of Pelletized Biofuels

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April 2000

Executive Summary

Increasing concerns about climate change mitigation and rising oil prices are creating unprecedented interest in the development of economical and convenient renewable energy fuels. Recent advances in biomass feedstock development and conversion technologies have created new opportunities for using agricultural land as a means of producing these renewable fuels in larger quantities than relying on wood and agricultural residues alone. Dedicated agricultural feedstocks such as switchgrass and short rotation willow can abate greenhouse gas emissions by increasing carbon storage in the landscape, as well as by displacing fossil fuels in combustion applications. This project examined the potential of using these materials and other biomass residues as new feedstocks for the pellet industry.

Switchgrass has been identified as a promising pelleting feedstock as it facilitates higher throughput rates and requires less energy for crop drying than wood. Although switchgrass is a higher cost feedstock to procure than wood residues, it could become an economical biofuel. The overall energy balance of switchgrass is 14.5:1, which includes energy for switchgrass production, transportation to the conversion facility, preprocessing, pelleting and marketing.

As a herbaceous pelleting feedstock switchgrass behaves similarly to alfalfa, enabling research on alfalfa pelleting to be applied to switchgrass pelleting. Based on a literature review and pilot laboratory studies, the main factors which were identified to contribute to the successful pelleting of switchgrass were the length of chop, the applictaion of high temperature steam and the use of a die with a suitable length/diameter (L/D) ratio. Strong research support and significant production experience in the alfalfa pellet industry in Canada provides a solid foundation for switchgrass to be developed as a pellet feedstock for bioenergy applications. There also appears to be significant scope for further advances in technologies to increase pellet durability and productivity.

Combustion trials conducted by the CANMET laboratories using switchgrass in the Del-Point close coupled gasifier indicated that switchgrass has a similar combustion efficiency (82-84%) to wood (84-86%). Switchgrass also has a fuel energy content that is 96% of the energy of wood pellets on a per tonne basis. Some adjustment of the cleaner grate settings on the Del-Point close coupled gasifier stove is required to burn switchgrass more efficiently, as clinker formation was observed when high feed rates of switchgrass were used in the combustion appliance.

High yielding closed loop biofuels harbor significant potential for assisting Canada to meet its climate change commitment, while stimulating rural development and export market opportunities. Further advances in biomass

energy feedstock production, pelleting technologies and combustion appliances to burn these materials will create strong economic momentum for switchgrass pellets to become a leading low cost greenhouse gas abatement strategy from the agricultural sector.

List of Symbols

J joule
MJ Megajoule (10^6 joules)
GJ Gigajoule (10^9 joule)
KWh kilowatthours (3.6 MJ)
Hp horsepower
amp (A) ampere
^{0}C degrees Celsius
h hour
g grams
kg kilograms (10^3 grams)
Mg Megagrams (10^6 grams)
t metric tonne (10^6 grams)
lbs pounds (0.454 kg)
l litre
m meter
mm millimeter (10^{-3} meters)
cm centimeter (10^{-2} meters)
in. (") inches (2.54×10^{-2} meters)
ha hectare (10^4 square meters)

I. Introduction

International concern about rising anthropogenic greenhouse gas emissions has stimulated interest in the development of new technologies to mitigate climate change. Fossil fuel emissions from space and process heating are one of the major sources of greenhouse gas emissions, particularly in northern climates. The development of biofuel heating systems could play a major role in helping countries such as Canada meet greenhouse gas reduction targets. New efforts are required to make these fuels economical and user friendly, if they are to be widely accepted by the public.

One strategy to increase the accessibility of biomass heating fuels is densification of the material. There are many advantages of densified fuel pellets:

- The amount of dust produced is minimized
- The fuel is free flowing, which facilitates material handling and rate of flow control
- The energy density is increased, easing storage and transportation
- Uniformity and stability permit more efficient combustion control

Improvements have recently been made in the combustion efficiency of pellet stoves due to the advent of new close coupled gasifier technology. These new stoves (www.pelletstove.com) have combustion efficiency rates of over 80% (SERBEP, 1998) and can use moderate to high ash biomass (such as bark, agricultural residues, and herbaceous and woody crops) as fuel. The current project examines a range of feedstocks to assess their potential for efficient pelletization and burning, with the goal of providing a low cost biofuel for residential and commercial space heat applications.

This project represents a turning point towards developing a larger biofuel pellet research and development program in Canada. This report reviews the current state of pelleting technologies, and presents results from preliminary research to improve this technology. The economic and energetic aspects of fuel pelleting are also assessed. Promising agricultural and forest residue biomass resources are evaluated for their suitability for pelleting and fuel quality. Finally, a review of the combustion performance of switchgrass in the Dell-Point close-coupled gasifier pellet stove is also presented.

II. Overview of the Pelleting Process

The process of pellet making was developed for the livestock feed industry and is outlined in Figure 1. The biomass is chopped to a length of fibre that ensures the pellet can be properly formed. It is then continuously fed into the pelleting cavity, where it is directed equally on either side of the edges, formed by the rollers and the inside face of the die. The rollers turn as the die rotates, forcing the material through the die holes by the extreme pressure caused by the wedging action. As the pellets are extruded, adjustable knives cut them to the desired length. The goal is to produce a pellet with a good hardness and a minimum production of fines (material broken off in the pelleting and handling process).

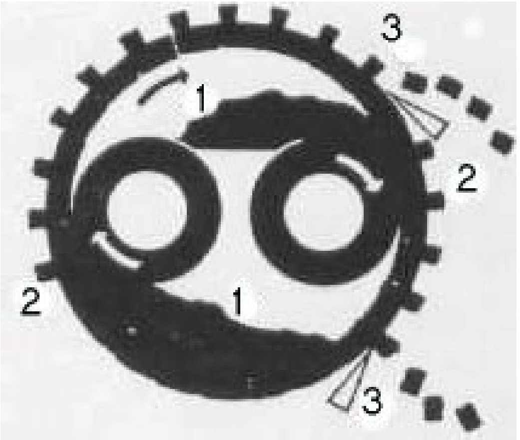


Figure 1. Diagram of Pelleting Process: (1) Loose material is fed into pelleting cavity. (2) Rotation of die and roller pressure forces material through die, compressing it into pellet. (3) Adjustable knives cut pellets to desired lengths

A number of properties are commonly known to affect the success of pelleting, including:

- moisture content of the material,
- density of the material,
- particle size of the material,
- fibre strength of the material,
- lubricating characteristics of the material

- natural binders

Pelleting productivity is measured by manufacturers in terms of production yield, in units of pounds or kg per Hp. In the case of sawdust residues, this value varies from about 15-35 lbs per Hp, depending on the source of the wood residue; hardwoods are in the low range and softwoods are in the high range (Drisdelle, 1999). In theory, the more pliable the fibre, the easier it is to exude through the roller die. Other factors influencing productive yields include steam and residency time (cooking or conditioning) in order to create a more pliable fibre. The overall goal is to create a more fluid pelleting process, where a lower friction co-efficient is created between the die extrusion surface and the fibre. The pellet is bound together by the lignin exuded from the feedstock. This process results when fibre passes through the extrusion holes, heating up the die and creating elevating temperatures (75-85 ^{o}C). Lignin within the material starts to flow from the fibre cell walls and has the effect of binding with other fibres during extrusion. During the process some moisture is driven off as steam. The resulting product is a uniform flowing material with a bulk density several times higher than that of the starting raw material.

III. Overview of the Pelleting Industry

Canada has both a wood pellet and alfalfa pellet industry. The alfalfa dehydration (alfalfa dehy) industry is mainly found in the productive agricultural regions of the western provinces, with Saskatchewan and Alberta holding 61% and 33% of the production, respectively. Only 4% of production is in Eastern Canada while another 2% is found in Manitoba and British Columbia (Canadian Dehydrators Association, 2000). The more recently developed wood pellet industry has evolved near industrial wood processors mainly in British Columbia, Ontario and Quebec. Some alfalfa pellet mills (mainly in Eastern Canada) are also producing wood pellets during the off-season if they can locate local wood fibre resources. In western Canada, most alfalfa pellet mills have a main enterprise of harvesting freshly harvested green chopped alfalfa and consider processing of stored surplus sun cured alfalfa as a secondary enterprise. Years with low moisture result in reduced alfalfa production and only a green chopped alfalfa dehy product is produced. There may be potential for the large alfalfa dehy producers in western Canada to use alternative crop residues or dedicated drought tolerant fibre crops such as switchgrass to enable year round utilization of these facilities.

In general, large producers of both alfalfa and wood pellets tend to be more profitable then smaller producers. The alfalfa dehy industry in Eastern Canada tends to be less competitive than the larger producers of western Canada, which have total pellet mill machine capacities of 1000-1250 hp (vs typically 150-300 hp units in Eastern Canada). The more efficient wood pellet producers are often integrated with a wood processing industry and have a minimum of 600 hp of installed capacity.

The alfalfa dehy industry is primarily oriented for export to Asia (particularly Japan). Production of alfalfa pellets peaked in 1994-95 at 570,000 tonnes per year of pellets and 301,000 tonnes of cubes (Canadian Dehydrator’s Association, 2000). In 1998-99, production had dropped to 348,000 tonnes of pellets and 201,000 tonnes of cubes and has remained rather depressed in recent years, partially because the overall consumption of fuel pellets in North America is stagnant. However, production is currently increasing mainly as a result of exports for power generation into Northern Europe. Approximately 100,000 tonnes of wood pellets are expected to be exported into Northern Europe from Canada in the year 2000. Rising fossil fuel prices and increasing concerns about greenhouse gas emissions should create new opportunities for both domestic and foreign markets for fuel pellets. However, a major problem with expansion of the industry is a shortage of fibre source for pelleting. Fortunately, there appears to be significant potential for utilization of agri-fibre fuels in the future to help meet this demand.

IV. Literature review

As Canada is the one of the largest producers of alfalfa pellets in the world, there has been significant effort to improve the physical quality of pellets (fines reduction) and increase throughput to make the pelleting process more economical. The main factors that have been studied to improve the pelleting process are die geometry, steam conditioning temperature, moisture optimization, length of the grind, and binding agents. A review of these factors and the basics of the binding process are described below.

Binding Process:

A review of the binding process and characteristics of plant tissues to form pellets has been recently made (Tabil et al, 1997; Sokhansanj et al, 1999). The mechanism of binding is made possible by natural cohesion between particles and the mechanical load that forces inter-particle contact and can include:

- Solid bridges which develop at elevated high temperatures and pressures from chemical reaction, crystallization of dissolved substances, hardening of binder, and solidification of melted substances

- Capillary pressure and interfacial forces which develop in the presence of water or other liquids
- Viscous binders and thin adsorption layers resulting in immobile liquid bridges
- Inter-particle attraction forces caused by electrostatic or magnetic forces
- Mechanical interlocking occurring as a result of fibers and flattened or bulky particles interlocking or folding about each other

Length of Chop

Most pellet mills are producing a 6.4 mm (¼ inch) pellet in North America. A number of studies have examined the impact of the length of chop on the pellet process. Overall it has been realized that fine grinding produces denser pellets and increases the throughput capacity of machines as the material passes through the machine more easily (Dobie 1959). Fine chopped material also provides a greater surface area for moisture addition during steam treatment. As well, fine chopping creates materials that have smaller fissures that can lead to breakage. Most commercial alfalfa pellet mills are using hammermills with a 7/64 (2.8 mm) inch screen to produce a suitable length of chop. It is often recommended that the chop size be one half the diameter of the pellet being produced. In alfalfa production, Hill and Pulkinen (1988) reported a 15% improvement in pellet durability from using a 2.8 mm hammermill screen compared to a 6.4 mm screen. Alternatively, Tabil and Sokhansanj (1997) found no significant difference in pellet durability when using a 2.4 or 3.2 mm screen, but attributed this to the relatively small difference tested and experimental variability. It is likely that fibre sources of low forage quality will require more grinding than high quality alfalfa to maintain pellet quality. Sokhansanj et al.

(1999) found grind from high quality chop had greater compressibility and produced a pellet with a higher tensile strength relative to lower quality chops. Overall, as fine grinding can be energy intensive, a balance needs to be struck between particle size reduction, pellet durability and production rates.

In the alfalfa dehydration industry the forage is primarily fresh chopped in the field using a forage harvester, generally into .4-5cm lengths, and subsequently hammermilled using a 2.8 mm screen size. Wood pellet processing plants use wood residues and also have two chopping operations, a coarse grinder and a hammermill, for final sizing.

Die Configuration

In North America, most wood and alfalfa pellets are 6.4 mm (¼ inch) long. In northern Europe, the most common sizes are, in decreasing order, 7-8mm, 9-10 mm and 6-7mm (Vinterback et al. 1998). In trials on commercial alfalfa mills in western Canada, Hill and Pulkinen (1988) found bulk density, energy consumption and pellet durability to decrease as the extrusion diameter increased from ¼ to ½ inch, using dies of 8 L/D. When the experiment was repeated using a ¼ inch and ½ die of L/D of 10, the durability and bulk density of pellets improved even further. In a survey of alfalfa pellet producers this same trend was observed; increases in the die L/D from 5 to 9 increased pellet durability from 50% to approximately 80%.

Tabil and Sokhansanj (1997) also found dies with higher L/D ratios produced more durable pellets, particularly on the larger diameter pellets. They observed that a 6.2 mm die could process alfalfa grind of 7.5-9.0 % moisture, while a 7.8 mm die could tolerate a moisture range up to 12%. Since alfalfa grind particles can tend be gummy when moist and hot, smaller diameter dies offer more resistance to the grind particles. For alfalfa dehy production, Hill and Pulkinen (1988) recommended an L/D ratio of 10 to optimize pellet durability. It was also found that smaller size dies, when combined with fibres that are relatively difficult to pelletize, require slower RPM. In a laboratory pellet study, higher speeds (501-565 rpm) were found to plug 6.1 mm dies, but low quality alfalfa was successfully pelleted at rotation speeds of 250-316 rpm (2.8 and 2.6 m/s respectively). Heinemans (1991) recommended a low peripheral die speed of 4 to 5 m/s for low density products that require a large volume of air to be expelled during compaction. Rapid die rotation tends to overload the pellet motor due to the high fiber content of the forage. Additionally, as die speeds increase, particles flowing through the die are subject to more centrifugal force.

Modest increases in pellet size could likely be tolerated on most pellet stoves without changing grate sizing. Thus, the potential for increasing pellet size in North America may warrant investigation if suitable L/D dies can be used in conjunction with the bigger size pellet produced. This may reduce costs by reducing grinding size requirements.

Conditioning Temperature

The alfalfa dehy industry commonly aids the pelleting process through application of a constant quality steam at a predetermined pressure that supplies additional heat and moisture. This steam can help release and activate natural binders and lubricants in biomass sources. In the case of alfalfa it is now well documented that high temperature steam additions enhances pellet durability, and reduces energy consumption in the pelleting process. Tabil and Sokhansanj (1996) found that alfalfa pellet durability increased linearly as conditioning temperature was raised from 65 to 95° C. This pretreatment also influenced the final temperature at which the pellet left the ring role press. Hill and Pulikinen (1988) found that pellet durability was improved by 30-35 % when the conditioning temperature increased from 55 to 85° C. Pellet power consumption also declined by nearly 30% through increasing pellet temperature from 65 to 95° C. One of the alfalfa dehy producers currently producing in western Canada is currently using 110 ° C for steam conditioning.

Shen (1992) developed a patented process to bind biomass fibres using very high temperature steam, a set residency time and atmospheric pressure. The technology enables the creation of a binderless board from the conversion of some of the hemicellulose into a thermoset waterproof adhesive. The basis of the invention is the exposure of lignocellulosic material (containing at least 10% hemicellulose to high-pressure steam in the range of 160-260° C. This technology may help address pellet durability concerns, particularly for long distance shipping when pellets are exposed to moisture. There is room for further investigation of higher temperature steam treatments, acid treatments, and increased residency time as a means to improve durability and production rates of pelleted biofuels. A number of patents have been identified which relate to the potential of these treatments (Appendix 2).

Binding Agents

The use of binding agents has been investigated as a means to reduce the dust and fines generated during transport and handling of fuel pellets. Tabil et al. (1997) tested five binding agents on three grades of alfalfa chop, and found that binding agents only improved the durability of pellets from the poorest quality chop. An inclusion rate of either 0.5% of hydrated lime or pea starch was found to be sufficient to improve pellet quality. The hydrated lime used contained 94.5% available calcium hydroxide, a chemical binder that hydrates when added to water. Pea starch is a product of the dry processing of yellow peas and contains 82.1 % starch and 5.3% protein. It is not clear whether these materials are currently being used commercially by the pellet fuel industry. The cost of including these materials at inclusion rates of 0.5% was $1.30 and $3.40 per tonne for the calcium hydroxide and pea starch, respectively.

V. Estimated Production Rates of Commercial Pellet Producers

To estimate production rates with current pelleting technologies used in the alfalfa and wood pellet industry, two wood pellet mills and two alfalfa pellet mills, all ‘industry leaders,’ were contacted to determine current pelleting technologies and throughput rates. Both of the wood pellet mills were using 2 x 300 hp machines, and neither were using steam. These mills reported average daily throughput rates of 20 and 29 lbs per hp using hardwood and softwood materials respectively, and wood pellet production of 5.4 and 7.9 tonne/hour, respectively. These rates are greater than the 3.5 tonnes/hr average production level cited in a survey of Pellet Fuels Institute members. The 30% lower production rate for the hardwood mill relative to the softwood mill is consistent with what is reported in the industry (Council of Great Lakes Governors, 1995). .

The two alfalfa mills interviewed had installed capacities of 1000 hp and 1250 hp, respectively. They reported the use of high-pressure steam at 180-205° C and 250° C. Pellet production rates were found to vary according to season and whether the mill used fresh cut or sun cured (baled) alfalfa. In the case of fresh cut alfalfa, average production rates of 51 and 62 lbs per hp were reported for each of the operations. In terms of sun cured alfalfa processed at one of the mills, production rates of 41 lbs per hp were obtained. One of the individuals interviewed indicated that the production rates of alfalfa decline as the forage maturity increases. He reported production rates up to 90 lbs per hp during the early season, which progressively declined as the material matured. A monitoring of alfalfa dehy producers in western Canada found production rates varied from 39.7-79.4 lbs/hp among producers, with an average value of 62 lbs/hp (Hill and Pulkinen, 1988). Thus, much higher pelleting throughputs are achieved with alfalfa compared to wood based raw materials. This suggests that other agri-fibres such as grasses could have much higher throughput rates than woody raw materials, making the pelleting of such materials economically attractive.

VI. Research and Production Tests on Various Biofuel Feedstocks

The test facilities used for grinding and pelleting the material for the study were at the Macdonald Campus of McGill University. The team consisted of Mark Drisdelle and Claude Lapointe of Dell-Point Bioenergy Research Inc., Roger Samson of REAP-Canada and Michael Viau of Vifam Pro-Services Inc. Sample analysis for energy, ash, and moisture content was performed under the supervision of Dr. E. Chavez of Macdonald Campus, McGill University.

The two main devices used for the study were:

California Pellet Mills Lab Model Pelleter

This is a standard lab pelleter marketed by CPM, a 2Hp, 1800 rpm CL Type 5. A new 6.4 mm (1/4") x 63.5mm (2.5") die was purchased for the machine, as this was the standard sized pellet used in North America for combustion appliances.

Figure 2. The 2HP California Pellet Mill-CL Type 5 lab model pelleter used in the studies

California Pellet Mills 25 Hp Master Mill

This is the smallest master mill offered by CPM and it provides for a more realistic assessment of how material will pellet on larger sized units (typically in the 150-300 Hp range) used by most biofuel producers.

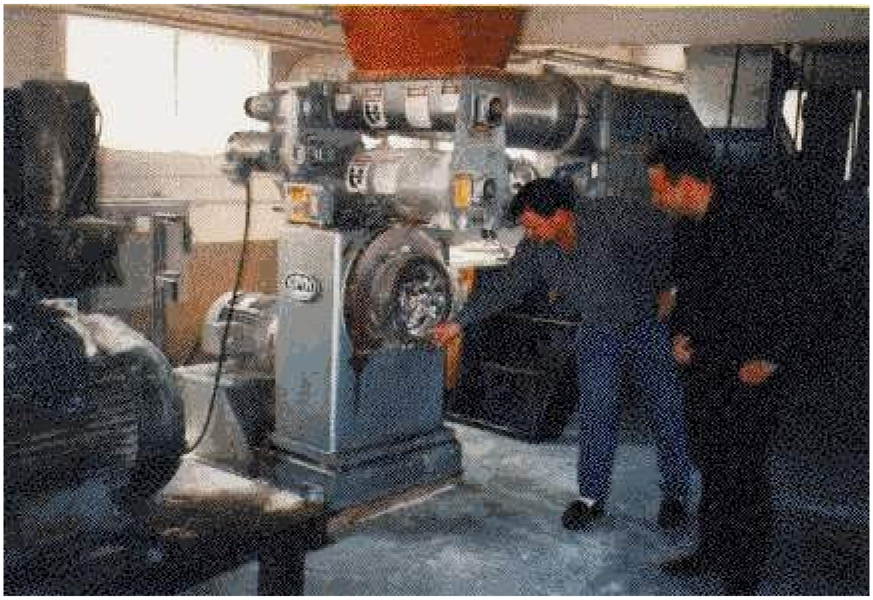


Figure 3. The 25 hp CPM pellet mill

VII. Results

The main activity undertaken was to assess the pelleting suitability of four feedstocks. The materials tested were as follows:

Pine Needles (*Pinus Strobus*):

The pelleting suitability of pine needles was evaluated because they are a potential rural cooking fuel source in some developing countries. The needles also create a potential risk for forest fires during the dry season. Red pine needles were gathered from the forest floor of a red pine plantation at the Morgan Arboretum in Ste. Anne de Bellevue, Quebec, in November 1999.

Switchgrass (*Panicum virgatum* L.):

Switchgrass is a warm season tall grass prairie species with relatively modest ash levels that is currently under widespread evaluation in North America as a perennial biofuel crop. The switchgrass used in this study was harvested in May, 1998 after overwintering. It was then stored indoors in bale form at the Macdonald campus of McGill University.

Hybrid short rotation (SR) willow (*Salix alba* sp.):

Chopped and dried short rotation forestry willow was obtained from the State University of New York. The university has an ongoing program of biofuel feedstock development funded by the US Department of Energy and is seeking higher value markets for willow chips than as a feedstock for power generation.

Sunflower hulls (*Helianthus annus L.*)

Although the acreage of sunflowers in Canada is currently somewhat limited, it could be a crop that experiences expansion if warmer and drier conditions continue in the prairie provinces, and thus become a contender for pelleting applications. Sunflower hulls were obtained from western Canada as an essentially free byproduct of the sunflower processing industry.

1. Pelleting of Pine Needles

The pine needles were hand sorted to remove small twigs and bark. The material was passed through two grinding devices to create a relatively uniform product for pelleting that would pass through a # 4 screen. The pine needles shattered during the grinding process and no dust was observed. Due to the dry nature of the needles, which had been in storage for three months, water was added 24 hours prior to pelleting.

Using the CPM lab mill, 6.4 mm pellets were produced. The chopped material flowed evenly through the pelleting apparatus. The resins present in the needles bound the material quite well, producing uniform pellets with no fines. The amperage use was lower (6-7 amps) for pine needles compared to the willows and switchgrass. This low resistance suggests that the material has a high throughput potential. The temperature of the pellets upon extrusion was also low at 50 ^{o}C.

Pine Needle Pellet Quality

The pine needle pellets were of high quality and tested over 30 on the Pfizer hardness test. No fines were observed. The pellets were extremely well formed and shiny, with a moisture content of 8.7%. They had a high energy content of 21.3 GJ/ od (oven dried) Mg (Table 1). The ash content was relatively elevated, at 5.89 %, placing pine needles in the C grade industry standard (above 3% ash content). However, this high ash content probably wouldn’t reduce the use of pelletized pine needles in developing countries, as the needles have a high energy content and ash disposal is quite simple in rural areas.

Table 1. Summary of pelleting quality and chemical analysis for four different pelleting feedstocks.

	Pine Needles	**Switchgrass**	**Sunflower Hulls**	**SRF Willow**
Estimated throughput (lbs/Hp)	50-75	45-70	50-75	35-45
Pellet hardness	>30	>30	>30	>30
Fines	None	Low	Trace	Trace
% Ash	5.9%	3.5%	3.6%	1.5%
Energy content (GJ./odMg)	21.3	19.2	20.0	19.2

2. Pelleting of Switchgrass

Switchgrass was a dry and dusty product to grind. However, one pass through the grinder provided a sample in which 100% of the material could pass through a # 4 mesh. Hot water was added prior to pelleting to ensure the product had even flow. The initial bench top pellet mill trial provided high quality pellets. However, on several occasions during the production of 6.4 mm pellets, the apparatus became plugged. The 63.5 mm (2.5") thick die appeared to be too thick to throughput the material with ease. Additionally, the high L/D ratio of 10 created a large surface area that appeared to resist the flow of the minimally conditioned material. It was decided to pellet the remaining material on the 25 Hp machine, which produced 4.8mm (3/16") diameter pellets with a 38.1mm (1.5") thick die (L/D of 7.9). The switchgrass was pelleted easily using this die, particularly with the addition of more water. The pellets reached a temperature of 67 ^{o}C off the mill.

The research team felt switchgrass would pellet similarly to steam conditioned alfalfa and would run at 45-70 lbs/Hp in a commercial mill. Pelleting was performed most efficiently with a thick pad of switchgrass on the die face. Rough surface roller shells could be well suited for this pelleting application by adding additional grinding on the die face. A die specified for wood use or a slightly thicker die on the 25 Hp machine would have been ideal, in addition to steam conditioning. Eight kg of the 4.8mm pellets were re-pelleted on the 6.4 mm lab die to produce pellets suitable for performing combustion tests. The lab mill ran at 10 amps, which was higher than the 6-7 amps during pine needle pelleting.

Switchgrass Pellet Quality

The pellets produced were of excellent quality and tested over 30 on the Pfizer tablet hardness tester. The original chopped material had a bulk density of 175 grams/litre (gr/l), the 4.8 mm pellets had a bulk density of 615 gr/l and the 6.4 mm pellets, which had gone through a double pelleting process, had a bulk density of 700 gr/l Of the three materials pelleted, switchgrass produced the most fines. The pellets had an ash content of 4.5%, a level that was considered high. Two other samples of switchgrass from other sites had ash levels of 2.75% from a sandy soil and 3.21% ash from a clay soil. A desired ash value would be less than 3%, which would place it in the B grade. This level could probably best be obtained from switchgrass grown on sandy soils, which are known to result in a lower ash content (Samson and Mehdi, 1998). However, even with higher ash content, switchgrass pellets should find a market. Bark pellets are currently being used as an industrial fuel and have an average ash content of 3.6%.

The energy content of the switchgrass pellets was 19.4 GJ/tonne. Spring harvested switchgrass from other sites in Quebec had energy contents between 19.07 and 19.11 GJ/tonne. Due to the lower ash content of spring harvested switchgrass, it generally has a superior energy content to fall harvested material. The average energy content of three spring harvested materials (19.2 GJ/tonne) is 3% lower than wood pellets, at 19.8 GJ/tonne. Fall harvested switchgrass is approximately (18.5GJ/tonne) or 6.6% lower than wood. The other advantage to using spring harvested switchgrass is less problematic combustion. Lower nitrous oxide levels occur, as spring harvested switchgrass contains 0.33% N, while fall harvested material contains 0.46% N. The potential for clinker formation is also minimized , as the potassium content is reduced by 94% through the overwintering process (Samson and Mehdi, 1998).

3. Pelleting of SR Willow

Nine kg of dried willow chips (approximately 1/2" in size) were ground with the same device used for the switchgrass. Of pine needles, switchgrass and willow, the willow was the most difficult to grind. A # 4 screen was used to remove oversized pieces from the ground material prior to pelleting. The willow was run on the 25 Hp CPM master mill, and with sufficient moisture, there were few difficulties. In general, however, willow was slightly more difficult to throughput than switchgrass.

The willow, upon extrusion from the die, reached a warmer temperature (77 ^{o}C) than the switchgrass and had a medium amperage draw. The rolls were run far from the die face. As in the case of switchgrass, rough textured roller shells could provide a more thorough grinding on the die face. It was felt that steam conditioning could also increase production and pellet quality for the willow.

Based on these preliminary tests, the research team estimated the material would run in the 35-45 lbs per Hp range.

SRF Willow Pellet Quality

The pellets produced were of excellent quality (Table 1), of uniform length and produced only a very small amount of fines. They tested at over 30 on the Pfizer tablet hardness tester, and contained 7.3% moisture. The material had an ash content of 1.54%, characterizing it as a grade B pellet .(1-3% ash). The pellets had an energy content of 19.2 GJ/tonne. The main quality problem associated with this feedstock was its high water content (typically 50% at harvest), which adds considerable drying costs to the cost of the raw material.

4. Pelleting of Sunflowers Hulls

10 kg of sunflower hulls (approximately 10 mm in length) were pelleted directly without preprocessing. The research team felt the material would be sufficiently ground at the die face to produce a pellet of suitable quality. The material was run on the 25 Hp CPM master mill. Once sufficient moisture was added (approximately 30%), the product ran fairly easily.

Upon extrusion from the die the sunflower hull pellets reached a temperature similar to switchgrass (70 ^{o}C) and had a medium amperage draw. The rolls were run far from the die face. As in the case of switchgrass, rough textured roller shells could provide a more thorough grinding on the die face. It was felt that steam conditioning could also increase production and sunflower pellet quality. Based on these preliminary tests, the research team estimated the material would run in the 50-75 lbs per Hp range. Overall it was considered an excellent product for pelleting, especially as it required minimal preprocessing.

Sunflower Hull Pellet Quality

The pellets produced were of excellent quality (Table 1), of uniform length and produced only a very small amount of fines. They tested at over 30 on the Pfizer tablet hardness tester, and contained 8.7% moisture. The material was found to have an ash content of 3.6%, and an energy content of 20.0 GJ/tonne.

VIII. Overview of the Economics of Pelleting Biofuels

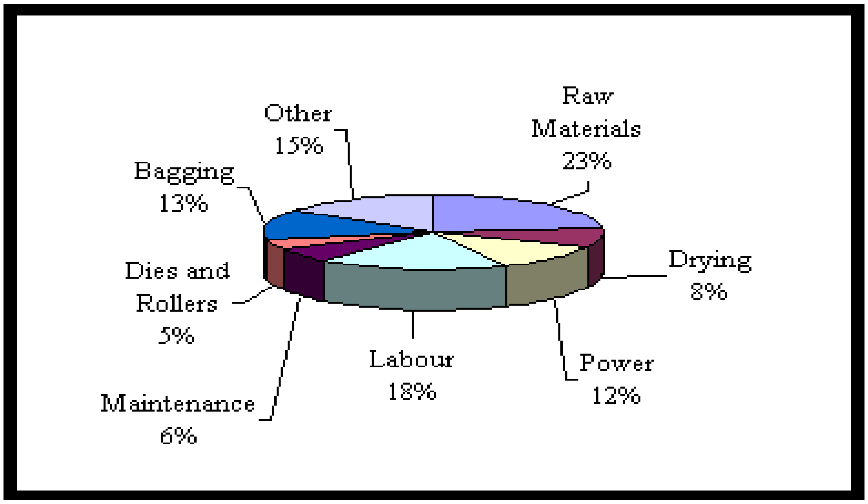
The main costs associated with pelleting biofuels are plant operating costs and feedstocks costs. The Pellet Fuels Institute in the United States has done some analysis of the costs of wood pelleting (Council of Great Lake Governors, 1995). From a sample business plan estimate, the overall cost of a wood pellet facility (adjusted to 1999 costs and converted to Canadian dollars) producing 7-8 tonne per hour was estimated to be 2.1 million dollars while the cost of a 3-4 tonne per hour facility was 1.4 million dollars (Table 2). Based on average production rates of 3.5 and 7.5 at each of the facilities, the capital investment per tonne of production is $400,000 and $280,000 for the small and large wood pelleting facility (Figure 4). If the plants were producing higher throughput raw material such as switchgrass or sunflower hulls, the investment would be further reduced to an estimated 200,000 and 140,000 per tonne of production for the small and large plant respectively.

Item	3 to 4 tons per hour (TPH)		7 to 8 tons per hour (TPH)	
	Capital Cost (Can.$)	**Installation Cost (Can.$)**	**Capital Cost (Can.$)**	**Installation Cost (Can.$)**
Miscellaneous Conveyors	23,000	11,500	29,600	14,800
Front-end Loader	106,800	0	205,300	0
Feed Hopper	9,900	5,700	12,300	6,600
Primary Grinder	32,900	24,600	49,300	36,100
Dryer, Burner & Air System	328,500	139,600	410,600	164,300
Secondary Grinder	52,600	27,900	73,900	32,900
Live Bottom Bin	19,700	16,400	29,600	19,700
Pellet Mill(s)	197,100	115,000	394,200	213,500
Pellet Cooler	29,600	23,000	39,400	29,600
Pellet Shaker	19,700	15,600	29,600	18,100
Boiler/Water Heater	24,600	29,600	29,600	32,900
Bagging Bin	6,600	4,100	8,200	4,900
Bagging System	41,100	8,200	98,600	12,300
Fork Lift	29,600	0	41,100	0
Building	57,500	0	82,100	0
Total	**$979,200**	**$421,200**	**$1,533,400**	**$585,700**

It is evident from this analysis that the larger the facility, the greater the potential to reduce production costs if adequate feedstock resources are available for the plant. An analysis of the alfalfa pellet industry indicated that larger pellet plants reduced processing costs relative to smaller pellet plants (Kulshreshtha and Storey, 1990). The total processing costs were $70.76 dollars per tonne for the large plant and $87.67 dollars per tonne for the small plant. Operating costs were 11.2% lower in the large plant and administrative costs were 40% lower. Almost all the operating cost savings were based on labour. Administrative cost savings resulted from reduced depreciation and lower management wages.

In 1994, an analysis of the production costs of wood pellets was developed from a membership survey by the Pellet Fuels Institute (Council of Great Lake Governors, 1995). The survey of pellet manufacturers indicated that raw material, energy, labour and bagging costs were the largest costs associated with pellet production (Figure 5). The survey also indicated that 48% of pellet producers have experienced raw material supply shortages and know of producers that are concerned about rising feedstock costs. The production of high yielding biomass feedstocks such as switchgrass could help stabilize feedstock costs and reduce drying costs. Other needs of the pellet industry are to develop higher throughput pelleting technologies, and bulk delivery systems to help reduce labour, bagging, and plant maintenance costs.

Figure 5. Breakdown of costs associated with pellet manufacturing



A preliminary exploration of the economics of pelleting dedicated bioenergy crops such as SRF willow and switchgrass was made using the estimated throughputs derived from earlier pelleting trials (Table 1). A US pellet industry survey provided baseline data for wood pelleting (Council of Great Lakes Governors, 1995). In Table 3, it is assumed that in the case of the wood pellet industry, throughput is 30 lbs/Hp/hr, switchgrass throughput is 45-70 lbs/Hp/hr and willows, 35-45 lbs/Hp/hour. If production costs drop proportionally with increased throughput, direct pelleting costs should be in the range of $25.12-$39.33 for switchgrass and

$39.33-$50.57 for SRF willow. This preliminary analysis indicates that although switchgrass feedstock costs are high relative to wood residues, it could still be competitive with wood if minimal drying is required and higher throughputs were realized under commercial production. In the case of willow, the high initial feedstock cost and high moisture content at harvest (50%) suggests that it will be a relatively more expensive source of fuel pellets. Nonetheless, willow is approaching the cost of forestry residues and would likely be closer to energy end use markets than forest derived materials. Regional pellet plants using switchgrass and SRF willow would also facilitate the use of the material in bulk form, making the fuels more cost effective by removing bagging costs and minimizing transport costs. Farmers, in particular, should be quite receptive to this concept as they are already handling pellets in bulk for livestock feeding, and use seed and fertilizer in bulk form. A thorough analysis is required from commercial pelleting trials to verify these preliminary estimates.

Table 3. Summary of preliminary feedstock production costs (Canadian $ /tonne) [a]

	Wood pellet costs[b]	**Projected switchgrass pellet costs**	**SR Willow**
Feedstock	$ 34.35	$46-$68[c]	$58-$85
Drying	$11.93	$0	$15.00
Direct Pelleting Costs	$59.00	$25.29-39.33	$39.33-$50.57
Bagging	$19.25	$19.25	$19.25
Total cost	$124.53	$90.54-$126.58	$131.58-$169.82

[a] Direct pelleting costs are based on 30 lbs./HP for wood residues and 45-70 lbs per HP for switchgrass and 35-45 lbs/hp for SRF willow..

[b] Costs from survey of wood pellet producers, Council of Great lake Governors, 1995.

[c] Feedstock costs for switchgrass from Girouard et al., 1999

IX. Energy Analysis

An analysis of the energy costs associated with biomass fuel pelleting is needed to identify the greenhouse gas offset potential of the technology. This also enables comparisons with other biofuel production systems and other carbon sequestering land use strategies to help mitigate greenhouse gas emissions. The analysis below is based on the use of switchgrass as a pellet feedstock.

According to the analysis in table 4, the energy cost of switchgrass production for a large industrial user such as a pulp and paper or ethanol plant is estimated to be 0.91GJ/tonne, while that of a pellet plant is 0.79 GJ/tonne (Samson et al., 2000). The difference between energy costs is related to hauling distances to each facility. Because pellet conversion facilities are much smaller (200 tonne/day) than pulp and paper or ethanol plants (1500 tonne/day), pelleting plants can be situated in closer proximity to the site of switchgrass production. Assuming that 5% of the landscape is converted to switchgrass production and a harvestable yield of 10 tonne/ha is obtained, the switchgrass can be sourced within a 20 km radius of a pelleting plant, versus a 60 km radius for a large industrial user. This shorter radius would reduce the energy used in delivery from 0.177 GJ/tonne (19.5% of the total energy cost) to 0.059 GJ/tonne (7.5% of the total energy cost), and improve the energy output to input ratio for switchgrass production from 20 to 23:1.

Table 4. Switchgrass Energy Costs for a Biofuel Pellet Plant

Activity	Large Energy/Fibre Conversion Facility		Switchgrass Biofuel Pellet Plant	
	Requirement/GJ/tonne	Percentage	GJ/tonne	Percentage
Establishment	0.028	3.1%	0.028	3.5%
Fertilizer and application	0.460	50.6%	0.460	58.2%
Mowing	0.034	3.8%	0.034	4.3%
Baling	0.197	21.6%	0.197	24.9%
On-farm Transport	0.013	1.4%	0.013	1.6%
Off-farm Transport	0.177	19.5%	0.059	7.5%
Total	0.91GJ/tonne		0.79 GJ/tonne	

A forage harvester was reported to require 31 MJ/tonne (Lopez, 1986) which is much lower than the 197 MJ used for the baling estimate in Table 4. Field chopping the material would likely have a similar energy requirement as baling, although the energy and financial costs associated with breaking and coarse chopping the bales would make bulk handling more attractive for pellet plants. Alfalfa pellet mill operators interviewed in western Canada reported higher production costs for stored alfalfa then freshly cut material, including higher drying costs, suggesting that bulk handling of switchgrass would be more desirable than baling. An analysis of miscanthus production in Europe also indicated that while bulk harvesting and hauling for big baled and chopped fibre was almost identical for the first 20 km of hauling distance, the cost of the supply chain for big bales became more attractive with longer hauling distances (e.g. 80 km) (Huisman et al., 1996). Bransby (1999) field tested field chopping as an alternative to baling and found it to be a suitable alternative to baling for harvesting and handling switchgrass. The material was mown with a mower conditioner and then picked up and chopped with a pull behind a forage harvester. Although facilities are equipped to handle bales, it is probable that switchgrass pellet plants will evolve to feedstock supply systems similar to the alfalfa industry, with the majority of the material handled in bulk. For the purpose of the energy analysis at the pelleting plant, it is assumed that the material is processed following field chopping, has a 0.5-4 cm length of chop, and contains approximately 10-15% moisture.

Overall Pellet Plant Energy Costs

The energy costs associated with pellet plant operations can be approximated from existing pellet facilities. An analysis of switchgrass pelleting/delivery has recently been estimated for a small plant of 2.7 tonnes/hour (King, 1999). The energy cost for pellet equipment operation for this plant was estimated to be 103 kWh/metric tonne (371 MJ/tonne). As a reference point, a 7.5 tonnes/hour (180 tonnes/day) west coast softwood pellet producer, using primarily sawdust as a raw material, consumed 78 kWh/ metric tonne (281 MJ/tonnes). Additionally, a hardwood pellet plant in Quebec using sawdust as a raw material had an electrical energy consumption of 250 kwh/tonne (900 MJ/tonne). The wood pellet plants would also have additional energy costs associated with drying the wood fibre.

Processing of the biomass prior to pelletization influences both the quality of the pellets and the energy use of the pelleting process. For instance, comminuting the biomass to approximately 3.2 mm (half the diameter of a normal fuel pellet in North America) optimizes pellet quality while minimizing costs. Preprocessing also influences the energy use of the pelletization process. For example, the energy requirement of alfalfa pelletization increases if the biomass is in bale form due to pretreatment costs such as straw bale breaking, coarse grinding and fine hammermilling (Sokansanj, 2000). An estimated 20 kwhr/tonne (72 MJ/tonne) was required to run a Champion hammermill for processing alfalfa prior to pelleting.

The present analysis assumes that the switchgrass arrives at the pelleting plant coarsely chopped and in bulk form. Since switchgrass is likely slightly more difficult to fine chop than alfalfa, the pretreatment of the biomass is expected to use 25 kwhr/tonne (90 MJ/tonne). This value is comparable to the 100 MJ tonne estimated to be required for the pelletization pretreatment of 15% moisture straw (Novem,1996). If switchgrass is to be processed from baled form, straw shredding appears to be the most viable approach for the initial downsizing of the material. Equipment is now available from manufacturers for this operation. In Denmark, large bales are increasingly broken down using straw shredder systems, which reduce energy and processing costs relative to conventional chaff-cutting systems (Centre for Biomass Technology, 1998).

Hill and Pulkinen (1988) reported that alfalfa pelletization had an energy consumption of 52-72 MJ/tonne (14 to 20 kw/hr), depending on the conditioning temperature used. Energy costs associated with alfalfa pelleting were reported to be 30 kwh/tonne to produce a durable pellet (Tabil and Sokhansanj, 1996). King (1999) estimated that 45 kwhr/tonne was used for pelleting switchgrass. For straw pelleting, an estimated 300 MJ/tonne was required for the pelleting process (Novem, 1996). For the purpose of this analysis, a value of 30 kwhr/tonne (108MJ/tonne) for switchgrass pelleting will be used.

Total pelleting operational energy also includes the energy costs associated with conveyers, cooling fans, elevators and lighting, which are estimated to be another 0.46GJ/tonne. The values for these items in Figure 6 are based on King (1999) and Sokansanj (2000). All pellet mill operational energy costs thus total 244 GJ/tonne. It is evident from figure 6 that the major energy requirements are associated with downsizing the material to a suitable size for pelleting, and with the pellet operation itself (Figure 6). King (1999) identified these two items to be approximately 80% of pellet-mill operation energy costs, and 67% of all energy costs for processing/marketing and delivery. As such, reducing the energy requirement of these activities is critical to creating a strong net energy gain from switchgrass fuel pellet production.

Total Energy Costs Associated with Switchgrass Pellet Production

The energy cost associated with switchgrass fuel pellet production is estimated to be 1.27 GJ/tonne (Table 5). Surprisingly, production and delivery of switchgrass represent 62% of the energy required in the entire switchgrass fuel pellet production chain, from field to delivery to the consumer. This is largely due to the energy associated with fertilizer use and application, which represents 36% of the total energy cost. Nonetheless, the switchgrass biofuel has a net energy output to input ratio of 14.6:1, assuming an energy content of 18.5

GJ/tonne in the feedstock. Considering that this material can be used quite conveniently as a substitute for fuel oil heating, it appears an excellent strategy to maximize the energy output from a hectare of land.

Table 5. Energy associated with switchgrass pellet production

Process	**GJ/tonne**
Switchgrass establishment[a]	0.028
Switchgrass fertilization and application	0.460
Switchgrass harvesting	0.231
Switchgrass transportation	0.072
Pellet mill construction[b]	0.043
Pellet mill operation	0.244
Management, sales, billing and delivery of pellets	0.193
Total Input Energy	**1.271**
Total Output Energy	**18.5**
Energy Output/Input Ratio	**14.6**

[a] Switchgrass information derived from Girouard et al., 1999 and Samson et al., 2000

[b] Pellet mill construction, operation, management sales, billing and delivery of pellets from King, 1999

X. Combustion Study

In the mid 1990's Dell-Point Technologies established a partnership with the Natural Resources Canada Advanced Combustion Laboratory with the goal of creating a high efficiency, low emission pellet stove capable of burning fuels with moderate ash levels, such as bark and switchgrass. The result was the 1998 licensing of a close coupled gasification technology pellet stove with an overall efficiency of 81-87%, which compares favorably to the more modest efficiencies of 35-69% of most pellet stoves on the market. The design of the close coupled gasifier technology is such that a lower operating temperature exists in the bottom of the gasifier where the first stage of the combustion occurs, allowing the ash to fall through the grate into the ash pan and reducing the production of clinker. The stove's efficient performance is largely due to its use of one-seventh of the excess air relative to current technology. A hydronic (providing combined heat and hot water) pellet furnace of 35 kWh (120,000 BTU/h) is currently under development and scheduled for field testing this year and commercial production in 2001.

Combustion of switchgrass pellets was evaluated by performing test burns in the Dell-Point stove at the Advanced Combustion Laboratory in Ottawa. The efficiency of the stove was assessed at medium and high output levels and was compared with values from combustion of hardwood fuel pellets. The laboratory trials indicated that switchgrass provided a relatively high combustion performance efficiency, with efficiencies of 82% and 84% at the medium output and high output range setting, respectively. These efficiencies were only about 2% lower than levels obtained with wood at each respective setting. This was considered to be a high level of performance, considering that the burner was not optimized for switchgrass pellet burning.

The switchgrass fuel had a dry calorific value of 19.01 MJ/kg (Table 6). As fired at 4.96% moisture, it had an energy content of 18.07 MJ/kg. In comparison, the hardwood pellets had an energy content of 19.60 GJ/tonne, and as fired at 5% moisture, possessed an energy content of 18.65 MJ/tonne. The energy content of the overwintered switchgrass fuel thus appeared quite comparable to wood, at 97% of wood's energy content.

Particulate levels from switchgrass combustion were greater than those obtained for wood, with peak levels of 2.5 g/hour at the high range setting. This elevated particulate concentration is likely due to the plant's moderate ash content relative to wood. Nonetheless, even at the peak value of 2.5 g/hour, switchgrass particulate values were well below the 7.5 g/hour EPA limit for pellet stoves.

Switchgrass was found to be a slightly more challenging fuel to burn than wood in the Dell-Point stove. At the high range setting, switchgrass pellets formed weak bridges within the stove, causing some fuel accumulation above the grate. It is likely that programming the stove's grate cleaner to run more frequently than three times every 60 seconds would resolve this problem. Other possible modifications include changing the grate spacing and modifying the nozzle placement to change the temperature profile in the bottom of the burn chamber.

Although more difficult to burn than wood, switchgrass is easier to burn relative to corn. Corn kernels were found to fuse and liquefy at high temperatures and eventually formed a hard cake-like layer over the grate. The Dell-Point close coupled gasifier furnace currently under development has an under-feed design that should minimize problems of grate obstructions and further widen the range of agricultural fuels that can be efficiently combusted.

Table 6: Fuel Quality Comparison of

Switchgrass versus Wood Pellets

	Switchgrass	Hardwood
Dry Calorific Value (MJ/kg)	19.01	19.60
Fuel Moisture (% Wet Basis)	4.96	4.86
As-fired C.V. (MJ/kg)	18.07	18.65

Table 7: Combustion Performance of Switchgrass versus Wood Pellets

	Switchgrass	Switchgrass	Hardwood	Hardwood
	4/4 power/fan setting	9/9 power/fan setting	4/4 power/fan setting	9/9 power/fan setting
Particulate IDG (g/h)	0.95	2.5	0.46	1
NO_x (ppm)	185	290	62	98
% Efficiency	83.56	81.93	85.53	83.61

Economics of Heating with Pelleted Biofuels

In North America, the adoption of biomass energy from switchgrass pellets could play an important role in reducing costs associated with fossil fuel use.

Compared to electricity, oil and natural gas, switchgrass pellets offer a fuel savings of 46%, 28% and 30%, respectively (Figure 7). Fuels savings could be particularly striking in regions of North America where limited supplies of natural gas and oil create higher heating costs. For example, in Quebec, where approximately 50% of homes are heated with electricity, combustion of pelletized agricultural and forest residues using the new gasifier pellet stove technology could largely replace the use of electricity for heating purposes. This electricity could subsequently be exported out of province to displace the use of fossil fuel or nuclear power plants in other provinces or states. The rising prices of oil and natural gas will increasingly make the replacement of these fuels with biomass energy more financially attractive to consumers. In contrast, since the real dollar prices of agricultural commodities have historically followed a declining trend, the price of switchgrass pellets should remain relatively stable through time, as has been the case for wheat prices.

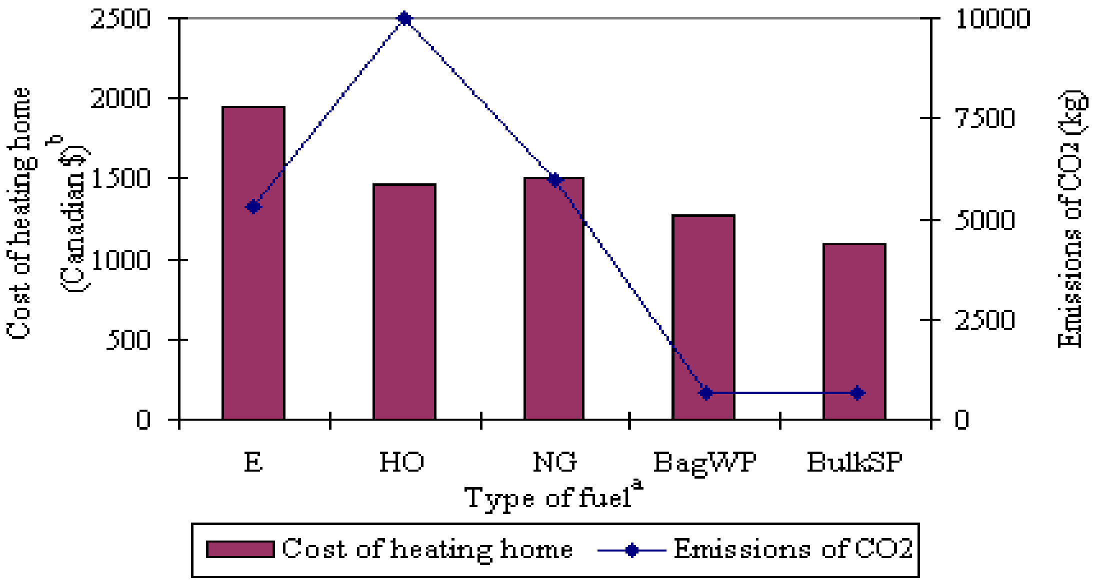


Figure 7. Fuel Costs and CO_2 emissions associated with home heating in SW Quebec

[a] Assumptions:

E= Electricity has an energy content of 3.6 MJ/kWh, a delivered fuel value of 6.87 cents/kWh, a CO_2 loading value of 52.2 kg CO_2/GJ and is converted at 98% efficiency, Approximate electrical mix: 63% hydro-power, 15% nuclear, 16.5% coal, 3% oil, 2% natural gas (Jaques, 1992).
HO= Heating Oil has an energy content of 0.0382 GJ/l, a delivered fuel value of 46.01 cents/l, a CO_2 loading value of 81.8 kg CO_2/GJ, and is converted at 82% efficiency
NG= Natural Gas has an energy content of 0.0375 GJ/m^3 ,a delivered fuel value of 47.85 cents/ m^3, a CO_2 loading value of 50.6 kg CO_2/GJ, and is converted at an average efficiency of 85%
BagWP= Bagged Wood Pellets have an energy content of 19.8 GJ/tonne, a delivered fuel value of $207/tonne, a CO_2 loading value of 5.3 kg CO_2/GJ, and are converted at 82% efficiency
BulkSP= Bulk Switchgrass Pellets have an energy content of 19.2 GJ/tonne, a delivered fuel value of $172/tonne, a CO_2 loading value of 5.3 kg CO_2/GJ, and are converted at 82% efficiency.

All delivered fuel values include taxes of 7% GST and 7.5% TVQ.

[b] Heat estimates made for a new detached 2000 sq. foot home with a heat requirement of 100 GJ (Natural Resources Canada, 1997). The analysis does not include capital costs associated with equipment.

Greenhouse Gas Emissions of Switchgrass Fuel Pellets

There is considerable variation in the amount of $C0_2$ released from the use of different fuel sources for heating purposes (Figure 7). Emissions from the combustion of switchgrass pellets are considerably lower than those from fossil fuel sources. Pellet fuel heating reduces greenhouse gas emissions by 88%, 93% and 89% compared to electricity, oil and natural gas, respectively. However, the greatest potential to reduce $C0_2$ emissions is through the replacement of electrical heating with biomass energy in places such as Quebec, which are heavily reliant on electricity for heating applications. Quebec's unused electrical power could be exported, enabling the retirement of coal-generating energy plants in neighbouring provinces or states. This exchange could significantly reduce greenhouse gas emissions, as power generation by coal has a greenhouse gas loading factor of 245 kg $C0_2$/GJ (568 lbs. $C0_2$./MBtu), 4.7 times the $C0_2$ emissions of the Canadian electrical grid. Coal-derived electrical heating emits 38 times more $C0_2$ than switchgrass pellets in home heating applications. It is evident that substituting fossil fuel-based space heating applications with biofuel heating systems would be a highly effective strategy to reduce greenhouse gas emissions.

Future Directions

The current agri-fuel pellet project partnership aims to commercialize closed loop agricultural biofuels as a practical and economical solution to help reduce greenhouse gas emissions. Optimization of the production of perennial grass fuel pellets has now been initiated to examine means of reducing the fuel chain costs, from field to final space heating costs. This work will entail harvesting, storage, comminuting, pelleting, delivery and finally, burning in the Dell-Point pellet furnace and stove.

These initiatives, combined with improvements in biomass feedstock development through plant breeding, could enable pelleted biofuels to become a low cost contender in the search for greenhouse gas offset strategies in temperate regions. Canada is well positioned to take advantage of this opportunity through its existing expertise in pellet production and combustion stove technology, its proven production record of low cost commodities on its large agricultural land base, and its ideal position to expand export of pelleted biofuels into the US and European markets.

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Appendix 1. CANMET Laboratory Fuel Assessment-Combustion Reports for Switchgrass and Hardwood

FUEL PERFORMANCE EVALUATION

Fuel:	Switchgrass pellets
Test appliance:	Dell-Point Stove s.n.
Date:	00-03-09
	4/4 power/fan setting

DATA SUMMARY

Enter beginning row number:	4
Enter final row number:	454
Enter sampling duration (min)	120

Note: Enter value from cell B8 in B14 equation!

Particulate Sample

Volume sampled:	35.77	cu ft
Wt of particulate:	0.0037	g
Sample time	120	min
Static pressure	0.55	"H20
Pitot tube rdg	0.053	"H20
Barometric press.	29.35	"Hg
Pitot factor	0.85	
Tunnel diameter	6	"
Velocity:	13.0	fps
Total Tunnel flow	18332	cu ft
Particulate ldg	1.896	g
	0.95	g/h
	0.82	g/kg fuel

Average Test Results:

SCALE	1.15	kg/h
	2.5	lb/h
Stack @ Psample location	26.7	deg C
Unused	31.9	deg C
Stack @ sample	124.6	deg C
Ash door centre	33.3	deg C
Top frame rail	31.3	deg C
Left side wall centre	42.2	deg C
Inside combustor side wall	461.9	deg C
"13"" above combustor"	389.7	deg C
Unused	47.8	deg C
Stove exit	169.5	deg C
Shrouder wall TC	31.6	deg C
Particulate filter holder	30.8	deg C
O2	13.7	%
CO	84	ppm
CO2	6.87	%
NOx	185	ppm

CALCULATION OF STOCIOMETRIC PRODUCTS, ACTUAL PRODUCTS, AND EFFICIENCY

Dry Calorific Value (MJ/kg)	**19.01**	(	8173	BTU/lb)
Fuel Moisture (% wet basis)	**4.96**	(	5.2	% db)
As-Fired C.V. (MJ/kg)	18.07	(	7767	BTU/lb)

ULTIMATE ANALYSIS(dry basis)	
carbon	**47.83**
hydrogen	**5.86**
sulphur	**0.05**
nitrogen	**0.52**
ash	**4.18**
oxygen	**41.56**
Total	100.00

Flue Gas Values:			
% CO2	**6.87**	from O2:	6.96
% O2	**13.68**	from CO2	13.77
% CO	**0.00835**		
Flue (C)	**125**	256	F
Amb't (C)	**31**	88	F

% Combustible in Ash:	**0**

CONVERSION FACTORS:
MJ/kg = BTU/lb*.002326
F = 9/5*C+32   C = 5/9*(F-32)
MC(wb)=MC(db)/(100+MC(db))
MC(db)=MC(wb)/(100-MC(wb))

Air & Flue Gas	from co2	from o2
% Excess Air	192.81	189.17
comb'n air(Sft3/lb fuel)	208.4	205.9
dfg (lb/lb dry fuel)	17.2	17.0
tfg (lb/lb dry fuel)	17.8	17.6
dfg (Aft3/lb dry fuel)	302.7	299.0
dfg (Sft3/lb dry fuel)	207.9	205.4
tfg (Aft3/lb dry fuel)	319.4	315.7
tfg (Sft3/lb dry fuel)	219.4	216.8
CO (lb/lb dry fuel)	0.001	0.001
vol fraction H2O in flue	0.052	

LOSSES	BTU/lb dry fuel	BTU/lb as fired	% loss
DFG	693	658	8.47
Fuel H2O	58	55	0.71
H2	590	561	7.22
CO	6	6	0.02
Comb. in Ash			
Total Loss	1347	1280	16.43
% Efficiency			83.57

STOCIOMETRIC VALUES

Stociometric Air req'd (lb/lb dry fuel)	
Carbon (32/12.011*.01*C)	1.274
Hydrogen (8/1.008*.01*H)	0.465
Sulphur (32/32.066*.01*S)	0.000
Total	1.740
Less O2 in fuel	0.416
O2 from air	1.324
Associated N2 (76.85/23.15*O2)	4.396
Total dry air:	5.720

Stociometric Combustion Products	lb/lb dry fuel	Sft3/lb dry fuel
Stociometric CO2	1.75	14.29
Stociometric N2	4.40	56.40
Stocimetric SO2	0.00	0.00
Total dfg	6.15	70.70
Wet products		
H2O (reaction)	0.52	10.43
H2O (fuel)	0.05	1.04
Total flue gas	6.73	82.17
Stociometric % CO2	20.2	

FUEL PERFORMANCE EVALUATION

Fuel:	Switchgrass pellets
Test appliance:	Dell-Point Stove s.n.
Date:	00-03-09
	9/9 power/fan setting

DATA SUMMARY

Enter beginning row number:	4
Enter final row number:	118
Enter sampling duration (min)	31

Note: Enter value from cell B8 in B14 equation!

Average Test Results:

SCALE	1.74	kg/h
	3.8	lb/h
Stack @ Psample location	28.0	deg C
Unused	35.1	deg C
Stack @ sample	179.6	deg C
Ash door centre	31.9	deg C
Top frame rail	34.0	deg C
Left side wall centre	49.6	deg C
Inside combustor side wall	292.6	deg C
"13"" above combustor"	588.5	deg C
Unused	55.9	deg C
Stove exit	234.1	deg C
Shrouder wall TC	34.9	deg C
Particulate filter holder	38.2	deg C
O2	11.2	%
CO	66	ppm
CO2	9.34	%
NOx	290	ppm

Particulate Sample

Volume sampled:	9.18	cu ft
Wt of particulate:	0.0025	g
Sample time	31	min
Static pressure	0.56	"H20
Pitot tube rdg	0.05	"H20
Barometric press.	29.34	"Hg
Pitot factor	0.85	
Tunnel diameter	6	"
Velocity:	13.0	fps
Total Tunnel flow	4747	cu ft
Particulate ldg	1.293	g
	2.50	g/h
	1.44	g/kg fuel

CALCULATION OF STOCIOMETRIC PRODUCTS, ACTUAL PRODUCTS, AND EFFICIENCY

ULTIMATE ANALYSIS (dry basis)	
carbon	47.83
hydrogen	5.86
sulphur	0.05
nitrogen	0.52
ash	4.18
oxygen	41.56
Total	100.00

Dry Calorific Value (MJ/kg)	19.01	(	8173 BTU/lb)
Fuel Moisture (% wet basis)	4.96	(	5.2 % db)
As-Fired C.V. (MJ/kg)	18.07	(	7767 BTU/lb)

Flue Gas Values:			
% CO2	9.33817	fromO2:	9.40
% O2	11.16	fromCO2:	11.23
% CO	0.00662		
Flue (C)	180		355 F
Amb't (C)	34		93 F

% Combustible in Ash:	0

CONVERSION FACTORS:

MJ/kg = BTU/lb*.002326

F = 9/5*C+32   C= 5/9*(F-32)

MC(wb)=MC(db)/(100+MC(db))

MC(db)=MC(wb)/(100-MC(wb))

Air & Flue Gas	fromco2	fromo2
% Excess Air	115.73	114.33
comb'n air (Sft3/lb fuel)	153.6	152.6
dfg (lb/lb dry fuel)	12.8	12.7
tfg (lb/lb dry fuel)	13.4	13.3
dfg (Aft3/lb dry fuel)	253.7	252.0
dfg (Sft3/lb dry fuel)	153.1	152.1
tfg (Aft3/lb dry fuel)	272.8	271.0
tfg (Sft3/lb dry fuel)	164.6	163.6
CO (lb/lb dry fuel)	0.001	0.001
vol fraction H2O in flue	0.070	

LOSSES	BTU/lb dry fuel	BTU/lb as fired	% loss
DFG	803	764	9.83
Fuel H2O	60	57	0.74
H2	611	581	7.48
CO	3	3	0.02
Comb. in Ash			0.00
Total Loss	1479	1405	18.07
% Efficiency			81.93

STOCIOMETRIC VALUES

Stociometric Air req'd (lb/lb dry fuel)		
Carbon (32/12.011*.01*C)		1.274
Hydrogen (8/1.008*.01*H)		0.465
Sulphur (32/32.066*.01*S)		0.000
	Total	1.740
	Less O2 in fuel	0.416
	O2 from air	1.324
Associated N2 (76.85/23.15*O2)		4.396
Total dry air:		5.720

Stociometric Combustion Products	lb/lb dry fuel	Sft3/lb dry fuel
Stociometric CO2	1.75	14.30
Stociometric N2	4.40	56.40
Stocimetric SO2	0.00	0.01
Total dfg	6.15	70.71
Wet products		
H2O (reaction)	0.52	10.44
H2O (fuel)	0.05	1.04
Total flue gas	6.73	82.19
Stociometric % CO2:	20.2	

The equations used are from "A Combustion Handbook for Canadian Fuels" by Friedrich and Hayden, 1974

FUEL PERFORMANCE EVALUATION

Fuel:	Bear Essentials hardwood pellets
Test appliance:	Dell-Point Stove s.n.
Date:	00-03-08
	4/4 power/fan setting

DATA SUMMARY

Enter beginning row number	4
Enter final row number:	454
Enter sampling duration (min	120

Note: Enter value from cell B8 in B14 equation!

Average Test Results:

SCALE	0.93	kg/h
	2.0	lb/h
Stack @ Psample location	23.8	deg C
Unused	27.9	deg C
Stack @ sample	104.5	deg C
Ash door centre	35.2	deg C
Top frame rail	27.7	deg C
Left side wall centre	37.3	deg C
Inside combustor side wall	478.8	deg C
"13"" above combustor"	376.0	deg C
Unused	43.0	deg C
Stove exit	145.6	deg C
Shrouder wall TC	27.9	deg C
Particulate filter holder	28.2	deg C
O2	13.6	%
CO	94	ppm
CO2	7.23	%
NOx	62	ppm

Particulate Sample

Volume sampled:	38.262	cu ft
Wt of particulate:	0.0019	g
Sample time	129	min
Static pressure	0.55	"H20
Pitot tube rdg	0.053	"H20
Barometric press.	29.84	"Hg
Pitot factor	0.85	
Tunnel diameter	6	"
Velocity:	13.2	fps
Total Tunnel flow	20025	cu ft
Particulate ldg	0.994	g
	0.46	g/h
	0.50	g/kg fuel

CALCULATION OF STOCIOMETRIC PRODUCTS, ACTUAL PRODUCTS, AND EFFICIENCY

ULTIMATE ANALYSIS(dry basis)	
carbon	**49.81**
hydrogen	**6.06**
sulphur	**0.06**
nitrogen	**0.15**
ash	**0.63**
oxygen	**43.29**
Total	100.00

Dry Calorific Value (MJ/kg)	**19.60**	(	8426	BTU/lb)
Fuel Moisture (% wet basis)	**4.86**	(	5.1	% db)
As-Fired C.V. (MJ/kg)	18.65	(	8017	BTU/lb)

Flue Gas Values:			
% CO2	**7.22**		
% O2	**13.578**		
% CO	**0.00937**		
Flue (C)	**105**	220	F
Amb't (C)	**28**	82	F

% Combustible in Ash:	**0**
from O2:	7.08
from CO2:	13.43

CONVERSION FACTORS:

MJ/kg = BTU/lb*.002326

F = 9/5*C+32 C = 5/9*(F-32)

MC(wb)=MC(db)/(100+MC(db))

MC(db)=MC(wb)/(100-MC(wb))

Air & Flue Gas	from co2	from o2
% Excess Air	179.17	184.94
comb'n air(Sft3/lb fuel)	206.5	210.7
dfg (lb/lb dry fuel)	17.0	17.4
tfg (lb/lb dry fuel)	17.6	18.0
dfg (Aft3/lb dry fuel)	284.7	290.6
dfg (Sft3/lb dry fuel)	205.9	210.2
tfg (Aft3/lb dry fuel)	301.0	306.9
tfg (Sft3/lb dry fuel)	217.8	222.0
CO (lb/lb dry fuel)	0.002	0.002
vol fraction H2O in flue	0.054	

LOSSES	BTU/lb dry fuel	BTU/lb as fired	% loss
DFG	565	538	6.71
Fuel H2O	57	54	0.67
H2	604	575	7.17
CO	7	6	0.03
Comb. in Ash			0.00
Total Loss	1233	1173	14.58
% Efficiency			85.42

STOCIOMETRIC VALUES

Stociometric Air req'd (lb/lb dry fuel)	
Carbon (32/12.011*.01*C)	1.327
Hydrogen (8/1.008*.01*H)	0.481
Sulphur (32/32.066*.01*S)	0.001
Total	1.809
Less O2 in fuel	0.433
O2 from air	1.376
Associated N2 (76.85/23.15*O2)	4.567
Total dry air:	5.943

Stociometric Combustion Products	lb/lb dry fuel	Sft3/lb dry fuel
Stociometric CO2	1.83	14.89
Stociometric N2	4.57	58.54
Stocimetric SO2	0.00	0.01
Total dfg	6.40	73.44
Wet products		
H2O (reaction)	0.54	10.79
H2O (fuel)	0.05	1.02
Total flue gas	6.99	85.25
Stociometric % CO2:	20.3	

The equations used are from "A Combustion Handbook for Canadian Fuels" by Friedrich and Hayden, 1974

FUEL PERFORMANCE EVALUATION

Fuel:	Bear Essentials hardwood pellets
Test appliance:	Dell-Point Stove s.n.
Date:	00-03-08
	9/9 power/fan setting

DATA SUMMARY

Enter beginning row number:	4
Enter final row number:	454
Enter sampling duration (min)	120

Note: Enter value from cell B8 in B14 equation!

Average Test Results:

SCALE	1.80	kg/h
	4.0	lb/h
Stack @ Psample location	28.8	deg C
Unused	34.1	deg C
Stack @ sample	165.0	deg C
Ash door centre	38.8	deg C
Top frame rail	33.9	deg C
Left side wall centre	47.2	deg C
Inside combustor side wall	520.4	deg C
"13"" above combustor"	535.0	deg C
Unused	55.4	deg C
Stove exit	219.3	deg C
Shrouder wall TC	34.4	deg C
Particulate filter holder	37.1	deg C
O2	11.0	%
CO	71	ppm
CO2	9.79	%
NOx	98	ppm

Particulate Sample

Volume sampled:	35.8	cu ft
Wt of particulate:	0.0039	g
Sample time	120	min
Static pressure	0.55	"H20
Pitot tube rdg	0.05	"H20
Barometric press.	29.77	"Hg
Pitot factor	0.85	
Tunnel diameter	6	"
Velocity:	12.9	fps
Total Tunnel flow	18268	cu ft
Particulate ldg	1.990	g
	1.00	g/h
	0.55	g/kg fuel

CALCULATION OF STOCIOMETRIC PRODUCTS, ACTUAL PRODUCTS, AND EFFICIENCY

ULTIMATE ANALYSIS(dry basis)	
carbon	49.81
hydrogen	6.06
sulphur	0.06
nitrogen	0.15
ash	0.63
oxygen	43.29
Total	100.00

Dry Calorific Value (MJ/kg)	19.60	(	8426	BTU/lb)
Fuel Moisture (% wet basis)	4.86	(	5.1	% db)
As-Fired C.V. (MJ/kg)	18.65	(	8017	BTU/lb)

Flue Gas Values:			
% CO2	9.79011		
% O2	10.9508		
% CO	0.00713		
Flue (C)	165	329	F
Amb't (C)	34	93	F

% Combustible in Ash:	0
from O2:	9.63
from CO2:	10.79

CONVERSION FACTORS:
MJ/kg = BTU/lb*.002326
F = 9/5*C+32 C = 5/9*(F-32)
MC(wb)=MC(db)/(100+MC(db))
MC(db)=MC(wb)/(100-MC(wb))

Air & Flue Gas	from co2	from o2
% Excess Air	106.33	109.64
comb'n air(Sft3/lb fuel)	152.6	155.0
dfg (lb/lb dry fuel)	12.7	12.9
tfg (lb/lb dry fuel)	13.3	13.5
dfg (Aft3/lb dry fuel)	243.9	247.8
dfg (Sft3/lb dry fuel)	152.1	154.5
tfg (Aft3/lb dry fuel)	262.8	266.7
tfg (Sft3/lb dry fuel)	163.9	166.3
CO (lb/lb dry fuel)	0.001	0.001
vol fraction H2O in flue	0.072	

LOSSES	BTU/lb dry fuel	BTU/lb as fired	% loss
DFG	720	685	8.55
Fuel H2O	59	56	0.70
H2	626	595	7.43
CO	4	4	0.02
Comb. in Ash			
Total Loss	1408	1340	16.69
% Efficiency			83.31

STOCIOMETRIC VALUES

Stociometric Air req'd (lb/lb dry fuel)	
Carbon (32/12.011*.01*C)	1.327
Hydrogen (8/1.008*.01*H)	0.481
Sulphur (32/32.066*.01*S)	0.001
Total	1.809
Less O2 in fuel	0.433
O2 from air	1.376
Associated N2 (76.85/23.15*O2)	4.567
Total dry air:	5.943

Stociometric Combustion Products	lb/lb dry fuel	Sft3/lb dry fuel
Stociometric CO2	1.83	14.89
Stociometric N2	4.57	58.54
Stocimetric SO2	0.00	0.01
Total dfg	6.40	73.44
Wet products		
H2O (reaction)	0.54	10.79
H2O (fuel)	0.05	1.02
Total flue gas	6.99	85.25
Stociometric % CO2:	20.3	

The equations used are from "A Combustion Handbook for Canadian Fuels" by Friedrich and Hayden, 1974

Appendix 2. Selected Patents Related to Fibre Transfomation that have Implications for Improving Pellet Quality and Throughput

USA Patent 5,017,319 (Shen, 1992)

Abstract

This invention relates to a process for converting hemicellulose of lignocellulosic material into a thermoset, waterproof adhesive. In one embodiment of the invention the thermoset, water-proof adhesive is used for converting other components of the lignocellulosic material into composite products such as panel products, reconstituted lumber and molded articles without the use of any other adhesive binders which are an essential part of the conventional dry process of manufacturing composite products, such as wood-based particleboard, waferboard, medium density fibreboard, et cetera.

1. Process for converting hemicellulose of lignocellulosic material into a thermoset, water proof adhesive, comprising:
(a) bringing lignocellulosic material in divided form and containing at least 10% hemicellulose, rapidly into contact with high pressure steam at a temperature high enough to release the hemicellose without carbonization thereof;
(b) maintaining the lignocellulosic material in contact with high pressure steam for a time sufficient only for the non-catalytic decomposition and hydrolization of hemicellulose into essentially low molecular weight, water soluble resin material selected from the group consisting of pentose and hexose sugars, sugar polymers, dehydrated carbohydrates, furfural products, organic acids and other minor decomposition products, with negligible carbonization of the hemicellulose and negligible degradation of cellulose;
(c) heating and pressing the water soluble resin materials thus produced in a concentrated form against a surface to be adhered thereto, at a temperature, time and pressure sufficient to polymerize, cross link and thermoset this material into a water proof adhesive adhering to the surface.

2. A process for converting hemicellulose of lignocellulosic material into a thermoset, water-proof adhesive, comprising;
(a) bringing lignocellulosic material, in divided form and containing at least 10 percent hemicellulose, rapidly into contact with high pressure steam at a temperature T (.degree.C.) in the range 160.degree. C. to 260.degree. C.,
(b) maintaining the lignocellulosic material in contact with the high-pressure steam only for a time t (S) seconds in the range according to the formula t.sub. (S) -10.sup.8.5836-0.02801T(.degree.C.)
whereby the temperature is high enough to release the hemicellulose, does not exceed the temperature for carbonization thereof, and, in combination with the limited treatment time t (S) is only capable of non-catalytic decomposition and hydrolyzation of hemicellulose into water soluble resin material selected from the group consisting of pentose and hexose sugars, sugar polymers, dehydrated carbohydrates, furfural products, organic acids and other minor decomposition products, with negligible degradation of cellulose having taken place,
(c) heating and pressing the water soluble resin material thus produced in a concentrated form, against a surface to be adhered thereto, at a temperature of at least 160.degree. C. and for a sufficient time and pressure to polymerize, crosslink and thermoset this material into a waterproof adhesive adhering to the surface.

3. A process according to claim 1, wherein,

(d) the lignocellulosic material, alone or in combination with other lignocellulosic material, in particle, fiber or flake form, containing the water soluble resin material from step (b) is concentrated, as soon as possible, by being dried to a low moisture content to prevent fermentation of the water soluble resin, then
(e) the dried lignocellulosic material, alone or in combination with other lignocellulosic material is formed into a mat, and then
(f) the mat is pressed in step (c) at a temperature in the range 160.degree. C. to 250.degree. C. to avoid charring the mat, and at a pressure and time sufficient, to first polymerize the water soluble resin into the said crosslinked polymeric substance, and thermoset the thus formed polymeric material into the water-proof adhesive, thereby bonding in situ the other components of the lignocellulosic material as the said surface to be ad ere to and forming a bonded, composite product.

4. A process according to claim 1, wherein the lignin portion of the lignocellulosic material is also decomposed and hydrolyzed into low molecular weight lignin and lignin products.

5. A process according to claim 1, wherein the hydrolyzed lignocellulosic material contains less then 30 percent by weight, of low molecular weigh t water solubles selected from the group consisting of sugars, sugar polymers, dehydrated carbohydrates, furfural products, organic acids, lignin, lignin products and other minor decomposition products.

6. A process according to claim 1, wherein the lignocellulosic material is brought into contact with the high pressure steam in a pressure vessel and, after maintaining the lignocellulosic material in contact with the high pressure steam for the time t (S) seconds, the steam pressure in the pressure vessel is released to atmospheric pressure with an explosive discharge to render the lignocellulosic material in fibrous and particulate form.

7. A process according to claim 1, wherein the lignocellulosic material is brought into contact with the high pressure steam in a pressure vessel and, after maintaining the lignocellulosic material in contact with the high pressure steam for the time t (S) seconds, the steam pressure in the pressure vessel is gradually brought to atmospheric pressure to retain the lignocellulosic

material, other than the hemicullose and lignin, substantially in the original form.

8. A process according to claim 1, wherein the lignocellulosic material is brought into contact with the high pressure steam in a pressure vessel and, the steam pressure is maintained within the pressurized vessel while steam treated lignocellulosic material is continuously extruded from the pressure vessel to atmosphere in the time t (S) seconds.

9. A process according to claim 3, wherein the lignocellulosic material, after the high pressure steam treatment, is dried to a moisture content of less than 18 percent to avoid fermentation.

10. A process according to claim 1, wherein t e lignocellulosic material is at least one substance selected from the group consisting of stem, stalk, shrub, foliage, bark, root, shell, pod, nut, husk, fiber, straw, vine, grass, bamboo, reed and wood.

11. A process according to claim 1 or 3 wherein the lignocellulosic material in steps (a) and (e) is selected from the group consisting of particles, fibers, strands, wafers or flakes.

12. A process according to claim 2, wherein a portion of hemicellulose of the lignocellulosic material is removed from the lignocellulosic material before the lignocellulosic material is rapidly brought into contact with high pressure steam in step (a).

13. A process according to claim 1, wherein the lignocellulosic material of step (b) is expressed, or treated with water, to extract unpolymerized, water soluble resin material therefrom as an aqueous solution, water is evaporated from the aqueous solution to concentrate the water soluble resin material, and the concentrated, water soluble resin material is used in step (c).

14. A process according to claim 13, wherein the water is evaporated from the aqueous solution under vacuum.

15. A process of converting lignocellulosic materials into reconstituted composite products, comprising:

(a) bringing lignocellulosic material in divided form and containing at least 10 percent hemicellulose rapidly into contact with high pressure steam at a temperature high enough to release the hemicellulose without carbonization thereof, for a time sufficient only for the non-catalytic decomposition and hydrolization of hemicellulose into essentially low molecular weight, water soluble resin material selected from the group consisting of pentose and hexose sugars, sugar polymers, dehydrated carbohydrates, furfural products, organic acids and otter minor decomposition products with negligible carbonization of the hemicellulose and negligible degradation of cellulose;
(b) immediately drying the lignocellulosic material to a water content of less than about 18%;
(c) shredding the lignocellulosic material to a fibrous state and forming it into a mat;
(d) pressing the said mat using heat and pressure to transform the decomposed and hydrolyzed products of hemicellulose to provide a thermoset adhesive bond and to yield a reconstituted composite product without charring the mat.

16. A process as in claim 15 in which the time in which the lignocellulosic material remains in contact with the high pressure stream is a time t (S) seconds in the range defined by the formula:
t.sub. S) =10.sup.8.5836-0.2801 T(.degree.C.).

17. A process as in claim 16, in which the temperature of the high pressure steam is in the range 160.degree. C. to 260.degree. C.

18. A process as in claim 17 in which the mat is pressed at a temperature of about 160.degree. C. to 250.degree. C. and at a pressure and time sufficient to first polymerize the water soluble resin into a cross-linked polymeric substance, and thermoset the thus formed polymeric material into a water proof adhesive, thereby bonding in situ the otter components of the lignocellulosic material and forming a bonded composite product.

19. A process as in claim 15 in which the lignin portion of the lignocellulosic material is also decomposed and hydrolized into low molecular weight lignin and lignin products.

20. A process as in claim 15 in which the hydrolized lignocellulosic material contains less than 30% by weight of said essentially low molecular weight water soluble resin material.

21. A process for converting lignocellulosic material into a thermoset resin material, comprising:

(a) bringing lignocellulosic material in divided form rapidly into contact with high pressure steam at a temperature high enough to decompose and hydrolyze hemicellulose contained in said lignocellulosic material without carbonization thereof;
(b) maintaining the lignocellulosic material in contact with high pressure steam for a time sufficient only for the decomposition and hydrolyzation of hemicellulose into low molecular weight, water soluble resin material selected from the group consisting of sugars, sugar polymers, furfural, dehydrated carbohydrate, organic acids and otter similar decomposition products, with negligible degradation of cellulose;
(c) separating out the water soluble resin material;
(d) bringing the remaining previously hydrolyzed lignocellulosic material in step (b) rapidly in contact with high pressure steam for a second time at a temperature high enough to decompose and hydrolyze cellulose without carbonization thereof;
(e) maintaining the previously hydrolyzed lignocellulosic material in contact with high pressure steam for a time sufficient for the decomposition and hydrolyzation of the cellulose into low molecular weight, water soluble resin material selected from the group consisting of hexose sugars, sugar polymers, hydroxymethyl furfural, organic acids and otter decomposition products;
(f) separating out the water soluble resin material from the hydrolyzed lignocellulosic material into the water soluble resin material and the hydrolyzed lignocellulosic residue;
(g) heating and pressing the water soluble material thus produced in steps (c) and (f) in concentrated form against a surface to be adhered thereto, at a temperature, pressure and for a time sufficient to polymerize, crosslink and thermoset this material into a waterproof adhesive bond adhering to the surface.

22. A process for converting hemicellulose of lignocellulosic material into a thermoset, water-proof resin adhesive, comprising:

(a) bringing lignocellulosic material, in divided form rapidly into contact with high pressure steam at a temperature in the range of 150.degree. C. to 260.degree. C.;
(b) maintaining the lignocellulosic material in contact with the high pressure steam only for a time sufficient to decompose and hydrolyze hemicellulose into low molecular weight, water soluble resin material selected from the group consisting of pentose and hexose sugar, sugar polymers, dehydrated carbohydrate, furfural, organic acids and otter decomposition products, with negligible degradation of cellulose having taken place;
(c) heating and pressing the water soluble resin material thus produced in a concentrated form, against a surface to be adhered thereto, at a temperature of at least 160.degree. C. and for a sufficient time and pressure to polymerize, crosslink and thermoset this material into a waterproof adhesive bond adhering to the surface.

23. A process for converting cellulose of lignocellulosic material into a thermoset, water-proof resin adhesive, comprising:

(a) bringing lignocellulosic material, which as been treated with high pressure steam to decompose and hydrolyze hemicellulose and from which the water soluble resin material has been extracted, rapidly into contact with high pressure steam at a temperature in the range of 150.degree. C. to 260.degree. C.;
(b) maintaining the lignocellulosic material in contact with the high pressure steam for a time sufficient to decompose and hydrolyze cellulose into low molecular weight, water soluble resin material selected from the group consisting of hexose and pentose sugars, sugar polymers, dehydrated carbohydrate, furfural, organic acids and otter decomposition products;
(c) heating and pressing the water soluble resin material thus produced in a concentrated form, against a surface to be adhered thereto, at a temperature of at least 160.degree. C. and for a sufficient time and pressure to polymerize, crosslink and thermoset this material into a water-proof adhesive bond adhering to the surface.

24. A process of converting lignocellulosic material into reconstituted composite products, comprising:

(a) bringing lignocellulosic material in divided form rapidly in contact with high pressure steam at a temperature high enough to decompose and hydrolyze hemicellulose without carbonization thereof, for a time sufficient for the decomposition and hydrolyzation of hemicellulose into low molecular weight, water soluble resin material selected from the group consisting of pentose and hexose sugars, sugar polymers, furfural, dehydrated carbohydrate, organic acids and otter decomposition products with negligible degradation of cellulose;
(b) immediately drying and reducing, by, in either order, the lignocellulosic material into fiber or particulate to a moisture content of less than 18%;
(c) forming the lignocellulosic material alone or in combination with otter lignocellulosic material in subdivided form into a mat;
(d) pressing said mat, using heat and pressure to transform the decomposed and hydrolyzed products of hemicellulose to provide a thermoset adhesive bond to yield a reconstituted composite product without charring the mat.

25. A process according to claim 21, wherein,

(h) the hydrolyzed lignocellulosic material, alone or in combination with otter lignocellulosic material, in particle, fiber or flake form, containing the water soluble resin material from steps (c) and (f) is concentrated, as soon as possible, by being dried to a low moisture content;
(i) the dried lignocellulosic material, alone or in combination with otter lignocellulosic material is formed into a mat, and then
(j) the mat is pressed at a high temperature to avoid charring the mat, at a pressure and for a time sufficient to first polymerize the water soluble resin material into the said crosslinked polymeric substance, and thermoset the thus formed polymeric material into the waterproof adhesive, t hereby bonding and bulking in situ the lignocellulosic material as the said surface to be adhered to and forming a bonded composite product.

26. A process according to claim 21, wherein the hydrolyzed lignocellulosic material containing 100% or less of water soluble resin material, in combination with otter lignocellulosic material, and in forms of particles, fibers or flakes from steps (b) and (e) is concentrated, as soon as possible, by being dried to a low moisture content, is formed into a mat, and then the mat is pressed at a temperature in the range of 160.degree. C. to 250.degree. C. to avoid charring the mat, and at a pressure and time sufficient to first polymerize the low molecular weight water soluble resin material into the said crosslinked, polymeric substance and thermoset the thus formed polymeric substance into the water-proof adhesive, thereby bonding and bulking in situ the otter components of the lignocellulosic material as the said surface to be adhered to and forming a bonded composite product.

27. A process according to claim 21, wherein the water soluble resin material which is extracted from steps (c) and (f) and eluted with water from the decomposed and hydrolyzed lignocellulosic material, is processed into concentrated form.

28. A process according to claim 21, wherein the water soluble resin material obtained from the decomposition and hydrolization of hemicellulose and cellulose of the lignocellulosic material is used, separately or mixed together, as a thermosetting resin adhesive in liquid or solid form.

29. A process according to claim 21, wherein the water soluble resin materials derived from hemicellulose and cellulose of single or mixed species are used separately or in mixture.

30. A process according to claim 21, wherein the divided lignocellulosic material is mixed with an acidic catalyst in an amount of no more than 5% by weight before steam treatment to accelerate the thermal decomposition and hydrolyzation of hemicellulose and cellulose into water soluble resin material.

31. A process according to claim 21, wherein the lignocellulosic material is derived from forest and agricultural plants of woody or non-wood nature in a single or mixed species.

U.S. Pat. No. 4,627,951

In the applicant's U.S. Pat. No. 4,627,951 there is disclosed a process for making composite products from sugar containing lignocellulosic material, specifically of annual plants of a non-woody nature, such as sugar cane bagasse, and stalks of corn, sorghum, and sunflower, et cetera. The natural sugars and other water soluble materials within the lignocellulosic material are chemically transformed, in situ, by the application of heat and pressure into an insoluble and infusible polymeric substance, acting as both a bonding and a bulking agent, to strengthen the reconstituted composite products with strong mechanical strength and superb dimensional stability.

However, this patented process is limited to lignocellulosic material containing natural free sugars and other water soluble materials and is not applicable to lignocellulosic materials, such as wood, cereal straws, rice husks, et cetera. The conventional process for making composite panel products from lignocellulosic materials relies exclusively on synthetic thermosetting resin binders for bonding. Since synthetic resins, such as phenol- and urea-formaldehyde, are expensive, they normally constitute a large portion of the production cost for the conventional panel products such as particleboard, waferboard, and medium density fiberboard. This holds specifically true in the case of agricultural residues. Because of their physical nature of agricultural residues, a relatively high content of resin binder is required for manufacturing, thus resulting in expensive panel products. The prohibitive cost of synthetic resin binders is the major reason why agricultural residues are not widely utilized today in the manufacturing of panel products, in spite of the abundance and availability of the raw materials.

In recent years a number of manufacturing processes have been developed to utilize agricultural residues around the world. However, none of the processes developed thus far have found commercial acceptance. Thus E.C. Lathrop et al. in "Hardboard from agricultural residues", Modern Plastics, p 126 (April 1951) reported the use of a combination of powdered thermosetting phenolic resin, pine gum and ground rice husks to make composite panel products. Lathrop et al found that the boards that contained as much as 15% phenolic resin were too brittle to be nailed. Moreover, the boards had a density of 1.12 (69.9 lbs. per cubic foot, pcf). This combination of 15% powdered resin and high density made the product too expensive to compete with existing products, and the brittleness of the board placed a severe limitation on its use.

The use of a specially formulated phenolic resin for bonding rice husks has been reported by R. C. Vasisshth in the U.S. Pat. No. 3,850,667, dated Nov. 26, 1974. According to VAsisshth, rice husk boards can be made with 8 to 10 percent of a water immiscible, caustic free, thermosetting phenol-formaldehyde resin and pre-treated rice husks. In this process, a pretreatment is essential in order to break up the rice husk pods into individual leaves, to remove loosely bonded surface material and to screen out fine particles. It is claimed that the inclusion of fine materials generated from the pretreatment would not only increase the resin consumption, but would also introduce some undesirable effects on the properties of the board.

More recently, "New opportunities in manufacturing conventional particleboard using isocyanate binders" reported by G. W. Ball (Proceeding--Washington State University Particleboard Symposium. No. 15, p 266-285, 1981), teaches manufacturing rice husk boards with pretreated rice husks, using 9% of a very expensive polymeric isocyanate resin as the bonding agent. Since isocyanate resin is more expensive than conventional phenolic resin, the production cost of rice husk board is very high. The high manufacturing cost of this rice husk board prevents it from being competitive with the conventional wood-based panel products.

Present day methods of manufacturing panel products from lignocellulosic materials rely exclusively upon synthetic thermosetting resin for bonding. Synthetic resin binders are expensive because they are derived from petro-chemicals. In general, the resin binder cost constitutes a major portion of the production costs for these panel products, thus limiting the type of lignocellulosic material which may be used, particularly those usually selected from agricultural residues. In view of the high resin binder cost and the limitation on the raw material selection, a process that eliminates synthetic resin for manufacturing of composite panel products and which can be used with any lignocellulosic materials would be very attractive economically and technologically.

Since lignin is believed to be the natural binder within lignocellulose and is phenolic in nature, it has been extensively studied and researched as a binder for lignocellulosic composite products. Over the years different methods have been developed for the conversion of wood and agricultural residues into composite products such as panel and moulded products by generating and releasing the natural component of lignin within lignocellulosic materials for use as a resin binder. The most common method of releasing and reactivating lignin is by subjecting the lignocellulosic material to a drastic hydrolysis in the presence of water or acids at an elevated temperature. The hydrolysis removes the hemicellulose portion of lignocellulosic material, hence increasing the ratio of lignin to cellulose over that which is normally present in lignocellulosic materials and therefore improving bonding efficiency.

The U.S. Pat. No. 726,029 by A. Classen uses steam to treat saw dust with acid and cooks it under pressure at a temperature of 105 to 145 degrees Celsius for 30 to 60 minutes to render the hemicellulose water soluble. At the end of the cooking, the reacted mass is washed with water to remove the water solubles before drying and moulding.

Likewise, Sherrard, et al, in U.S. Pat. No. 2,513,316 cooks dry fibrous vegetable material under pressure in a digestor. The resulting material is then thoroughly washed with water to remove the acid and water soluble reaction products. The remaining material is then subjected to heat action and then ground to a powder for moulding.

Again, Schorger and Ferguson, U.S. Pat. Nos. 2,196,277, 2,247,204 and 2,283,820, teach cooking a natural lignocellulosic material with water or with added materials to render a part of the lignocellulosic material water soluble and particularly to dissolve the hemicellulose. The residual products, after extraction of the water solubles and subsequent drying, contain a larger part of the original thermoplastic resinous lignin.

U.S. Pat. No. 2,303,345 by Mason and Boehm describes a process of making tough products from lignocellulosic material. Mason and Boehm use high pressure stream to separate lignin from the lignocellulosic material for bonding, in that hemicellulose is hydrolyzed into water solubles which are removed from the treated lignocellulose before the fibers are made into hardboard.

Consequently the removed water solubles are processed separately as a by-product with a trade mark of "Masonoid". In U.S. Pat. No. 2,224,135, issued to R. Boehm, "Masonid", the water solubles by-products from hardboard manufacturing, are used in making aldehydes, alcohols and organic acids. This patent also mentions that the water solubles thus obtained can be further concentrated and used as a water soluble adhesive. The use of "Masonid" as a water soluble adhesive is also taught in U.S. Pat. Nos. 2,643,953 and 2,716,613, issued to W. Schoel in 1949 and 1950 respectively. In these patents, it is stated that while these water solubles have adhesive properties, it has been found that they are not entirely satisfactory for use as an adhesive. One reason given is that these water solubles are undesirably hygroscopic and therefore, the bond formed by them in adhesive application is somewhat unstable. Under high humidity the adhesive bond formed by these water solubles absorbs moisture from the air, thereby weakening the adhesive bond, whereas under low humidity, the adhesive bond formed by these water solubles loses moisture and also weakens. Upon absorbing moisture, the adhesive bond formed by these water solubles tends to liquefy, while moisture loss tends to harden the board so that is approaches a state of brittleness (U.S. Pat. No. 2,643,953, Col. 1, Lines, 25-35).

Boehm and Schoel were not aware that these water solubles are thermosetting and capable of being used as a water-proof adhesive if proper processing application is followed. Instead, according to Boehm and Schoel patents the "Masonoid" may be used only as a water-soluble adhesive. Since they did not recognize the bonding nature of the water soluble materials, their patents did not teach thermosetting in their respective processes and the resulting bond which is not thermoset, is therefore not water-proof and has only limited commercial application.

The lack of appreciation and understanding of the potential of both Boehm and Schoel that the water solubles from hemicellulose hydrolyzation are capable of being thermoset into a water-proof adhesive bond, which is physically and chemically stable and resistant to boiling water, may be attributed to the logical development of the Masonite process in that the natural lignin is used as a binder, not the water soluble materials, which are removed as "Masonoid" in the Masonite process. The removal of water solubles is a key feature of Masonite process for making board products.

A similar Masonite process is taught in U.K. Patent 497,477 issued to W. W. Triggs in 1938, using steam at a temperature in the range from 216 to 285 degree Celsius with a time range from 12 seconds to 30 minutes to treat the lignocellulosic material for moulded products. Again, Triggs relies on the lignin for bonding and specifies the removal of water solubles generated during the steam treatment in order to obtain a high quality product.

All the processes mentioned above use lignin as a binder and remove the water solubles during the processes; therefore, requiring an enormous amount of water for processing. The commercial use of the Masonite process, which consumes a particularly large quantity of water has caused serious water pollution as well as other environmental concerns. This is one of the main reasons for the decline of the use of the Masonite process for making headboard since World War II. Today there are only a few remaining Masonite plants operating around the world. The only Masonite plant built in Canada was closed down in 1985.

Glab describes in 16 U.S. Pat. Nos. (2,706,160 the first and 3,252,815 the latest) the treatment of lignocellulosic material with high temperature steam for long duration in the presence of a chemical reactant capable of splitting at least a portion of lignin, which is used as a thermoplastic binder. In the examples cited in the Glab patents, steam at a temperature in the range of 218-232 degree Celsius to 254-288 degree Celsius is used with a treating time in the range between 20-30 minutes to 4-5 minutes. During this severe steam treatment, not only are the water solubles from hemicellulose hydrolysis inevitably further transformed by polymerization into a high molecular weight product, which is retained and used as a plasticiser in moulding operation, but the process also purposely reduces the alpha cellulose in molecular size to prevent swelling of moulded products (U.S. Pat. No. 2,984,580, Col. 1, Lines 34-38). In contrast to Classen, Sherrard, Schorger, Mason, Boehm and Triggs, all of whom remove water solubles from hemicellulose hydrolysis in their processes, Glab claims that the full utilization of lignocellulosic material is made by retaining the polymerized water solubles from hemicellulose as a plasticizer in the moulding operation, while the catalyzed lignin is used as a binder. Glab also claims that the flow of the mouldable material is improved by his process and a short time is required if a plasticizer is added (U.S. Pat. No. 2,984,578, Col. 4, Lines 20-23). Glab identifies and states that the preferred plasticizers are water, furfural, anile and phenol in a preferred quantity between 2-20%. Glab, like Classen, Sherrard, Schorger, Mason, Boehm and Triggs, was not aware, as the applicant has found, that the water soluble decomposition material from hemicellulose hydrolysis carried out in a mild steam treatment can be used as a thermosetting water-proof adhesive binder. Instead, Glab used very high steam temperature in combination with a long steaming duration and in the presence of a chemical reactant to break down lignin and alpha cellulose. In his process, Glab inevitably and unintentionally over cooked the hemicellulose and destroyed it beyond use as a binder. Glab polymerized, thermoset and converted the water solubles derived from hemicellulose decomposition and hydrolysis to high molecular weight materials which, after being thermoset could be used as plasticizers for the treated lignocellulose when moulded, while lignin is made to flow and function as a binder between the comminuted lignocellulose particles (U.S. Pat. No. 2,984,580, Col. 2, Lines 1-3). The steaming conditions (the combination of temperature and time) used by Glab were much more severe than those employed by Triggs. In comparison, Triggs' treating conditions are much too harsh to result in the present invention. The comparative severity of steam treating conditions employed by Triggs, Glab and the applicant is clearly shown in FIG. 1.

All processes known to the applicant, which use natural lignin as a binder, have one unique characteristic in that the final lignocellulosic moulding product is very dense and heavy. For any structural application, the specific gravity of the moulded products is always in the range of 1.0 to 1.4 (62.4 to 87.4 pcf). This is consistent with the use of lignin as a binder, resulting from the required very high moulding pressure which is necessary to make the lignin flow and bind. Furthermore, the severe treatment by high steam temperature for a long time in the known processes has also caused damage to the structural integrity of cellulose with a much lower degree of polymerization (D.P), particularly in the case of Glab, who specifies the controlled degradation so that the alpha cellulose is reduced in molecular size sufficiently to prevent swelling of the moulded products (U.S. Pat. No. 2,984,580, Col. 1, Lines 35-37). The damaged cellulose fiber, i.e. that with the lowered D.P., being the only structural component the moulded products has to rely on for the high density to compensate for the physical weakness imparted to the product, caused by the severe treatment. Thus high density products produced by these known processes have limited uses.

Cdn. Patent 1,267,407 METHOD OF RENDERING LIGNIN SEPARABLE FROM CELLULOSE AND HEMICELLULOSE AND THE PRODUCT SO PRODUCED.

The components of lignocellulosic materials such as wood, straw, bagasse and other lignocellulosics are dissociated in a reactor. The process raises their temperature using high pressure steam, to a temperature of 185 to 240 degrees celcius at which temperatures the input material softens. When the required softening temperature is achieved the steam is vented to a lower pressure and then released instantly to atmosphere. The lower pressure creates lower mechanical forces on the exiting material which results in a higher degree of polymerization of the lignin, xylan and cellulose fractions.

Cdn. Patent 1,282,777 A PROCESS TO DISSOCIATE AND EXTRACT THE LIGNIN AND OPTIONALLY THE XYLAN FROM THE PRIMARY WALL AND MIDDLE LAMELLA OF LIGNOCELLULOSIC MATERIAL WHICH RETAINS THE STRUCTURAL INTEGRITY OF THE FIBRE CORE AND THE PRODUCT SO PRODUCED.

This patent is related to the separation of the fibres from each other in lignocellulosic (straw, bagasse, wood) composites, and at the same time to dissociate the lignin and the xylan in the middle lamella and the primary wall of the lignocellulosic material, to enable a simple non reactive solvent extraction of the middle lamella and primary wall components while substantially retaining the structural integrity of the fibre core, sometimes referred to as the S2 layer, which is the strength member of the lignocellulosic fibre. The purpose of this process is to produce a fibre suitable to replace conventional chemical thermal mechanical pulp, for paper or as a carrier for high absorbency cellulose in diaper and similar absorbent material applications, and at the same time to recover the chemical components of the middle lamella and the primary wall of the fibre, as co-products in a marketable, chemically reactive form.

Cdn Pat 1,278,294: A METHOD FOR FRACTIONATION OF LIGNINS FROM STEAM EXPLODED LIGNOCELLULOSICS TO PROVIDE FRACTIONS WITH DIFFERENT BUT REPRODUCIBLE PROPERTIES AND SOME METHODS FOR THEIR INTERCONVERSIONS AND THE PRODUCTS SO PRODUCED.

The chemical components of lignocellulosic material which have been dissociated by a steam explosion process can be extracted from the mixture of components using a solvent extraction process. The solvents are water, alcohol and a mild caustic in that order, or the alcohol step can be by-passed and only water and caustic are used. The caustic is a stronger solvent and it will extract the alcohol solubles along with the caustic only solubles. The eluant from the these extractions contains a range of lignin derived substances, which have different applications, such as thermoplastic and thermosetting characteristics. This invention describes a method for partitioning these lignin components into reproducible fractions having definable characteristics for particular applications. For instance, many copolymer applications require a thermosetting only fraction of the lignin. Other applications require a thermoplastic only lignin. The patent also describes a process for converting the thermoplastic lignin fraction to thermosetting lignin.

Cdn Patent 1,768,260: METHOD OF PRODUCING CELLULOSE TRIACETATE FROM MERCERIZED OR UNMERCERIZED BLEACHED CELLULOSE PRODUCED FROM DISSOCIATED LIGNOCELLULOSIC MATERIAL PREPARED IN ACCORDANCE WITH THE TEACHINGS OF CANADIAN PATENTS 1,217,765 OR 1,141,376 OR COMPETING VERSIONS THEREOF AND THE PRODUCTS SO PRODUCED.

This invention relates to the use of an explosion process reactor for the production of high crystallinity, low DP and narrow DP distribution cellulose, for value added conversion of the cellulose component of the dissociated lignocellulosic starting material to a range of grades of cellulose triacetate having different degrees of purity, reactivity and polymerization. The first few steps in the process produce a standard bleached cellulose product, which can then be post bleach treated in a number of different ways dependent on end product requirements to produce a range of celluloses having varying degrees of polymerization, purity, reactivity and crystallinity, in a mercerized (cellulose II) or unmercerized (cellulose I) form for value added conversion to cellulose triacetate. These same post bleach treatments can be used to prepare cellulose for a wide range of other value added conversions and uses.

Cdn Pat 1,284,262 METHOD OF MOULDING USING DISSOCIATED LIGNOCELLULOSIC MATERIAL AND THE PRODUCT SO PRODUCED.

Dissociated lignocellulosic material produced by a process of explosive depressurization is moulded into products of widely varying densities. Various fibrous and woody materials can be incorporated into the moulded product to give a wide range of nailing and strength characteristics. Colour, water repellent, preservative and fire retardant materials can be mixed with the material before moulding. Other aggregates can be bound into the moulded product which can contain fire enhancement materials for fuel applications including the fireplace.

The economics of producing moulded board and other products can be improved significantly by the removal of the water soluble fraction of the dissociated lignocellulosic material, and separating the isolated chemicals. This is especially true because the cost of replacement crosslinking chemicals is less than the value of the water-soluble xylan fraction.

Cdn Pat 1,198,703:

METHOD OF PRODUCING LEVEL OFF DP MICROCRYSTALLINE CELLULOSE AND GLUCOSE FROM LIGNOCELLULOSIC MATERIAL

A cost effective process for producing a very pure form of industrial glucose has been developed. This glucose can then be converted to ethanol by routine fermentation technology. The process begins by exploding the lignocellulosic material by the Tigney Technology process. The material is then transferred to a column and water, alcohol and/or caustic extracted and may be bleached for extra purity. This leaves a pure (94%) form of unbleached cellulose or 98% pure bleached cellulose. A one to two percent mineral acid solution is then added to the cellulose by first pushing the caustic solubles out of the cellulose with water, then displacing the water with the mild acid solution. The material is then removed from the column, dewatered mechanically and then dried down to a moisture content in the 5 to 50 percent range. The acid impregnated cellulose is then placed back in the reactor where high pressure steam is rapidly injected into the material to bring its temperature to 234 degrees celcius in about 45 seconds. The cellulose is hydrolyzed to glucose. In the process it is converted from a fibre to a liquid form and is discharged rapidly from the reactor. The rapid discharge allows the steam to flash off, which cools the liquid glucose to quench the hydrolysis reaction. The value of the initially extracted water, alcohol and caustic co-products from the processed input material exceeds the total cost of the process. Thus, low cost ethanol is assured. One important aspect of this process that is not immediately obvious, is that by using the column to impregnate the cellulose with acid, one is assured of total and even contact between the acid and each of the cellulose molecules for good quality control on the process.

Depending on the process conditions and the concentration of the acid, a level off DP microcrystalline cellulose fraction suitable for use as a filler in plastics may also be produced and separated from the glucose by filtration. Another alternative is to bleach the cellulose, then extract the beta fraction for conversion to glucose and use the alpha cellulose fraction for high value added applications such as cellulose triacetate.