United States
Department of
Agriculture

**Forest
Service**

Forest
Products
Laboratory

Research
Paper
FPL-RP-523

Biopulping

A Glimpse of the Future?

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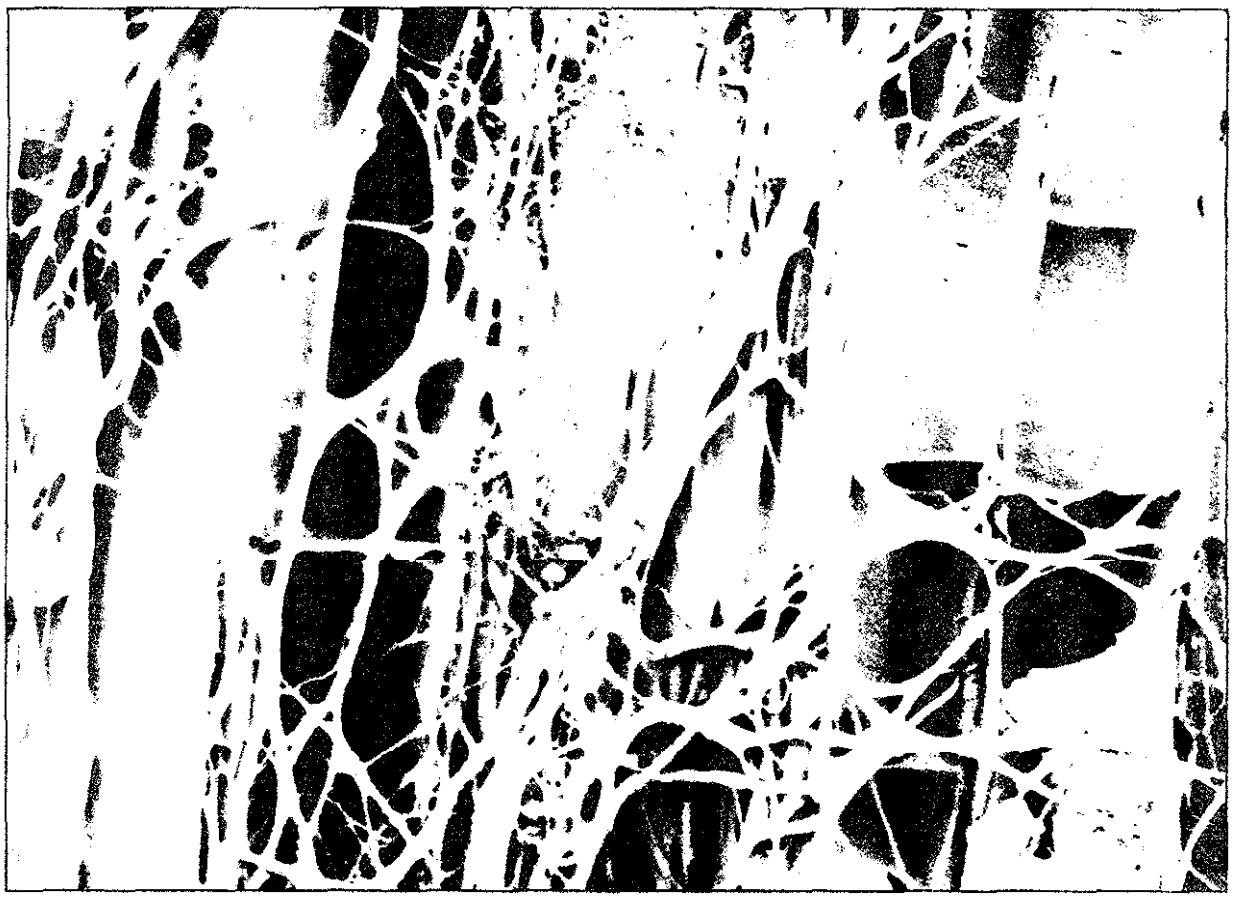

Abstract

This is the final report of Biopulping Consortium I, a 5-year research and information program involving the USDA Forest Service, Forest Products Laboratory (FPL), the University of Wisconsin (UW), the University of Minnesota, and industry. The objective of the Consortium research was to evaluate the technical feasibility of biopulping, defined as the fungal pretreatment of wood for pulping. The research focused on mechanical pulping, specifically on energy savings for the pulping itself, and on paper properties. Past work on biopulping has been minimal, but generally encouraging. In addition to the research objective, the Consortium served an information and education function, interfacing the industrial partners with developments in biotechnology.

The overall conclusion of this 5-year research effort is that biopulping works. Through the use of the proper lignin-degrading fungi, significant energy is saved in mechanical pulping, and paper strength properties are enhanced. Optical properties are diminished; however, brightness can be restored readily by bleaching. The process appears to be less polluting than chemi-mechanical processes, and the economics look favorable if the process can be performed in a chip pile-based system

Keywords: Biopulping, *Ceriporiopsis subvermispora, Phanerochaete chrysosporium, mechanical pulping, solid substrate fermentation, bioreactor*

Acknowledgments

We thank the following for significant contributions to this research: Michael C. Attridge, Andrew J. Baker, Sarah Costello, Leatha Damron, George Harpole, Thomas W. Jeffries, Jane D. Kohlman, Gary F. Leatham, Lou Lunte, Efrat Livny, Marc Ostermeier, Sanya Reyes-Chapman, Jane Sherwood, Freya Tan, and Theodore H. Wegner.

This research was partially funded by the following companies:

Andritz Sprout-Bauer
Boise-Cascade Corporation
Celulosa Arauco y Constitucion S.A.
Celulosa Puerto Piray S.A.
Champion International Corporation
Chimica del Friuli
Consolidated Papers, Incorporated
The Dow Chemical Company
Great Northern Nekoosa Corporation/Georgia Pacific
James River Corporation
Leykam Mürztaler A.G.
Mead Corporation
Metsä Serla Oy
Nalco Chemical Company
Novo Nordisk A/S
Potlach Corporation
Proctor and Gamble Cellulose Company
Sandoz Chemicals Corporation
Scott Worldwide
Union Camp Corporation
Weyerhaeuser Paper Company

December 1993

Kirk, T. Kent; Koning, John W. Jr.; Burgess, Richard R.; Akhtar, Masood: Blanchette, Robert A.; Cameron, Douglas C.; Cullen, Daniel; Kersten, Philip J.; Lightfoot, Edwin N.; Myers, Gary C.; Sachs, Irving; Sykes, Marguerite; Wall, Mary Beth. 1993. Biopulping—A glimpse of the future? Res. Pap. FPL–RP–523, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 74 p.

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Cover photo shows hyaphae of *Ceriporiopsis subvermispora* growing on an aspen wood chip. (1 cm = 6 μ).

Executive Summary

This is the final report of Biopulping Consortium I, a 5-year research and information program involving the USDA Forest Service, Forest Products Laboratory (FPL), the University of Wisconsin (UW), the University of Minnesota, and industry. The objective of the Consortium research was to evaluate the technical feasibility of biopulping, defined as the fungal pretreatment of wood for pulping. The research focused on mechanical pulping, specifically on energy savings for the pulping itself, and on paper properties. Past work on biopulping has been minimal, but generally encouraging. In addition to the research objective, the Consortium served an information and education function, interfacing the industrial partners with developments in biotechnology.

The overall conclusion of this 5-year research effort is that biopulping works. Through the use of the proper lignin-degrading fungi, significant energy is saved in mechanical pulping, and paper strength properties are enhanced. Optical properties are diminished; however, brightness can be restored readily by bleaching. The process appears to be less polluting than chemi-mechanical processes, and the economics look favorable if the process can be performed in a chip pile-based system.

More than 200 bench-scale biopulping runs were completed. They involved inoculating chips, incubating the chips under controlled conditions, producing refiner mechanical pulp, and making and testing paper handsheets. Measurements included weight loss on fungal treatment, refining energy consumption, and several paper strength and optical properties. In some runs, chemical brightening (bleaching) experiments were done, and in others, refiner effluents were collected and analyzed for toxicity, and biochemical and chemical oxygen demands.

A global evaluation of the data leads to the following conclusions regarding fungal pretreatments:

l Of the several hundred species and strains of lignin-degrading fungi examined, the relatively rare fungus *Ceriporiopsis subvermispora* was the best for saving pulping energy and improving paper strength properties with both pine and aspen woods. (The Consortium obtained a U.S. patent on the use of this fungus for biopulping.) Most of the research reported here was done, however, with *Phanerochaete chrysosporium,* which is the most studied lignin-degrading fungus. It is an effective biopulping organism with aspen, but not pine.

- Energy required for refining was reduced, in many runs by 40% or more.

- Effective pretreatments caused little loss of wood substance (<10%), except when high nutrient nitrogen supplements were used.

- Handsheet density was decreased.

- Tear index increased significantly; burst, tensile, and tensile energy absorbtion indices generally increased, but tensile elongation and zero span tensile were usually not affected significantly.

- Fiber length index was not usually affected.

- Brightness and scattering coefficient were reduced, but opacity was not significantly affected.

- Most runs involved 4-week incubations in the bioreactors; however, studies with *P. chrysosporium* showed that 2 weeks were sufficient for most gains with aspen.

The number of variables that can affect fungal pretreatment is large. Therefore, experiments were conducted to examine the effects of some of those (in addition to fungus species) that were considered likely to have the largest effect. Findings from the specific experiments include the following:

- Wood batch had little influence on the outcome of biopulping experiments (aspen).

- Chip storage method (fresh, airdried, or frozen) had no influence on biopulping.

- Inoculum age and form (spore, mycelium suspension, or colonized chips) were without significant influence.

- Adding nutrient nitrogen to the chips as a defined source (L-glutamate or ammonium tartrate) increased energy savings and improved strength properties, but led to high weight losses (up to about 22%). Addition of a nonchemically defined source (yeast extract) to aspen chips gave large biopulping benefits, using both *P. chrysosporium* and *C. subvermispora,* with low weight losses (<10%).

Aspen biopulp was responsive to both hydrogen peroxide and sodium hydrosulfite; it could be bleached to 80% brightness with peroxide and 60% brightness (newsprint level) with hydrosulfite.

The effluent (first refiner pass) from fungus-pretreated pulps was lower in toxicity, relatively unchanged in biochemical oxygen demand, and somewhat higher in chemical oxygen demand than that from control pulps.

Microscopy revealed that the normally rigid wood cell wall seems to relax and swell during fungal pretreatment, leading to greater fibrillation during pulping. However, the molecular basis for pretreatment efficacy was not fully clarified.

Options for biopulping scale-up range from enclosed, controlled aerated static-bed bioreactors to modified chip piles. Aerated static-bed bioreactors have the advantages of good process control and the ability to maintain asepsis with the drawback of high capital and operating costs. Modified chip piles are less costly but reduce process control capabilities. For each, the key design decisions include choice of organism, degree of asepsis, size and type of inoculum, physical conditions (temperature, moisture, and aeration), and type and amount of added nutrients.

Techniques to monitor dry weight loss, moisture content, and growth rate as functions of time using carbon dioxide production data were developed. To more easily obtain carbon dioxide production data, an instrumented bioreactor system was designed and constructed.

A macroscopic model was developed for the biopulping process, and the required operating conditions were determined. From mass transfer calculations, it was concluded that gaseous mass transfer limitations are negligible in an air-filled lumen but are critical in a water-filled lumen. Preliminary efforts were made toward development of a detailed model of bed dynamics. This model will be useful for applying data obtained at the laboratory scale to the design of an industrial-scale process. It is concluded that research must focus on determining the degree of process control strictly necessary for successful biopulping and designing a low-cost process based on these constraints.

The overall conclusion from this effort is that biopulping is technically feasible. The challenge is to make it commercially viable.

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Biopulping
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Introduction

Biopulping is the concept of deliberately harnessing white-rot fungi as a pretreatment for pulping. At present, pulp is produced from wood either by chemical delignification, mechanical separation of the cells (fibers), or combinations of chemical and mechanical methods. Mechanical pulping methods are used increasingly because they give much higher yields (>90%) than do chemical methods (40% to 50%). Mechanical pulping methods are also less polluting than chemical methods, and mechanical pulping mills are less expensive to build. The main disadvantages of mechanical pulps are low-quality pulps that are unsuitable for fiber products requiring high strength properties and the high energy requirement (cost) to make mechanical pulps.

Chemical pretreatments of wood chips are used to enhance the strength properties of mechanical pulps. However, making such chemi-mechanical pulps generates chemical waste streams that must be treated, decreases pulp yield by removing wood substance (hemicelluloses and lignin), and does not significantly reduce the energy requirement. Biopulping, as studied to date, is actually "biomechanical" pulping, the use of fungi to replace chemicals in pretreating wood for mechanical pulping.

Fresh wood chips destined and stored for pulp production are rapidly colonized by a variety of microorganisms, including many species of fungi. These organisms compete vigorously while easily assimilable foodstuffs last, and then their populations decrease. They are replaced by fungi that are able to degrade and gain nourishment from the cell wall structural polymers: cellulose, hemicelluloses, and lignin. Left unchecked, these last colonizers, mostly white-rot fungi, eventually decompose the wood to carbon dioxide and water. Some selectively degrade the lignin component, which is what chemical pulping processes accomplish. It is those fungi that are the focus of biopulping research.

Past Work

Chemical analyses of wood partly decayed by certain white-rot fungi revealed early on that lignin had been removed selectively; that is, the cellulose content had increased. Actually, some naturally white-rotted woods are so heavily delignified that they resemble chemical pulps and can be made into paper that has excellent properties. Thus, the concept of biopulping was probably obvious to initial investigators.

Perhaps the first serious consideration of fungal delignification for pulping was by researchers at the West Virginia Pulp and Paper Company (now Westvaco) research laboratory in the 1950s. Their investigation resulted in a published article (Lawson and Still 1957) that surveyed 72 lignin-degrading fungi and summarized what was known about how the fungi degrade lignin, which at that time was little. In about the same period, studies of the effect of natural decay of pine by white-rot fungi on chemical pulping showed that most paper strength properties increased as the extent of decay increased (Reis and Libby 1960, Kawase 1962).

Research on biopulping per se that might have been done by various companies from the 1950s to the present has not been published. Also unpublished, except as an internal report at the Forest Products Laboratory (FPL), was a study in 1972 of biomechanical pulping done in collaboration with North Carolina State University in Raleigh. Aspen wood chips ***were*** partly decayed by *Rigidoporus ulmarius* (Sow.:Fr.) Imaz., mechanically fiberized to a pulp in a PFI mill, and the pulp made into paper. The FPL found that the pulping required fewer revolutions in the PFI mill than for the untreated control wood, suggesting lowered energy consumption. It was also found that the paper from the biomechanical pulp was stronger.

Similar work was done shortly thereafter at the Swedish Forest Products Laboratory (STFI) in Stockholm, resulting in the first published paper on "biopulping" in Swedish (Ander and Eriksson 1976). In that report, results very similar to FPL's were described. In 1976, the Swedish researchers patented "a method for producing cellulose pulp" (Eriksson and others 1976). After the initial study, the Swedish group worked on various aspects of biopulping, primarily with the white-rot fungus *Sporotrichum pulverulentum* Novobranova. Meanwhile, work at the FPL focused on the mechanism of lignin degradation by a white-rot fungus that was tentatively referred to as *Periophora* "G." Both fungi were chosen because they grew and degraded lignin quite rapidly in comparison to other fungi, and they also produced copious conidia, making them easy to manipulate. It was a surprise to both laboratories when the two fungi were found to be synonymous; the species is now classified as *Phanerochaete chrysosporium* Burds. (Burdsall and Eslyn 1974).

The Swedish researchers made a number of contributions to biopulping (Eriksson and Kirk 1985). They described the growth rates of *P. chrysosporium* through wood, finding that colonization of pulpwood chips is unlikely to be rate-determining. Scanning and transmission electron microscopy were used to show the growth patterns in wood and the degradation patterns of the cell walls. The group conducted studies on biomechanical pulping, showing energy savings and paper strength improvements. Considerable effort went into developing cellulase-less mutants of selected white-rot fungi for biopulping (Johnsrud and Eriksson 1985). Attempts by the group to scale up the biopulping process were not notably successful (Samuelsson and others 1980). That work, however, was undoubtedly premature, because insufficient information was available on how to scale up the fungal treatment. Subsequent work on a large scale with bagasse, in cooperation with Cuban scientists, was more promising (Johnsrud and others 1987).

Biopulping received little attention outside of Sweden until our recent investigations. In one. small study, Bar-Lev and others (1982) reported that treatment of a coarse mechanical pulp with *P. chrysosporium* decreased the energy required for further fiberization and increased paper strength properties. Akamatsu and others (1984) found that treatment of wood chips with any of 10 white-rot fungi decreased mechanical pulping energy, and with 3 of the fungi (*Trametes sanguinea, T. coccinea,* and *Coriolus hirsutus*), increased paper strength properties.

Establishment of Biopulping Consortium

Taken together, the results of these previous studies suggested in 1986 that biomechanical pulping merited a comprehensive investigation. The concern was how to carry out the fundamental research necessary to determine the technical feasibility of biopulping. At this time, the pulp and paper research program of the FPL was reviewed by a liaison committee of the American Paper Institute and the Technical Association of the Pulp and Paper Industries (API/TAPPI). At the suggestion of the committee chairman, and then TAPPI president, Sherwood Holt, the FPL was requested to suggest areas of future research that it deemed important to the industry. Among other things, the committee urged FPL to establish closer research ties with industry and the University of Wisconsin (UW); it suggested further that a three-way consortium be formed to facilitate such cooperation. An *ad hoc* committee (Sherwood Holt, Arthur Dreshfield, Claus Globig, and William Cullison) was established to review these ideas. After considering six possible areas, biopulping was selected and referred to the API/TAPPI committee for endorsement. The committee endorsed the idea and the next step was to set up an organization to carry out the research. During this time, about 1 year, exploratory biopulping research was conducted at the FPL in the Institute for Microbial and Biochemical Technology (IMBT).

Working through the newly created UW Biotechnology Center (UWBC) and with support from FPL and TAPPI, a brochure was designed and sent to pulp and paper and associated companies. An organizational meeting was held in October 1986 to discuss the scope and organization of the biopulping program and outline goals. From this meeting, a Biopulping Consortium of the FPL, the UW, and industry was formed. The Wisconsin Alumni Research Foundation

(WARF) was chosen to handle the intellectual property that was expected to come from the Consortium's research.

In April 1987, a cooperative research program on biopulping began, involving the FPL, the UWBC, and nine pulp and paper and related companies. Each company contributed $15,000 and agreed to contribute $15,000 each year for the next 4 years for a total contribution of $75,000. Companies that joined later paid $20,000 or $25,000 for their first year contribution, and subsequently $15,000/year. The number of companies in the Biopulping Consortium had grown to 20 by April 1990.

The Consortium was co-directed by T. Kent Kirk, Director of IMBT at FPL, and Richard R. Burgess, Director of UWBC. The establishment and coordination of the Consortium were facilitated by John W. Koning, Jr. in concert with Jane Sherwood (UWBC) and Jane Kohlman (FPL).

The overall objective of the 5-year Consortium research effort was to evaluate the technical feasibility of using a fungal pretreatment for mechanical pulping to save energy and/or improve pulp and paper properties. In addition, it was assumed that the fungal pretreatment would have less environmental impact than would chemical pretreatments, which we viewed as significant in its own right.

This paper summarizes the findings of the Consortium research. Included are the data from more than 200 biopulping runs as well as statistical analyses. Needs for future research are briefly discussed.

Materials and Methods

The overall approach was to screen fungi, develop protocols, evaluate bioreactors, mechanically refine untreated and fungus-treated chips, prepare and evaluate handsheets for strength and optical properties, and analyze data. Experiments with biopulp brightening (bleaching), effluent analysis, economics, and engineering scale-up were added later. Not reported here, but also studied were fundamental aspects of the enzymology of biopulping fungi and of the molecular genetics associated with the enzymes. Results of these efforts were reported in the scientific literature (see Appendix A). The Consortium was served by an information group that screened the world's literature related to biopulping.

Fungus Screening

Fungi were obtained either from the Center for Mycology Research, FPL, or from the culture collection of the Department of Plant Pathology, University of Minnesota, St. Paul, Minnesota. Cultures were maintained on potato dextrose agar (PDA) slants at 4°C until used.

A standard *in vitro* wood decay procedure (Otjen and others 1987) followed by chemical analyses (Effland 1977) was used. Although these procedures were tedious, they provided several promising species and strains for biopulping.

During the 5-year research, additional screening procedures were explored in an attempt to increase efficiency. They are described in Results and Discussion.

Protocol Development

Wood Chips

The experiments were conducted mainly with aspen (*Populus tremuloides*) and later with pine (*Pinus taeda*). Logs were obtained as needed, debarked, and chipped to about 6 mm. Each batch of aspen chips was identified with a letter. Wood batches A through C were obtained from Consolidated Papers Corporation,[1] Wisconsin Rapids, Wisconsin. The logs used for batches D and E were cut by the research team on the Nicolet National Forest, Wisconsin. Pine logs were obtained from the Bienville National Forest, Mississippi. Newly made chips were mixed well, placed in plastic bags, and immediately frozen to prevent the growth of contaminating microorganisms.

Inoculum Preparation

For most experiments described here, inoculum consisted of chips thoroughly grown through with the desired fungus. To begin an inoculum preparation, potato dextrose agar (Difco Laboratory, Detroit, Michigan) plates were inoculated from the working stock cultures. The plate cultures were incubated at 27°C for 10 days for all the fungi except *P. chrysosporium,* which was incubated at 39°C for 5 days. The wood chips were thawed and sampled to determine the initial moisture content. A modified chemically defined medium (MCDM) (Table 1) was prepared as described by Leatham (1983). The nutrient solution was added to wood chips in a plastic bag in sufficient water to bring the moisture content of the chips up to 60% (wet weight basis). The chips were allowed to take up the water and nutrients; exposure time ranged from 2 to 24 h. [Note that the commercially acquired chips did not absorb the moisture as readily as did the laboratory prepared chips. Part of this could be a result of the difference in chip size; the commercial chips were nominal 18 mm and the laboratory chips were nominal 6 mm.] Chips (100 to 300 g dry weight) were then placed in 2,800-ml Fernbach flasks, which were autoclaved for 45 min and cooled to room temperature.

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table I--Contents of modified chemically defined medium

Nutrient	Ovendried chips (g/kg)
D-glucose	37.50
L-glutamic acid	0.38
KH_2PO_4	3.00
$MgSO_47H_2O$	3.00
Mineral stock solution[a]	15.00
Trace element stock solution [b]	1.50
Vitamin stock solution[c]	1.50

[a]Stock solution prepared by dissolving 3.67 g of $CaCl_2$•$2H_2O$, 3.60 g of $MnCl_2$•$4H_2O$, and 1.04 g of $ZnCl_2$ (anhydrous) in 1 L of water.

[b]Stock solution prepared by dissolving 14.1 g of Fe $(NH_4)_2(SO_4)$•$6H_2O$, 0.784 g of $CuSO_4$•$6H_2O$, 0.081 g of $CoCl_2$•$6H_2O$, 0.051 g of Na_2MoO_4•$2H_2O$, 0.081 g of $NiCl_2$•6H2O, 0.038 g of $SnCl_2$•$2H_2O$, and 2 ml of concentrated HCl in 1 L of water.

[c]Stock solution prepared by dissolving 1 g each of inositol and thiamine•HCL, 0.1 g each of pyriodoxine•HCl, nicotinic acid, sodium pantothenate and riboflavin, 0.03 g of biotin, and 0.01 g each of folic acid and cyanocobalomin in 1 L of water.

The chips in these "seed flasks" were inoculated aseptically with mycelium-covered agar plugs from the culture plates. The inoculated chips were mixed well and incubated, usually for 4 weeks, at 27 ± 1°C at 65 ± 5% relative humidity for all the fungi except *P. chrysosporium,* which was incubated at 39 ± 1°C at 65 ± 5% relative humidity. In some experiments, amendments were added to the inoculum chips, as described.

Bioreactor Evaluation

Scientific literature provides few guidelines that might be used to design a bioreactor for the fungus treatment of wood chips. Therefore, we examined a number of possible configurations. Three bioreactors that produced good results are described in the following.

The rotating drum bioreactor is constructed of 316 stainless steel consisting of two major parts: an outer case that serves as an incubator, with a large access door and ports for aeration and nutrient addition, and an inner drum for the wood chips (Fig. 1). During operation, the bioreactor resides within a temperature-controlled incubator; the speed of rotation can be varied from 1 rev/min to 1 rev/day. This design allows for aeration of the wood chips and, if a

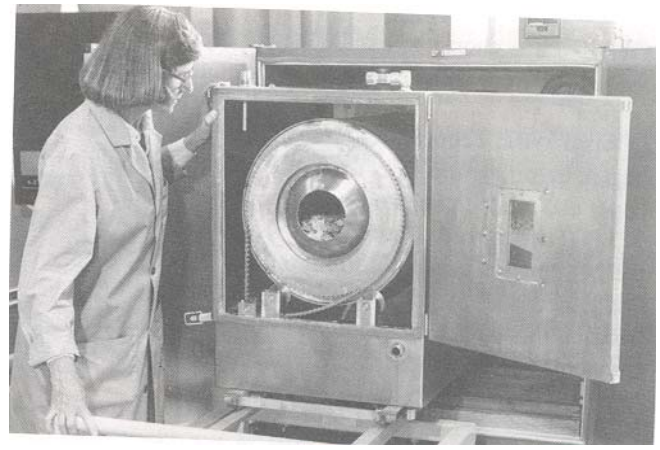


Figure 1—Rotating drum bioreactor (Myers and others 1988).

perforated inner drum is used, for drainage of metabolically produced water. For further details see Myers and others (1988). Several runs were made in this incubator (1-6, 9, 12, 15, 19, 21, 24-26, 29-33, 38-42, 79, 100, 101, 137).[2] The rotating drum bioreactor was later replaced by simpler units. Note: Eriksson and Vallander (1982) also used a rotating drum type of bioreactor in biopulping studies.

The stainless-steel, stationary-tray bioreactor is diagramed in Figure 2. Filtered and humidified air is supplied to the chips during the incubation period. For details, see Akhtar and others (1992) and patent by Blanchette and others (1991). This bioreactor type was used (runs 7, 8, 10, 11, 13, 16-18, 20, 23, 27, 28, 34-37, 51-74, 78, 80, 123-127, 169) until it was replaced by the aerated static-bed bioreactor.

The aerated static-bed bioreactor (Fig. 3) was used in all remaining runs. It was fabricated from a 21-L polypropylene vessel and is described in Akhtar and others (1992).

Chips for the bioreactor runs were thawed, mixed, and sampled for moisture content. The MCDM was added with sufficient water to bring the chip moisture content up to 55% or 60% (wet weight basis). For the fungal treatments, 2,700, 1,800 or 1,425 g of chips (ovendry basis) were put in the rotating drum bioreactor, stationary-tray bioreactor, or aerated static-bed bioreactors, respectively. The chips were autoclaved for 90 min and then cooled. The seed inoculum (previously described) was then added aseptically to the wood chips in the bioreactor. The chips were mixed well and the bioreactors incubated at 27 ± 1°C for all the fungi except *P. chrysosporium,* which was incubated at 39 ± 1°C; all bioreactors were aerated with moisture-saturated air (0.001 to 1.0 L/L/min).

[2]Run numbers refer to data in Appendix B.

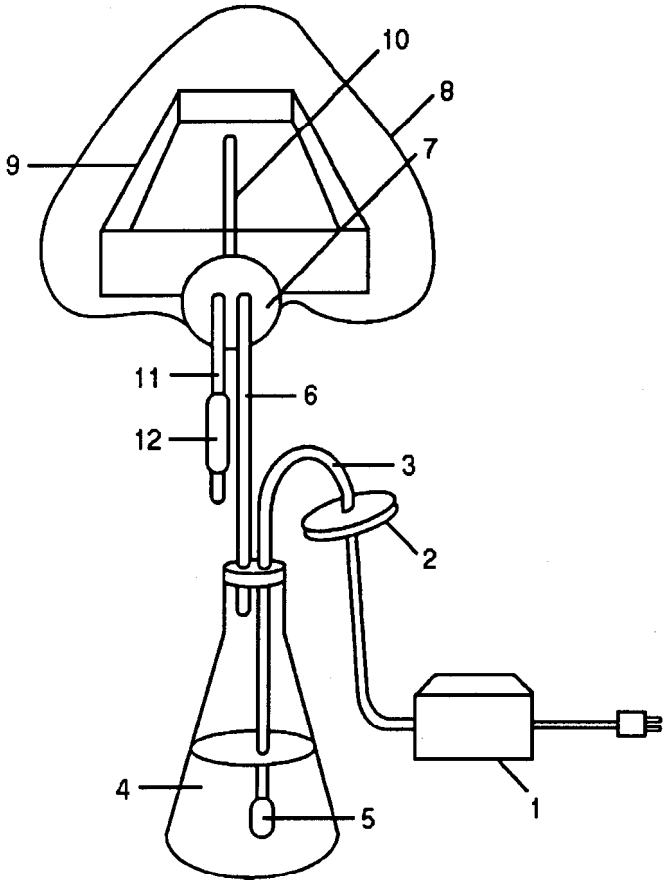


Figure 2—Stationary-tray bioreactor (Akhtar and others 1992, Blanchette and others 1991). A simple air pump (1) drives air through a 0.2-µm-pore-size membrane filter (2) and through tubing (3) to a humidification vessel (4) filled with sterilized water. The air inlet into the humidification vessel consists of a glass tube with a fritted glass gas dispenser (5) submerged below the water level. Humidified air connected by tubing (6) to the polypropylene containment bag (8) (manifold (7)), which completely surrounds the tray (9). Tray is constructed from &mesh, 316 stainless steel wire screen with dimensions of 53 cm (length) x 41 cm (width) x 8 cm (height). Tubing (10) extends down the center of the tray under the chips to deliver humidified air to the chips. An exhaust tube (11) extends from the containment bag to the atmosphere, through an exit tube (12).

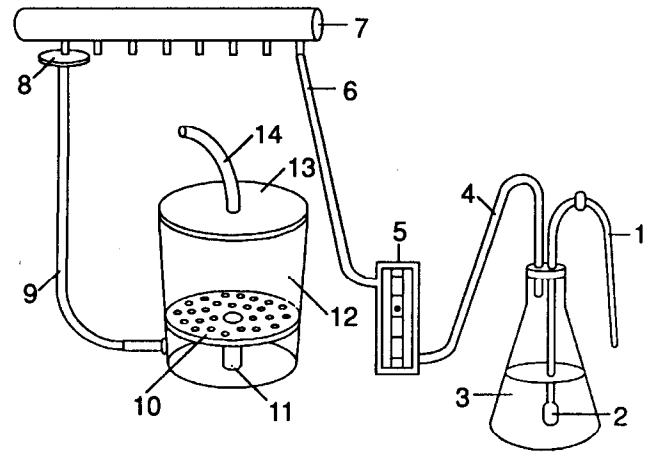


Figure 3—Aerated static-bed bioreactor (Akhtar and others 1992). The top of the 21-L vessel is sealed with a lid (13) which is vented to the atmosphere through an exit tube (14). Suspended above the bottom of the bioreactor (12) is a perforated polypropylene board (10) held in place by a stand (11). An 0.2 µm pore-size membrane filter (8) is provided that Is connected by tubing (9) to the base of the bioreactor (12). The filter (8) receives its input air supply from a manifold (7) that is supplied, in turn, through an air line (6) that is connected to a rotometer (5). The rotometer (5) receives air from an air line (4) connected to a humidifier (3), which passes incoming air through distilled water via a fritted glass gas dispenser (2) connected through tubing (1) to a regulated air supply.

Mechanical Refining of Chips

After incubation for various periods (usually 2 or 4 weeks), the control and the fungus-treated chips were removed from the bioreactors, weighed, and sampled for moisture content. The chips were then hand-fed into a 300-mm-diameter mechanical single disk refiner (Andritz Sprout-Bauer, Muncy, Pennsylvania) with the feed rate adjusted to maintain a constant load on the refiner motor. An integrating watt-hour meter measured total electrical power consumption for each refining batch. The initial refiner plate setting was 18 mils, and then clearance was reduced in subsequent passes. After each pass, the pulp was collected as it exited the refiner as a hot water slurry. The pulp was stored for at least 15 min in the slurry at about 2% consistency to remove latency. Between passes, the pulp slurry was dewatered in a porous bag with pressing. Dilution water (80°C) was then added each time as the pulp was fed into the refiner. Samples of the pulp slurry at a 7-mil plate setting and smaller were taken and tested for Canadian Standard Freeness (CSF), and the sampling was continued until the CSF dropped below 100 ml. This was usually about 15 passes for the control chips and fewer for fungus-treated chips.

Handsheet Preparation

For all pulps, 60 g/m^2 handsheets were made according to TAPPI T205 with the two pulp samples refined to just above and below CSF 100 ml. Handsheets were dried on polished plates, while clamped between drying rings, in a room maintained at atmospheric conditions specified in TAPPI T402.

Strength and Optical Property Measurement

In most cases, density, burst, tear, tensile, brightness, opacity, and scattering coefficient determinations were made on each set of handsheets, and the average and standard deviations were calculated. To facilitate comparison, strength and optical properties were regressed to 100 ml CSF. In some instances, tensile energy absorption (TEA), elongation, zero-span tensile, fiber length index, and Klason lignin were also determined. Handsheets from runs 1 through 90 were tested by the FPL Paper Test Laboratory. Paper testing was done by the Weyerhaeuser Technology Center, Tacoma, Washington, for runs 91 on, except for runs 100, 101, 110-113, 134-137, 139, and 140, which were tested at FPL. At both testing laboratories, standard TAPPI test methods were used to assess paper strength and optical properties, with the exception of tear index. At the FPL, tear index was tested by using multiple-ply (five sheets/test) specimens. At the Weyerhaeuser Technology Center, tear index was tested using single-ply specimens.

The standard deviation values of the two handsheet sets closest to 100 ml CSF were reviewed and the higher value selected. This means that when statistical comparisons were made, the error was conservative; thus, it would take more of a difference between averages to be statistically significant. Original test data were checked for those runs where the standard deviation values appeared unusually high. In a few instances, some values appeared to differ significantly from the others. In all instances, these values were left in the data sets rather than removing them; we did not use an outlier test in the statistical analysis. This decision meant that it took a greater difference between averages to be statistically significant; hence, a conservative analysis was made.

Effluent Analysis

Effluents collected from the refining of biopulps and their respective controls were evaluated for U.S. Environmental Protection Agency (EPA)-regulated parameters of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and toxicity.

Because we were unable to simulate mill production and effluent treatment in our pilot plant, this study compared the relative constituent levels of BOD, COD, and toxicity in biopulp effluents with raw refiner mechanical pulp control effluents. After we established that approximately 85% of the BOD and COD was removed during the first pass through the Sprout-Waldron disk refiner, all effluents were from first pass pulp slurries. The quantity of water used to refine 1 kg of wood chips in our Sprout-Waldron refiner was approximately 60 L. This volume compares with 17 to 20 L H_2O/kg pulp produced in a relatively "closed" system and the 99 L H_2O/kg commonly used 15 years ago in mechanical pulp mills (Springer 1986).

The BOD and COD concentrations were measured at the Wisconsin State Hygiene Laboratory using *Standard Methods for Examination of Water and Wastewater* (American Public Health Association and others 1985). Effluent toxicity was assessed by the Microtox assay and was conducted for us by Tim Hall, research biologist with the National Council for Air and Stream Improvement (NCASI), Anacortes, Washington.

Data Analyses

Data were analyzed by comparing the medians or means of the runs with fungus-treated chips with those from the control chips. For comparing means in the specific biopulping experiments, the confidence intervals (α = 0.95) were calculated using the following formula:

$$\text{Mean} \pm t\left(1-\frac{\alpha}{2}\right)\left(\frac{s}{\sqrt{n}}\right)$$

where t = the significance limit (corresponding to the sample size and desired significance probability) of the *Student* distribution, α (= confidence interval, s = standard deviation, and n = sample size.

For the analysis, notched box plots were used. This is a simple way to compare the medians of data sets and determine if they are statistically different (McGill and others 1978). By way of illustration, Figure 4 gives hypothetical average strength values for a group of different samples. A wide variety of possible data points is shown, ranging from a single value (A) to uniformly distributed values (B, C, D, E, F, and G) to skewed distributions (H, I, and J).

By using notched box plots, statistical inferences can be made. Thus, if the intervals (notched areas) around two medians do not overlap, the two population medians are different at about the 95% level. Because the data were not always normally distributed, the median was used rather than the average to get a truer picture of results. This approach is less sensitive to the effects of outliers.

The various components of the notched box plot are indicated in Figure 5. The hinges are the medians of the data from the minimum to the median (similar to a 25 percentile) and of the data from the median to the maximum (similar to a 75 percentile).

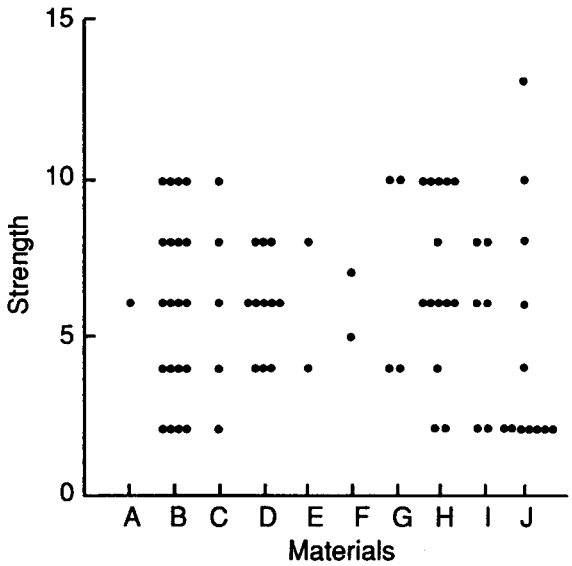


Figure 4—Dot plot example.

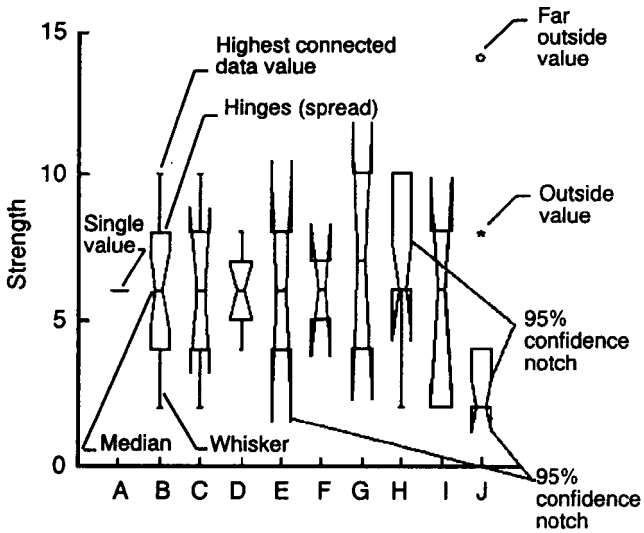


Figure 5—Notched box plot of data in Figure 4.

Results and Discussion

Screening Methods

Thousands of strains and species of white-rot fungi have varying capacities to degrade lignin, cellulose, and hemicellulose. We assumed that the species that selectively degrade lignin were of particular interest for biopulping. A screening program was therefore initiated that selected fast-growing species that could selectively remove lignin from wood.

Initial Screening Procedure

Our initial screening selected several species of fungi for further evaluation. The most effective were *Ceriporiopsis subvermispora, Phanerochaete chrysosporium, Phlebia brevispora, Phlebia tremellosa,* and *Dichomitus squalens.* It became clear as we tested these fungi on different types of wood that some species are effective with hardwoods, whereas others are effective on both hardwoods and softwoods. *Phanerochaete chrysosporium* and *C. subvermispora* were among the most effective fungi.

We also examined strains of selected species: 33 strains of *P. chrysosporium* and 9 strains of *C. subvermispora* (Blanchette and others 1991). These results clearly showed large differences among the strains in their capacity to degrade lignin and in selectivity. The most effective strains were used in the biopulping experiments: BKM-F-1767 for *P. chrysosporium* and FP-90031-sp for *C. subvermispora.*

New Screening Procedure

Following the initial screening with the wood decay/lignin degradation method, we further compared the most promising fungi in actual biopulping runs. This was the only method that provided unequivocal comparisons of biopulping efficacy. However, this procedure was tedious. Clearly, the rate at which biopulping can be optimized and fully evaluated is limited by the lack of rapid and reliable methods for predicting biopulping efficacy. Papermaking and testing methods are slow and cumbersome. Therefore, attempts were made to develop a rapid screening method. Unfortunately, we found no relationship between weight loss of the chips or bulk removal of lignin from the chips and energy savings or strength or optical properties (Leatham and others 1990a,b). We explored two other possibilities, one based on PFI milling followed by freeness testing and the other based on a simple staining procedure.

The PFI milling and freeness measurements were previously used to assess energy consumption of coarse pulps before and after fungus-treatments (Bar-Lev and others 1982; Eriksson and Vallander 1982). We found that PFI milling and freeness measurements can predict paper strength properties (Leatham and others 1990a,b). However, follow-up studies suggested that this method can only be used to discriminate fungal treatments from the controls for energy savings and not to discriminate among different fungal treatments (Akhtar and others ,1989).

Another approach seemed more promising. It involved the use of "Simons stain." This stain for microscopic examination of pulp fibers (Simons 1950, Wurz 1969) had been used by others in various investigations to evaluate the degree of fibrillation in beaten fibers. The stain consists of 1% aqueous solution of Pontamine Sky Blue 6BX and 1% aqueous solution of Pontamine Fast Orange 6RN mixed in a 1:1 ratio. After flooding the fibers on microscope slides with

the stain, slides are heated at 60°C until the water evaporates. A cover glass is placed over the fibers, which are then rinsed with distilled water to remove excess stain. Fibers are then microscopically examined and immediately photographed. Pulp absorbs the orange stain if the fibers are fibrillated or modified; fibers that are nonfibrillated or undamaged stain blue.

Our previous electron microscope studies in connection with biopulping showed that pulp from fungus-treated wood chips had more uniform fiber length, greater fibrillation, and appeared "wooly" compared with control pulps (Sachs and others 1990). This suggested that degree of fibrillation might be a good indicator of biopulping efficacy. Therefore, we tested the Simons staining method with aspen chips treated with *C. subvermispora* and untreated chips. Pulp obtained from the fungus-treated, refined chips had extensively fibrillated fibers that stained a deep orange. In contrast, pulp obtained from the untreated refined chips exhibited little fibrillation and stained a deep blue. Thus, the possibility exists that this stain can be used to rapidly screen different species and strains of fungi for biopulping performance and to select superior pretreatment conditions for the best strain so that an optimum biopulping process can be realized (Blanchette and others 1992).

Rapid Refining Protocol

In an attempt to speed up the biopulping evaluation, several runs were used to compare a "fast" refining protocol with the normal "slow" one (runs 177-182). In the fast protocol, the refiner disk plate settings were reduced more rapidly.

The control and the *C. subvermispora* treated aspen wood chips (4-week incubation in the usual manner) were refined. As indicated in Table 2, control chips took 15 passes in the slow refining protocol, and treated chips took 10 passes to achieve the desired freeness levels. In contrast, control chips took 10 passes and treated chips 5 passes in the fast refining protocol. The fast protocol was used in subsequent runs.

Table 2—Comparison of refining protocols

Refining (passes)			
Control chips		Fungus-treated chips	
Slow	Fast	Slow	Fast
18	18	18	18
15	5	15	5
12	4	12	4
9	3.5	9	3.5
7	3	7	3
6	2.5	6	
4.5	2	4.5	
4	1.5	4	
3.5	1	3.5	
3	0.5	3	
2.5			
2			
1.5			
1			
0.5			

Global Analysis of Data

Despite the late finding of the promising staining method, described above, the biopulping results reported here were obtained from biopulping runs involving treatment of chips on a bench scale with fungi, refining the chips in multiple passes through a single-disc refiner, and making and testing handsheets. Although tedious, the procedure was direct. The results of more than 200 biopulping runs are given in Appendix B. A global analysis of the data is presented in the following.

In all runs, untreated and treated chips were refined, made into handsheets, and evaluated as described in Materials and Methods. The results were analyzed using medians and notched box plots in a global analysis. This global (or exploratory) analysis used the data from all runs, separated by fungus and wood species. In essence, we treated *P. chrysosporium*/aspen, *C. subvermispora*/aspen, and *C. subvermispora*/pine as three separate sets of data for the analysis.

The large number of potential variables that could affect the biopulping results and the evolutionary nature of the experimental work meant that the runs would not fit into one large experimental design. Groups of runs were made to explore various parameters, and the results were compared with a control run at the same time. These experiments are reported in the next section. Each set of runs often had several changes from the previous set. Thus, when comparing any two sets of runs, several factors may be confounded. However, over the course of the program, variables were changed in numerous patterns, so it is unlikely that a simple confounding pattern still exists in the data. For the global analysis purposes, the effects of many variables were examined individually. It was felt that the constant shifting of confounding variables was most likely to increase the variability of the results and not produce a definitive bias in median response. As with any global study, it is beneficial to run confirming experiments designed to verify the information in this global overview. Therefore, the results given here are exploratory in nature, but we feel that the large number of runs and the consistency of the results are strong arguments that these effects would be reproduced in any confirmational study.

The data were plotted as notched box plots so that any statistically significant differences, at the ± 0.95 level, between the untreated controls and biopulped chips could be observed. Also, the plots give an indication of the skewness of the data by the nonsymmetrical shape of the notched box plots. The majority of research was conducted with aspen as evidenced by Figure 6. The notch plots in Figure 6 show that the pine took slightly less energy to refine than aspen.

As expected, the softwood and hardwood species reacted differently to the various organisms, so the analyses treat the two woods separately. Figures 6-8 include dot and notched box plots to facilitate interpretation of the data; note that the box plots deal with medians, not averages, so they are less sensitive to outlier influence.

During the course of 5 years, several batches of aspen wood were used. It was of interest to determine if these chip batches differed significantly. Based on these plots, it appeared that no significant difference was found between batches in terms of energy consumption for the control runs (Fig. 7). (Energy measurements were not made with batch B control runs.) When aspen was treated with *P. chrysosporium* (Fig. 8), batch B energy consumption was significantly greater, but no significant difference occurred among the other batches (the notched areas overlapped). The major difference between batch B chips and the other batches was that the former were from older logs that were >0.6 m in diameter, whereas chips in the other batches were from logs that ranged from 0.2 to 0.4 m in diameter. Thus, the age of the wood used in batch B might have been a factor. Note that many strength properties of the pulps made from batch B were significantly greater than those achieved with similar biopulping runs made with the other batches. Batch E chips were 18 mm; therefore, it is unlikely that chip size (6 to 18 mm) is a significant factor for biopulping.

Figures 9 and 10 show the energy required for the pine control and treated runs, respectively. Because only one batch of chips was involved, chip batch was not a variable.

The effects of bioreactor type on energy consumption are shown in Figures 11-14. Based on this overview, it does not appear that bioreactor type had a significant effect on the energy savings. The numbers of samples with the controls were too few to give meaningful data, as were the numbers with aerated static-bed and rotating-drum bioreactors with treated pine.

A comparison of two refining sequences, fast and slow, indicated no significant differences (Figs. 15 and 16).

A comparison of several fungal species in terms of energy savings when used with aspen is shown in Figure 17. A corresponding notched plot for pine is shown in Figure 18.

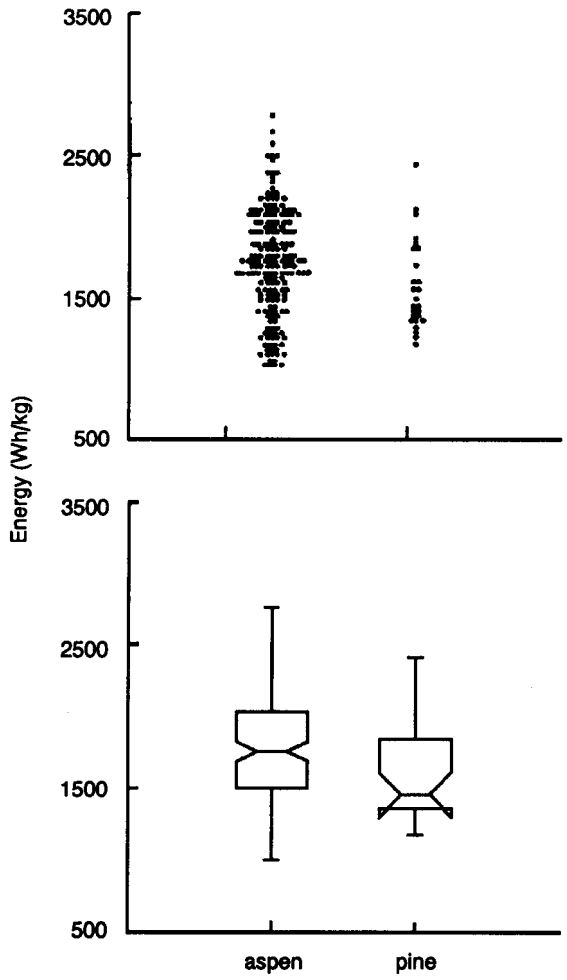


Figure 6—Amount of energy to refine aspen and pine chips.

With aspen, *Phlebia tremellosa, Phanerochaete chrysosporium,* and *Ceriporiopsis subvermispora* gave significant energy *savings.* With pine, *Phlebia subserialis, P. brevispora, Hypodontia setulosa,* and *C. subvermispora* gave significant energy savings. As noted and as is apparent from the dot plot (Fig. 17), *P. chrysosporium* and *C. subvermispora* were chosen for the bulk of the research.

Figure 19 compares the weight loss of aspen chips in the biopulping runs for various fungal species. Results indicate that regardless of fungal species, weight loss with most runs was less than 10%. Part of the reason for this low weight loss could be due to the addition of glucose; however, even in the few runs without added glucose, weight losses were still low: runs 31 (3.8%), 198 (2.06%), 200 (11%), and 202 (2.0%).

In all instances, the Klason lignin values for aspen were significantly reduced with *P. chrysosporium* and *C. subvermispora* (Fig. 20).

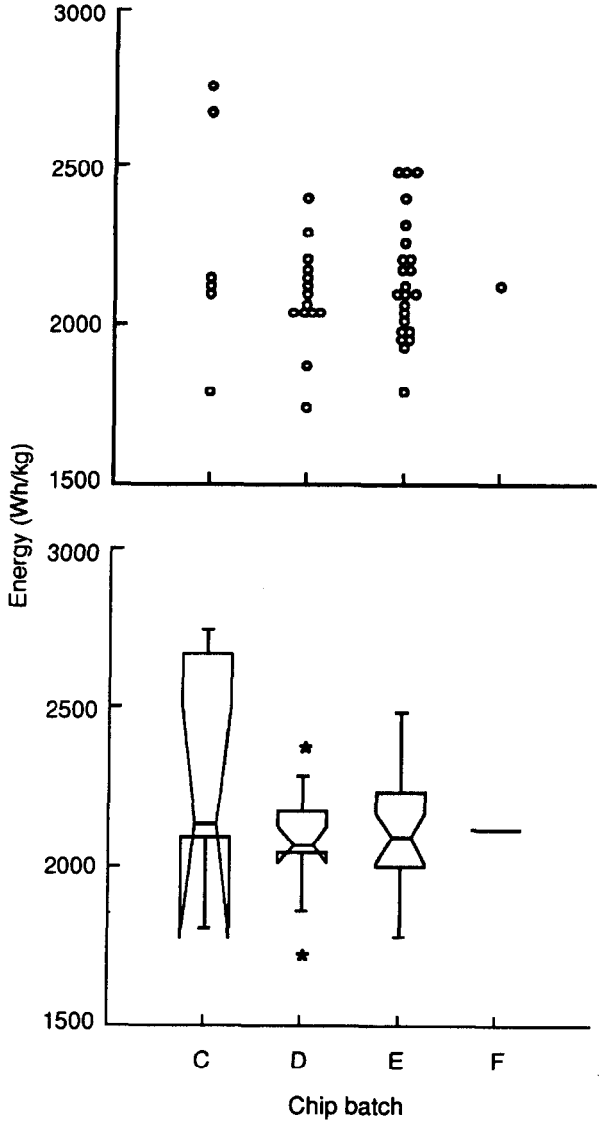


Figure 7—Amount of energy used to refine different batches of aspen control chips.

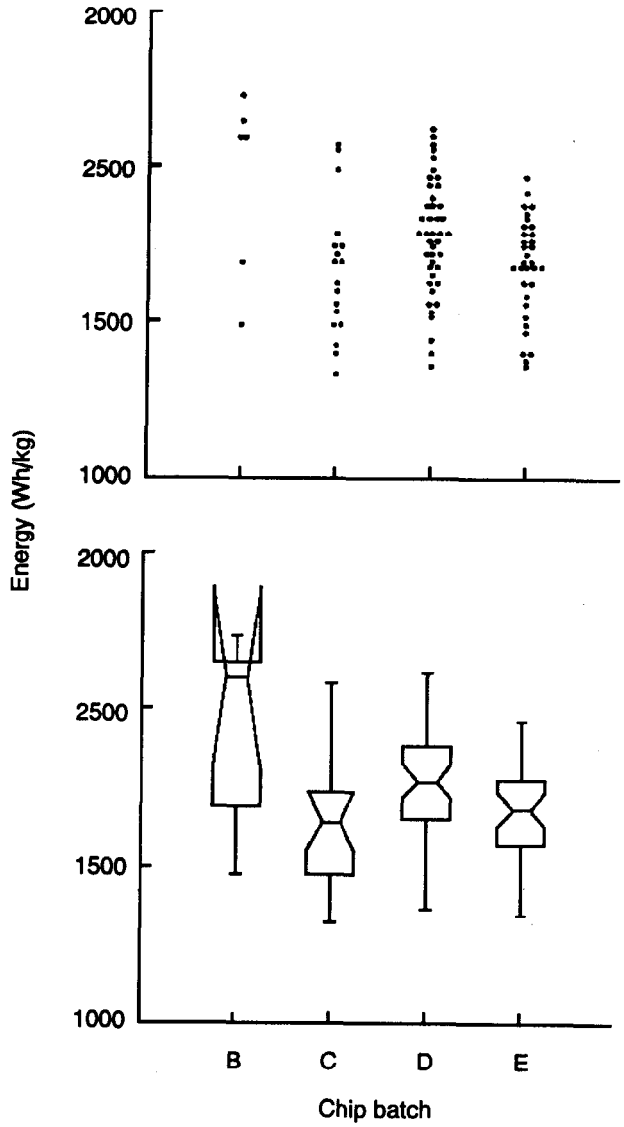


Figure 8—Amount of energy used to refine different batches of aspen chips treated with *P. chrysosporium.*

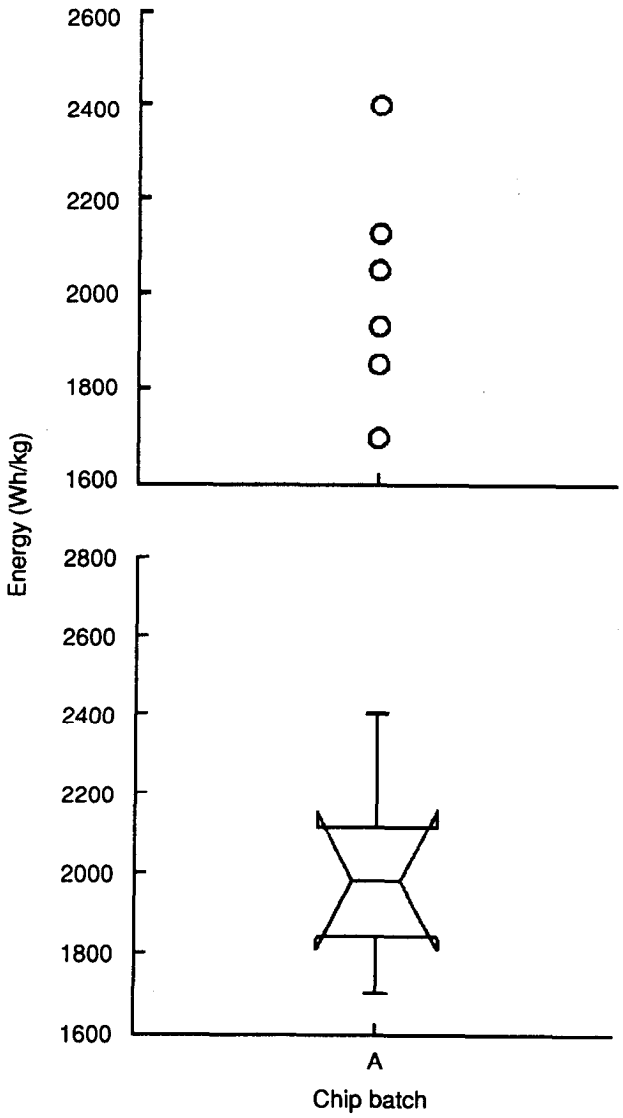


Figure 9—Energy consumption during refining of pine control chips.

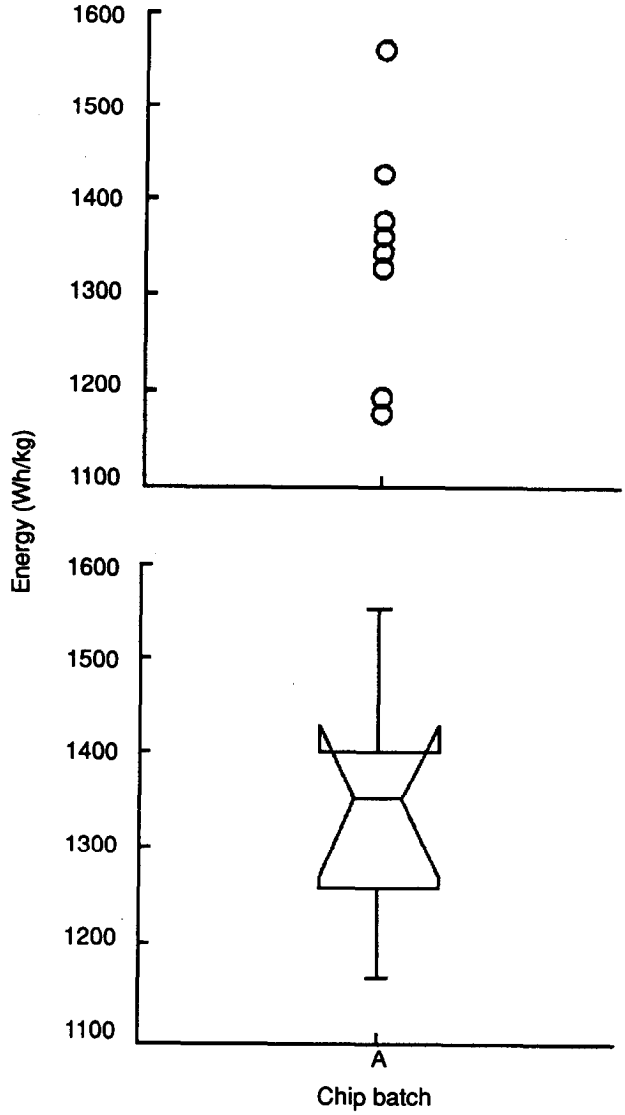


Figure 10—Energy consumption during refining of pine chips after treatment with *C. subvermispora.*

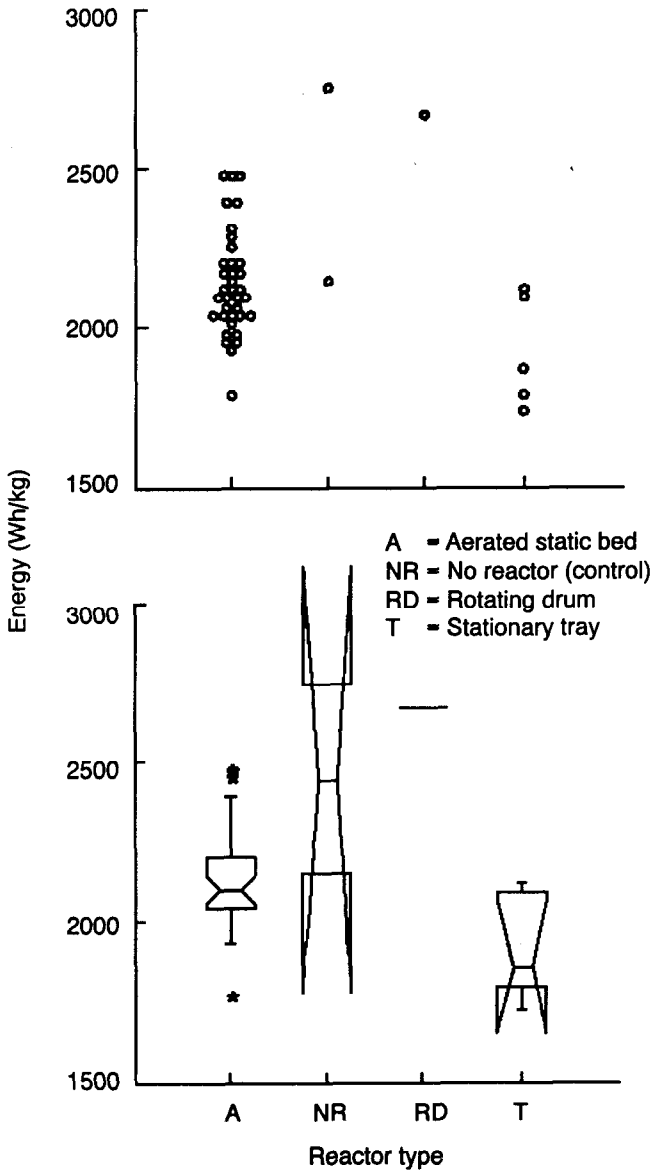


Figure 11—Energy as a function of bioreactor type for aspen control chips.

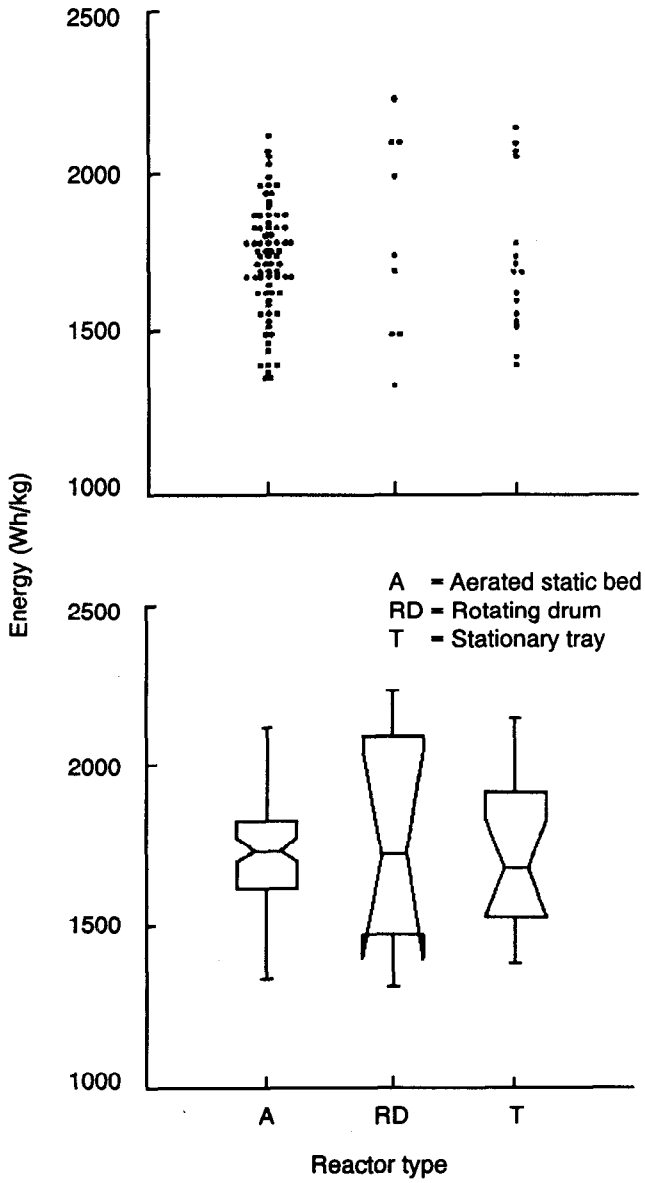


Figure 12—Energy as a function of bioreactor type for aspen chips treated with *P. chrysosporium.*

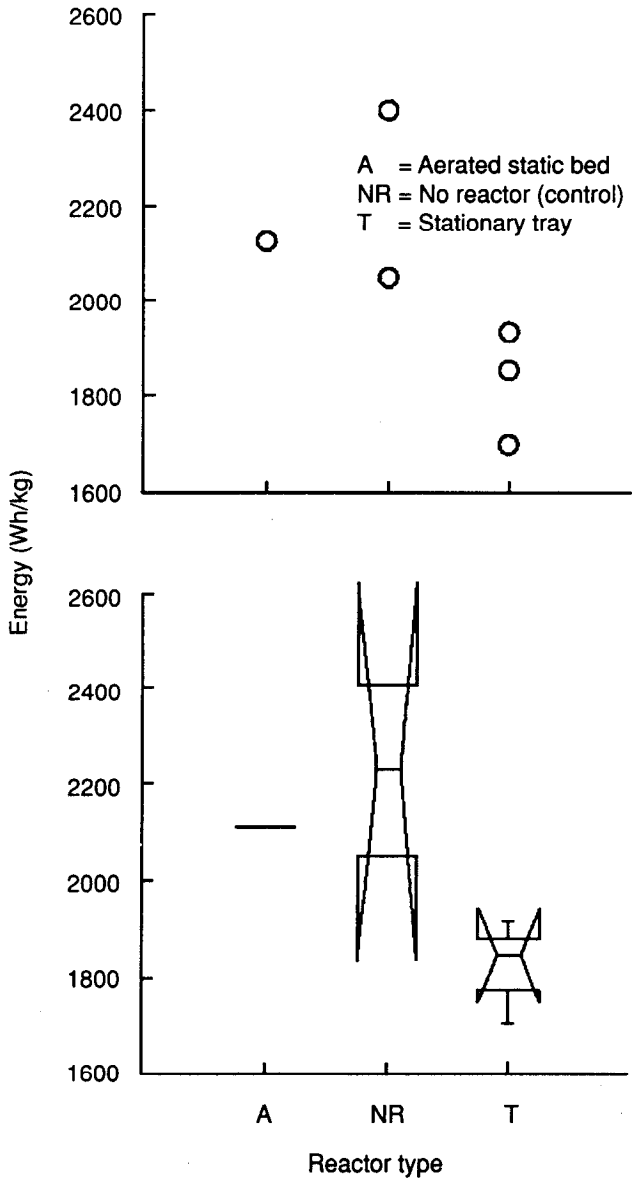


Figure 13. Energy as a function of bioreactor type for pine control chips.

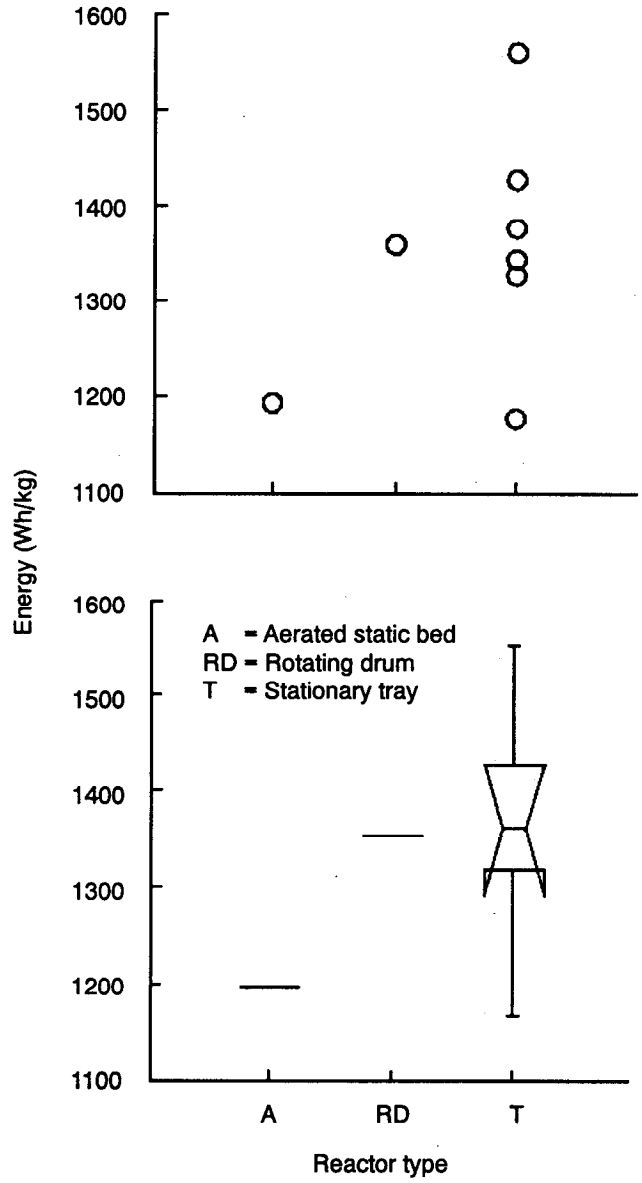


Figure 14—Energy as a function of bioreactor type for pine chips treated with *C. subvermispora.*

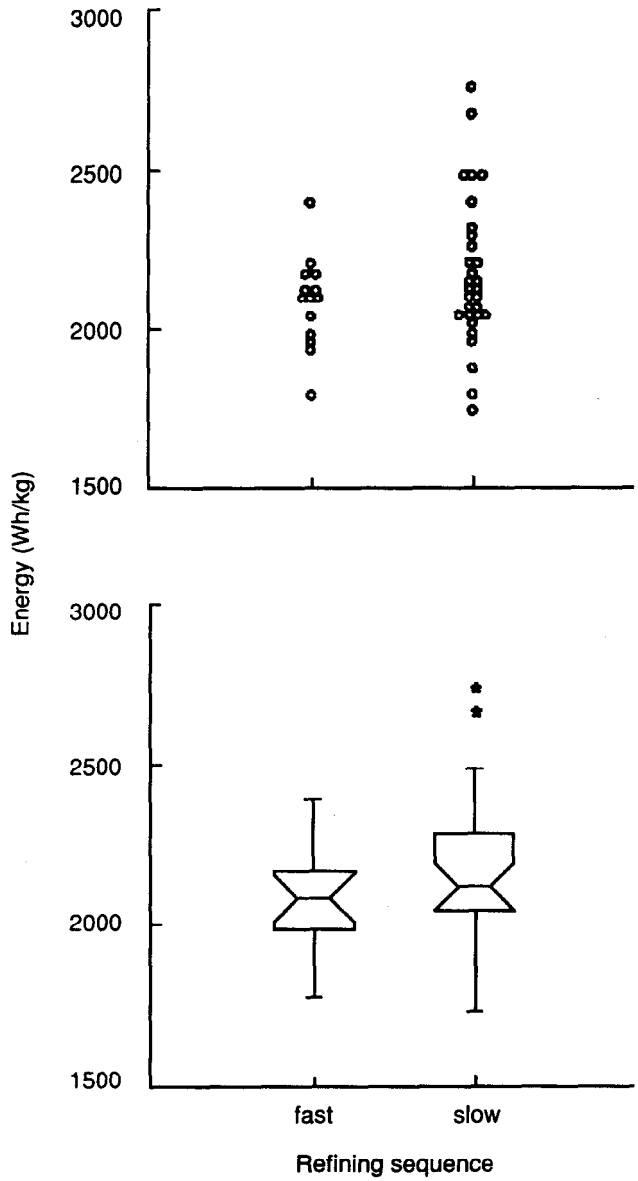


Figure 15—Energy as a function of refining sequence for aspen control chips.

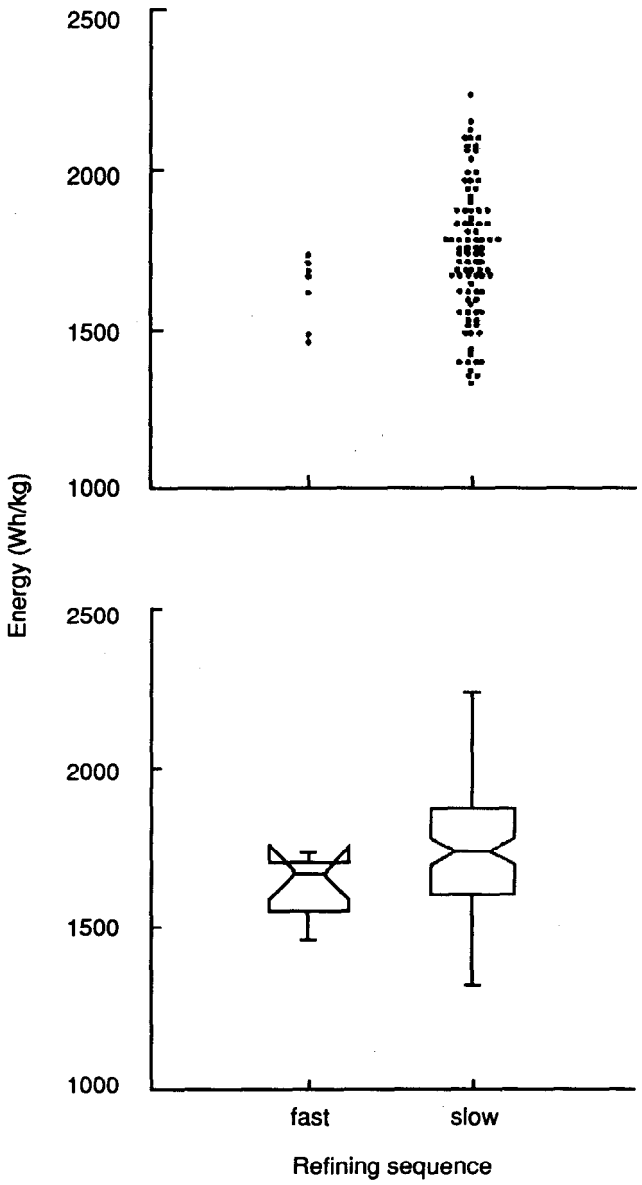


Figure 16—Energy as a function of refining sequence for aspen chips treated with *P. chrysosporium.*

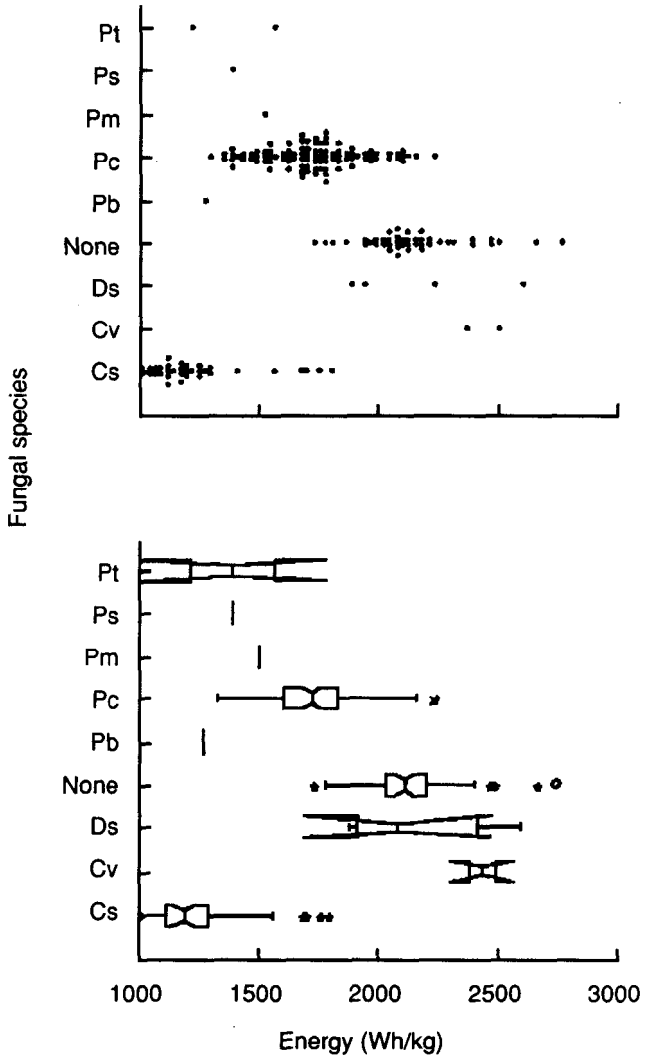


Figure 17—Energy as a function of fungal species with aspen. Pt = *Phlebia tremellosa,* Ps = *Phlebia subserialis,* Pm = *Pholiota mutabilis,* Pc = *Phanerochaete chrysosporium,* Pb = *Phlebia brevispora,* Ds = *Dichomitus squalens,* Cv = *Coriolus* versicolor, and Cs = *Ceriporiopsis subvermispora.*

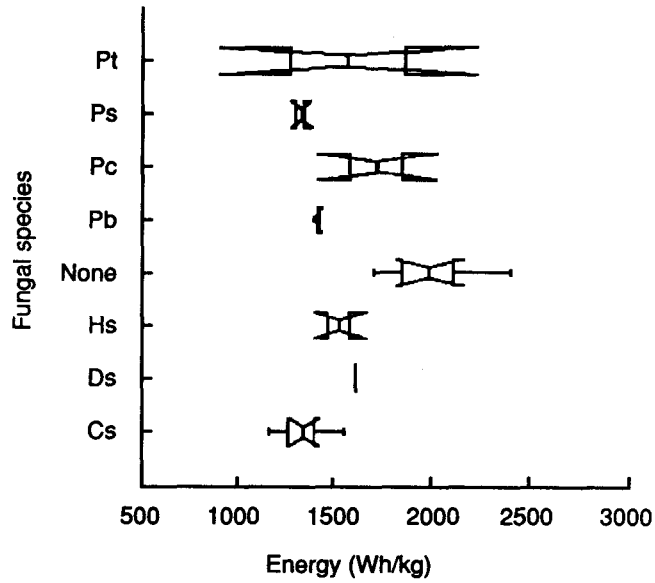


Figure 18—Energy as a function of fungal species with pine. Pt = *Phlebia tremellosa,* Ps = *subserialis,* Pc = *Phanerochaete chrysosporium,* Pb = *Phlebia brevispora,* Hs = *Hypodontia setulosa,* Ds = *Dichomitus squalens,* and Cs = *Ceriporiopsis subvermispora (see* also Figure 55).

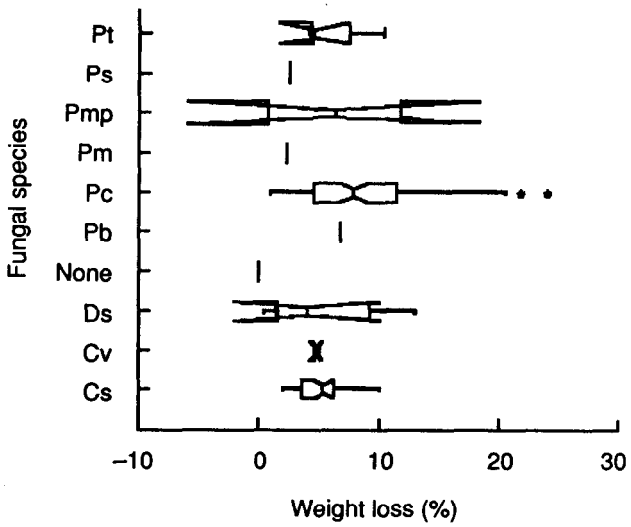


Figure 19—Weight loss as a function of fungal species with aspen. Pt = *Phlebia tremellosa,* Ps = *Phlebia subserialis,* Pmp = *Paria medrila-panis,* Pm = *Phollota mutabilis,* Pc = *Phanerochaete chrysosporium,* Pb = *Phlebia brevispora,* Ds = *Dichomitus squalens,* Cv = Coriolus versicolor, and Cs = *Ceriporiopsis* subvermispora.

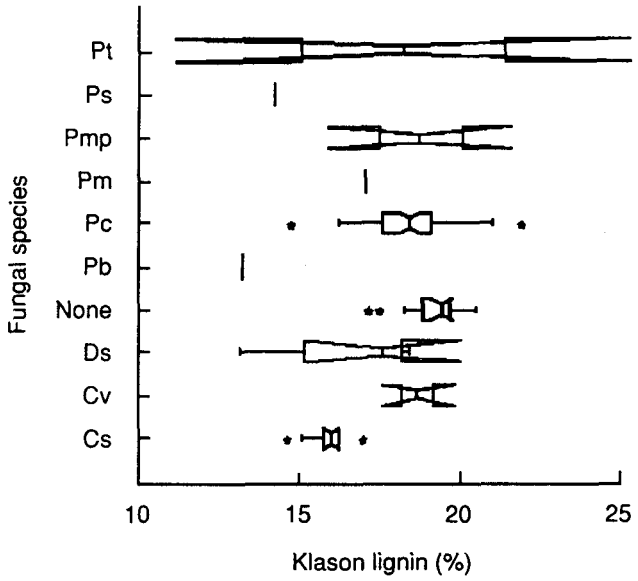


Figure 20—Klason lignin content of aspen as a function of fungal species. Pt = *Phlebia tremellosa,* Ps = *Phlebia subserialis,* Pmp = *Parla medrila-panis,* Pm = *Pholiota mutabilis,* Pc = *Phanerochaete chrysosporium,* Pb = *Phlebia brevispora,* Ds = *Dichomitus squalens,* Cv = Coriolus versicolor, and Cs = *Ceriporiopsis subvermispora.*

In general, the fungi in Figure 20 had similar effects on handsheet paper properties (data not shown); the small number of runs with most made it difficult to ascertain the significance of differences that were seen. Burst index was unaffected or increased; tensile and tear indices were increased; zero span tensile was usually unaffected, but tensile increased with *C. subvermispora.* Brightness and scattering coefficient were invariably decreased; opacity and fiber length were unaffected.

The effects of *P. chrysosporium* and *C. subvermispora* on the various strength and optical properties for aspen and pine are shown in Figures 21-34. Because few runs were made with pine, the results are less conclusive but some trends are indicated. Similar energy reduction patterns were observed for both aspen and pine. The median energy savings were 18% for aspen treated with *P. chrysosporium* and 44% for *C. subvermispora.* Pine treated with *P. chrysosporium* gave 14% savings, (not statistically different from controls); *C. subvermispora* gave 32% savings (Fig. 21).

The weight loss of aspen treated with *C. subvermispora* was about 36% less than that of aspen treated with *P. chrysosporium* (Fig. 22). The two outliers of aspen treated with *P. chrysosporium* were for chips amended with high amounts of nutrient nitrogen.

Handsheet density was reduced by 11% in aspen treated with *C. subvermisiora* and slightly reduced with *P. chrysosporium.* There was no significant difference with pine (Fig. 23).

Burst index was significantly greater than the controls for aspen treated with either fungus (Fig. 24). Aspen treated

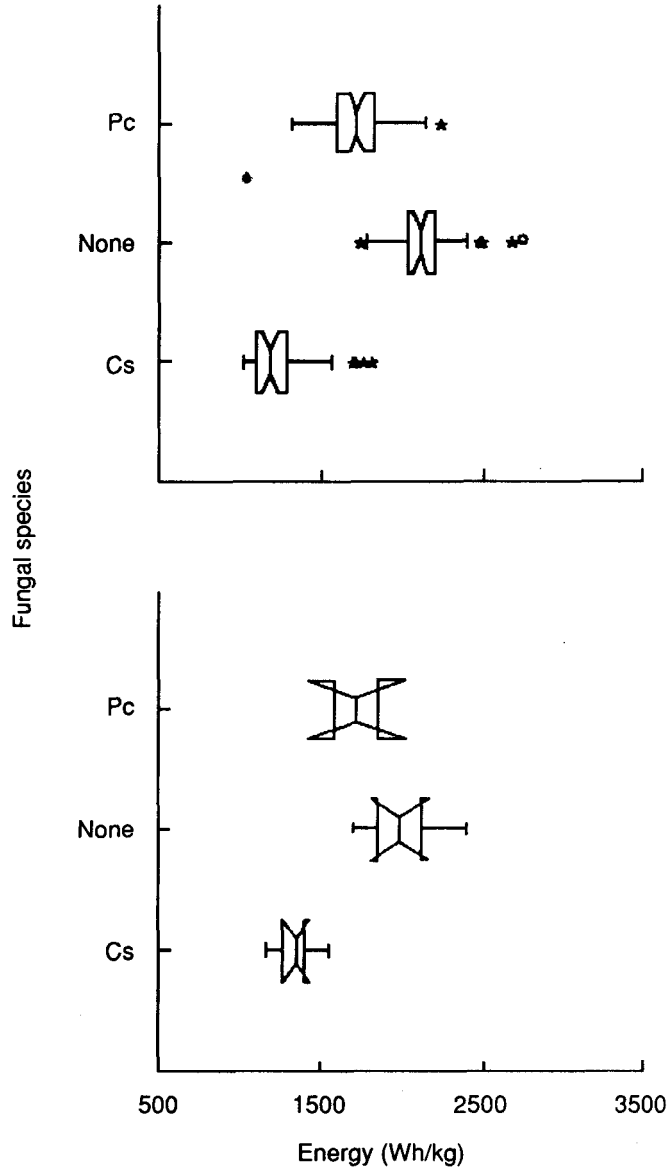


Figure 21—Refining energy for aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

with *P. chrysosporium* was 19% greater in burst, and with *C. subvermispora,* 28% greater. With aspen, high outliers were runs 15 and 26, which were made from batch B wood chips. The burst index of the pine treated with *C. subvermispora* was 32% greater than that of controls.

The tensile index was significantly greater for aspen treated with either fungus, but with pine, only *P. chrysosporium* gave significantly greater values (17%) (Fig. 25). The outliers with aspen treated with *P. chrysosporium* were again from runs made with batch B chips (runs 15, 20, 26).

Analysis of the data indicated that many of the handsheets made from the biopulps had significantly higher tear and tensile strengths than handsheets made from control pulps. Simultaneous increases in these two properties are not encountered with most other pulping processes.

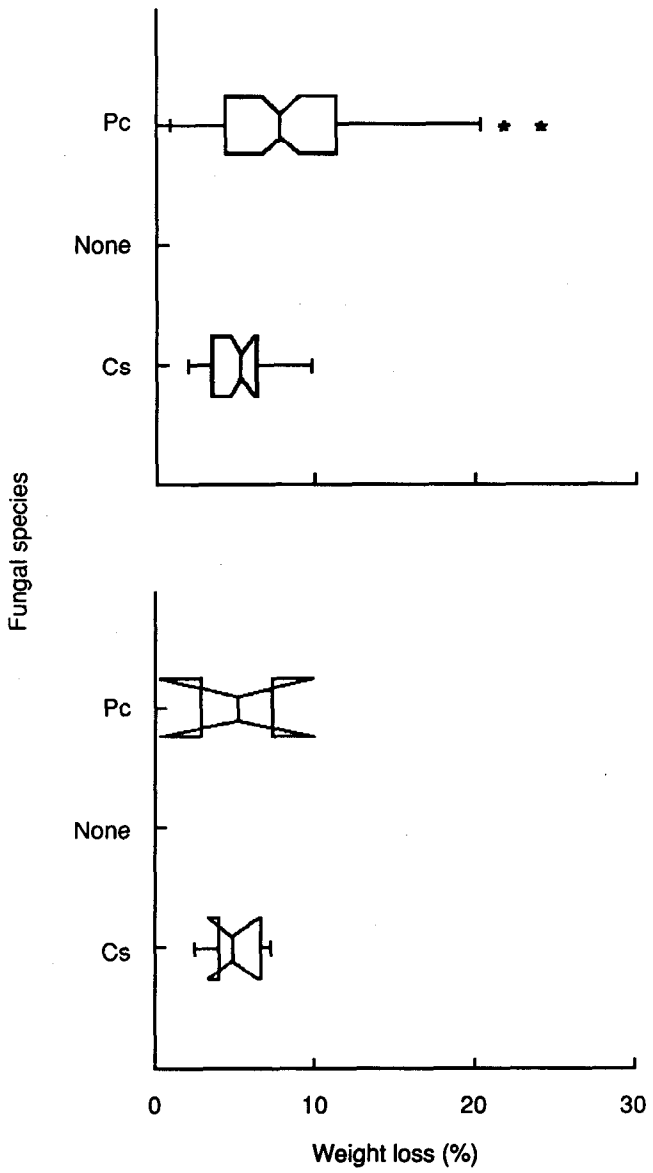


Figure 22—Weight loss of aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

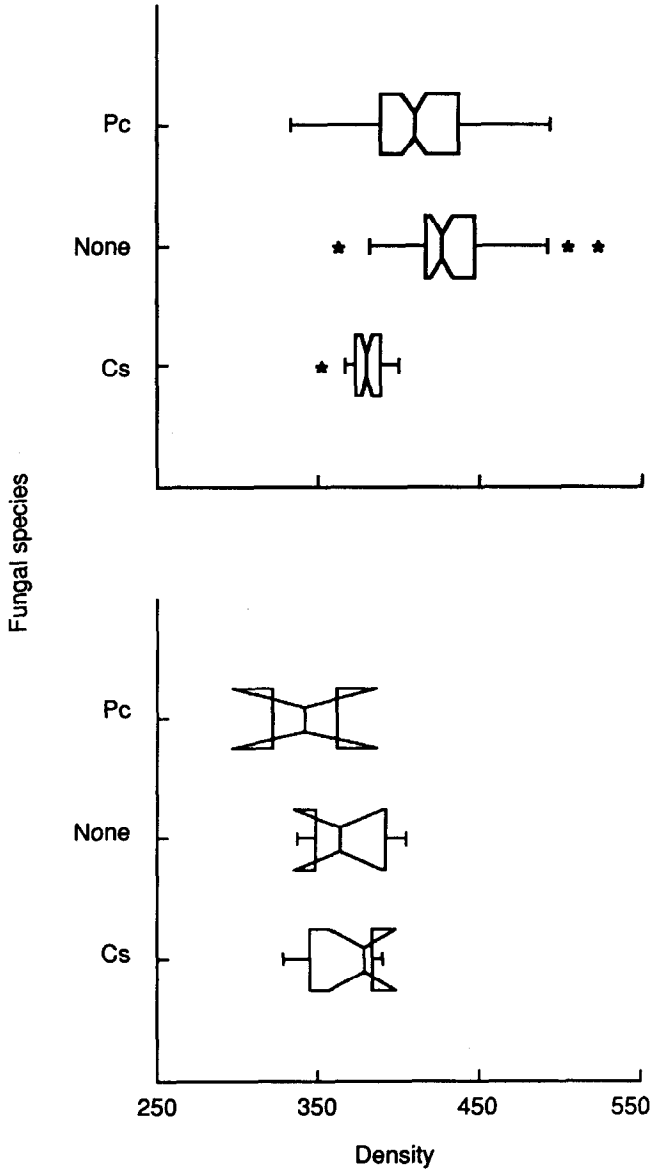


Figure 23—Density of handsheets made from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

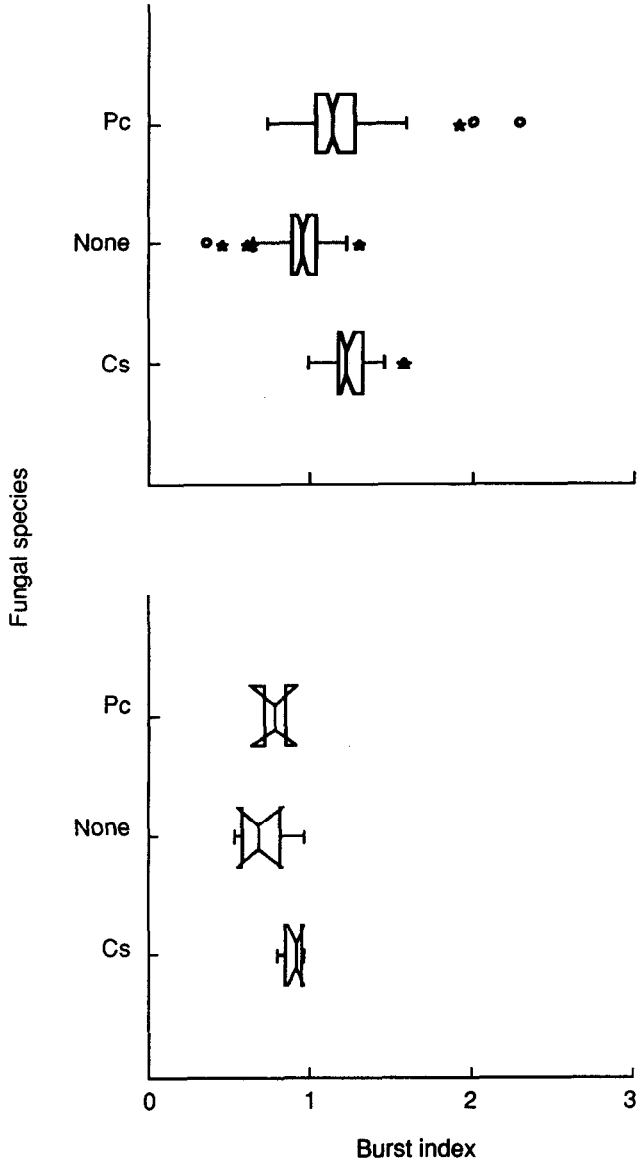


Figure 24—Burst index for paper from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

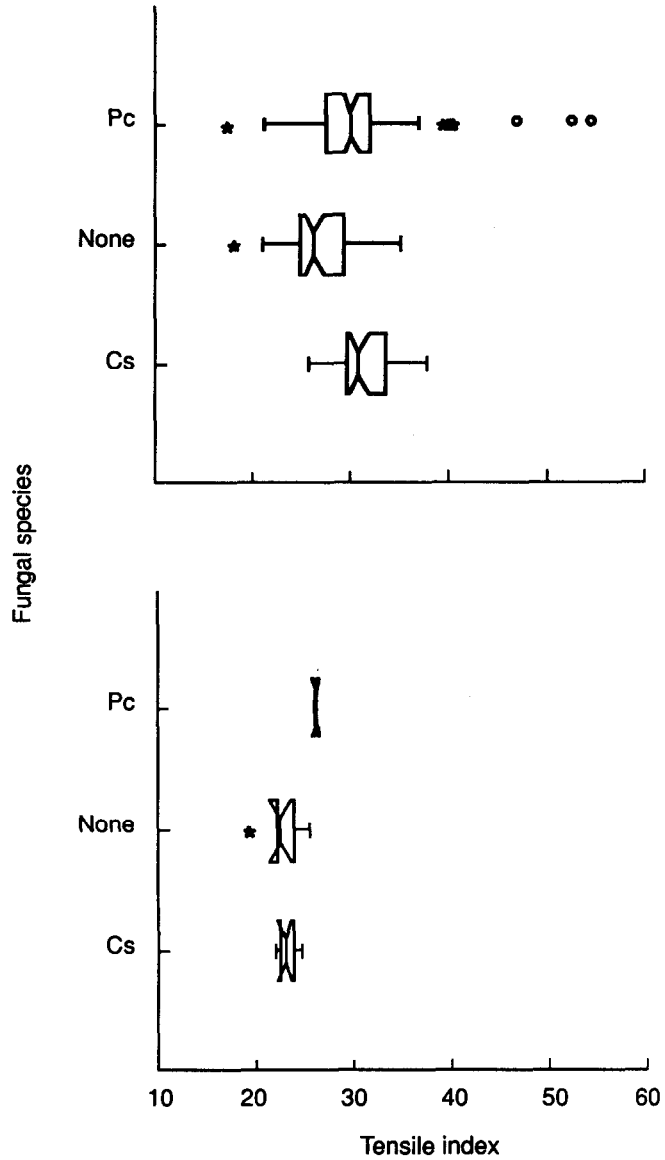


Figure 25—Tensile index for paper from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

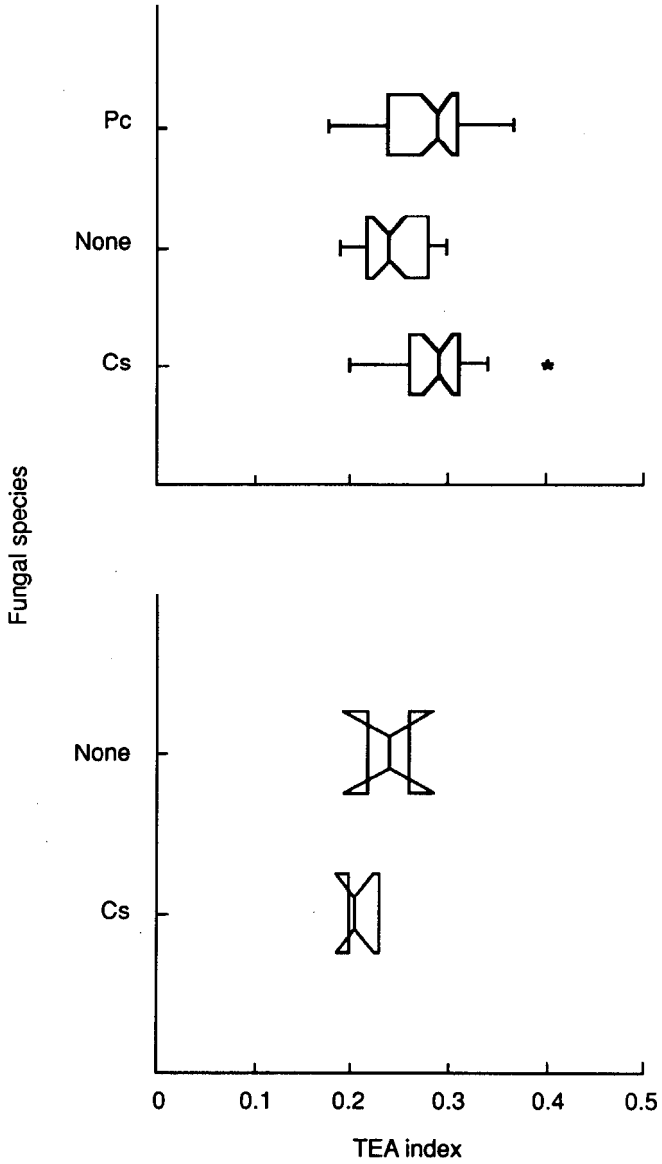


Figure 26—TEA index for paper from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

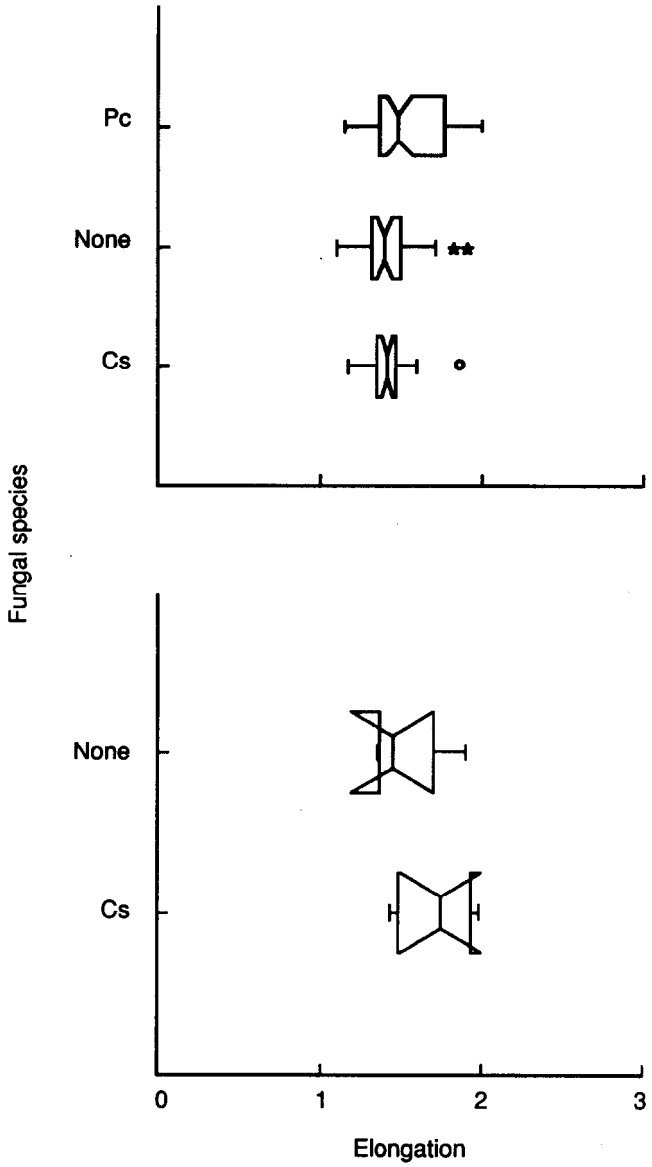


Figure 27—Elongation for paper from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

The TEA was significantly improved with aspen treated with either fungus, about 21%. but there was no difference on treatment of pine with *C. subvermispora* (Fig. 26). For aspen treated with either fungus or pine treated with *C. subvermispora,* no significant differences occurred in elongation or zero span tensile index (Figs. 27 and 28).

The tear index was significantly better with aspen treated with *P. chrysosporium* or *C. subvermispora,* and the same was true with pine treated with the latter. The large differences in tear were observed regardless of the type of tear test used, single- or multiple-ply (Figs. 29 and 30). Only two runs were made with pine and *P. chrysosporium,* and the results indicated no significant effect. With pine treated with *C. subvermispora,* the single-ply tear index was 53% greater than the control.

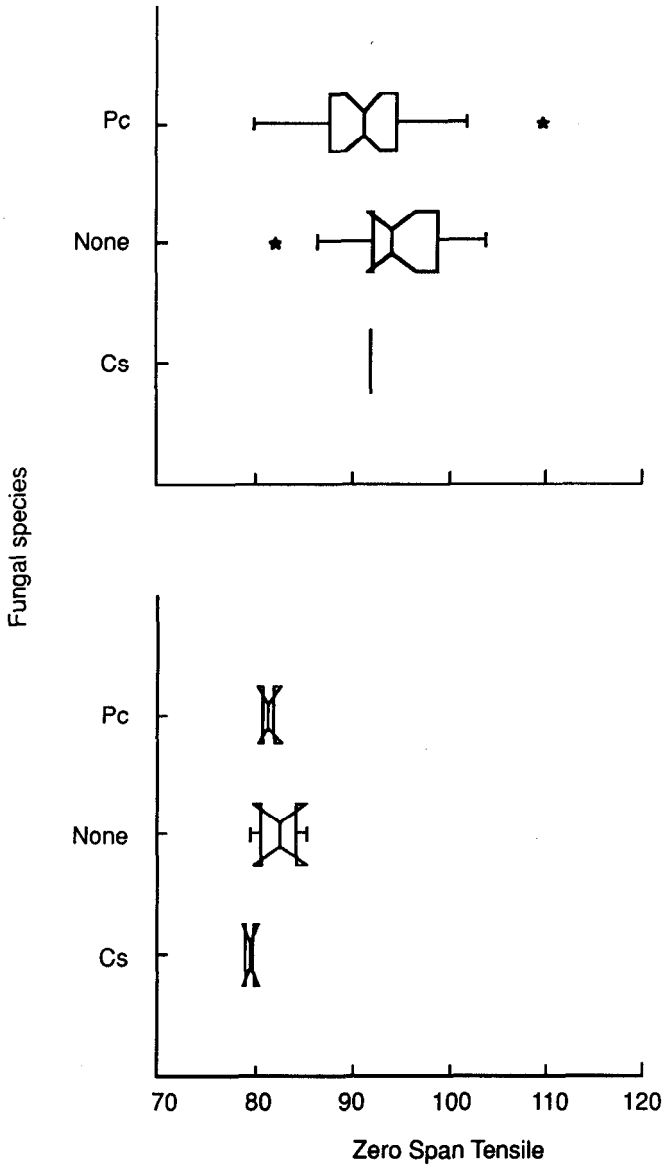


Figure 28—Zero span tensile for paper from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

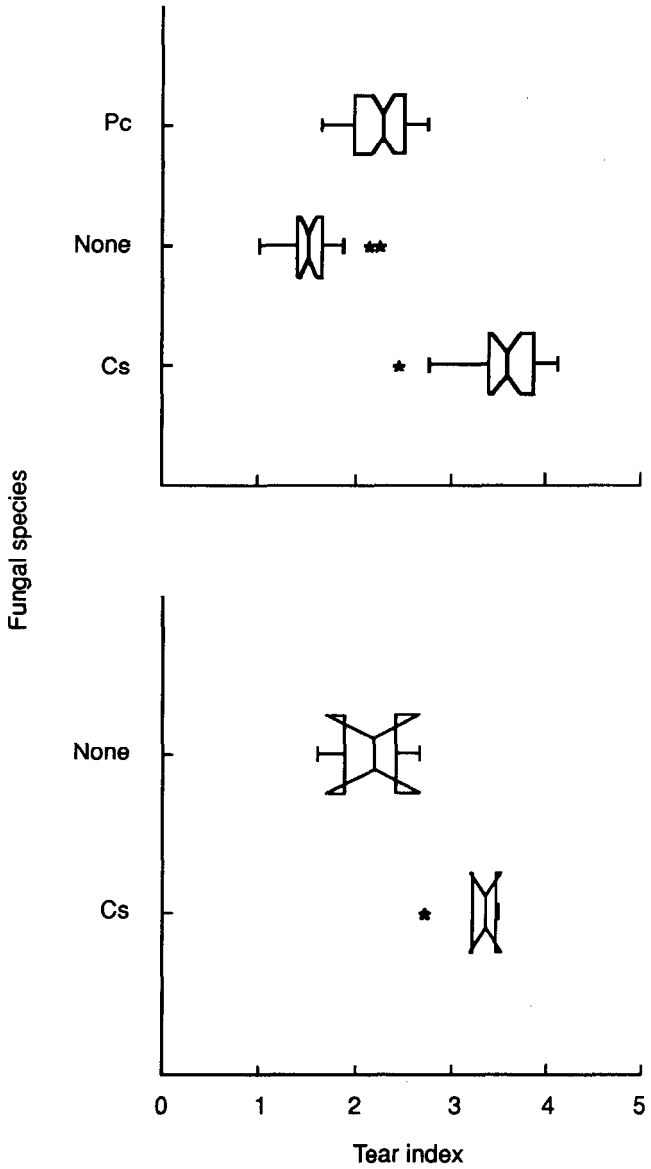


Figure 29—Tear index (single-ply tear) for paper from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

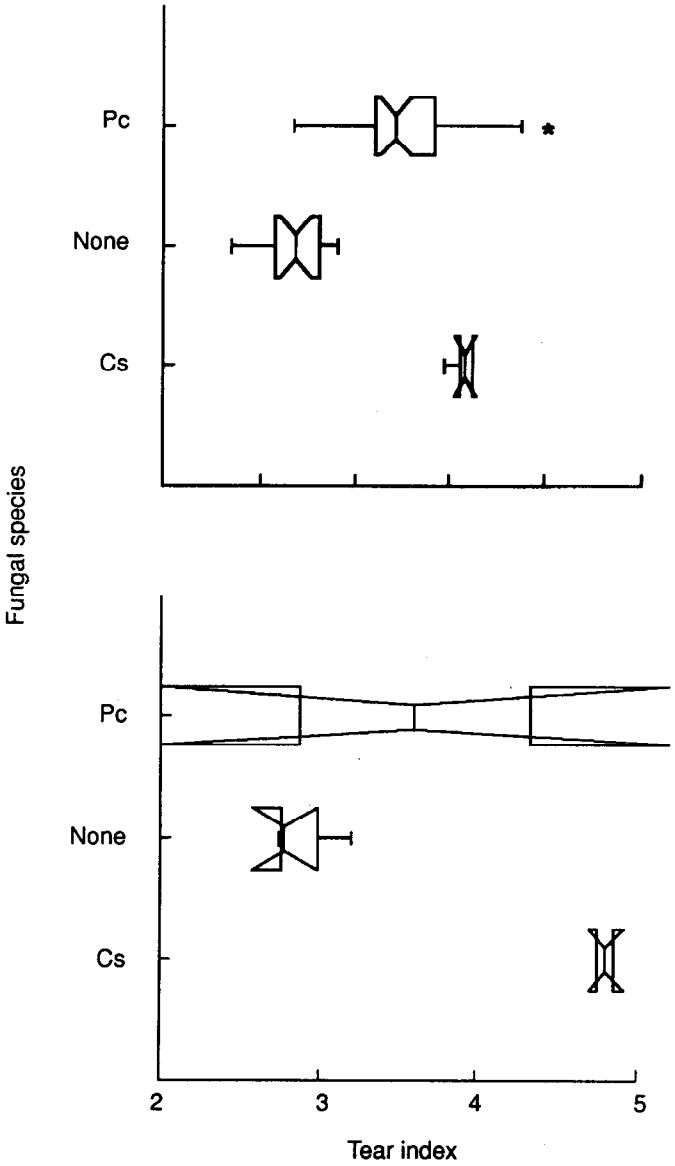


Figure 30—Tear index (multiple-ply tear) for paper from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

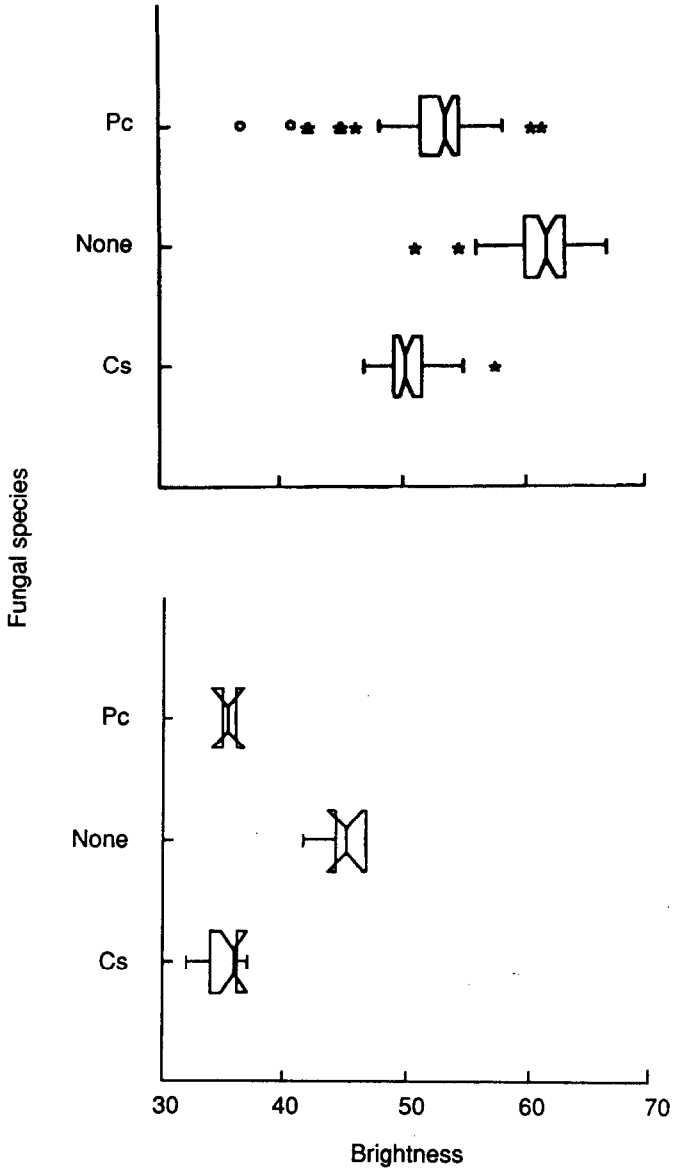


Figure 31—Brightness of pulps made from chips of aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

Regardless of organism or wood species, a significant reduction in brightness and scattering coefficient was observed (Figs. 31 and 32). For pine treated with *P. chrysosporium,* the change in brightness was -21%, and with *C. subvermispora,* -21% (Fig. 31). The corresponding changes in scattering coefficients were -21% and -30%. (Fig. 32). Figure 33 indicates no significant difference in opacity with pine, but the sample size was small.

A 21% increase in the fiber length index with aspen treated with *P. chrysosporium* was indicated (Fig. 34). The outlier was run 64, for which there was no clear explanation for the high value. There was no significant difference with pine.

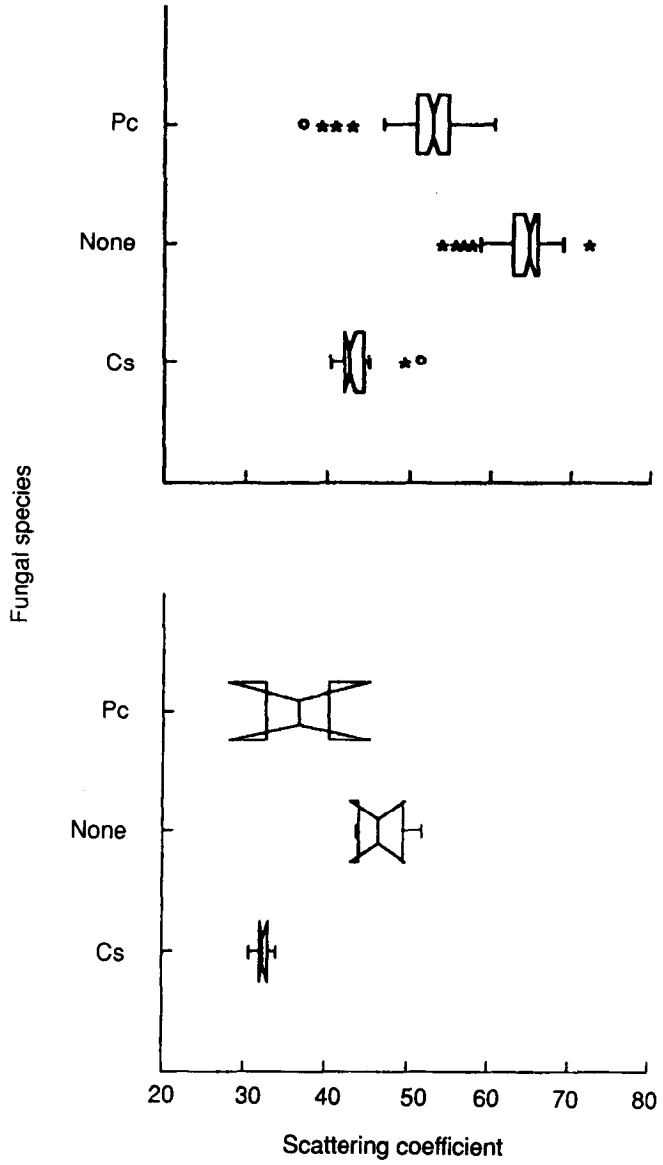


Figure 32—Scattering coefficient pulps made from chips of aspen (top) or pine (bottom) treated with *P. chrysosporium or C. subvermispora.*

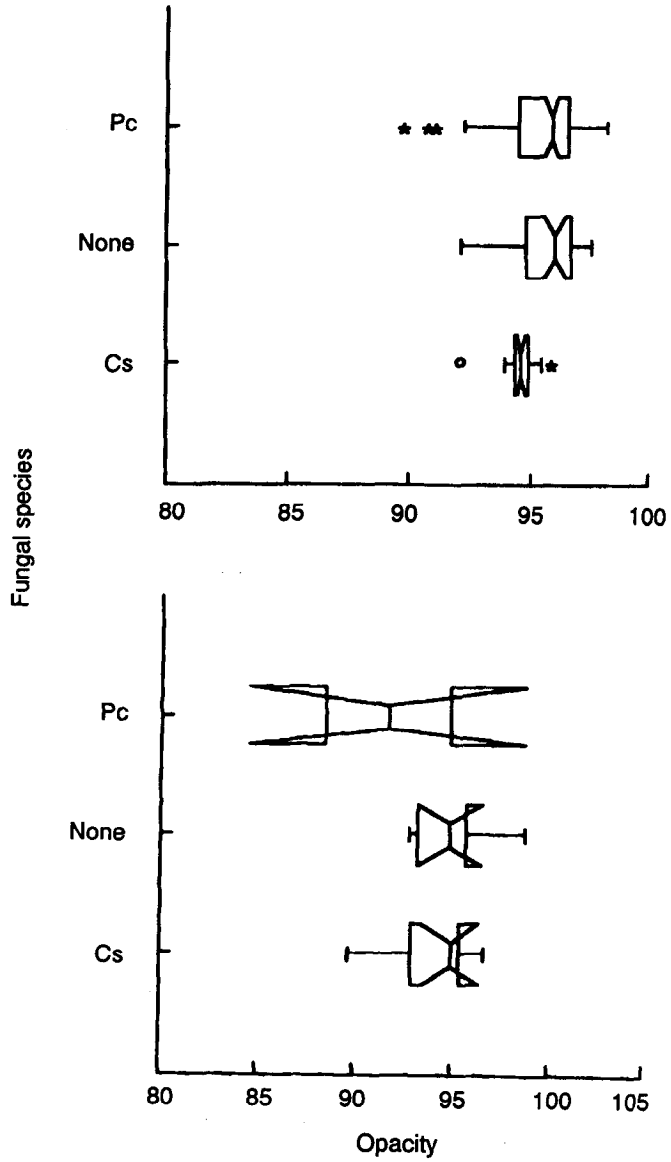


Figure 33—Opacity of paper from aspen (top) or pine (bottom) treated with *P. chrysosporium* or *C. subvermispora.*

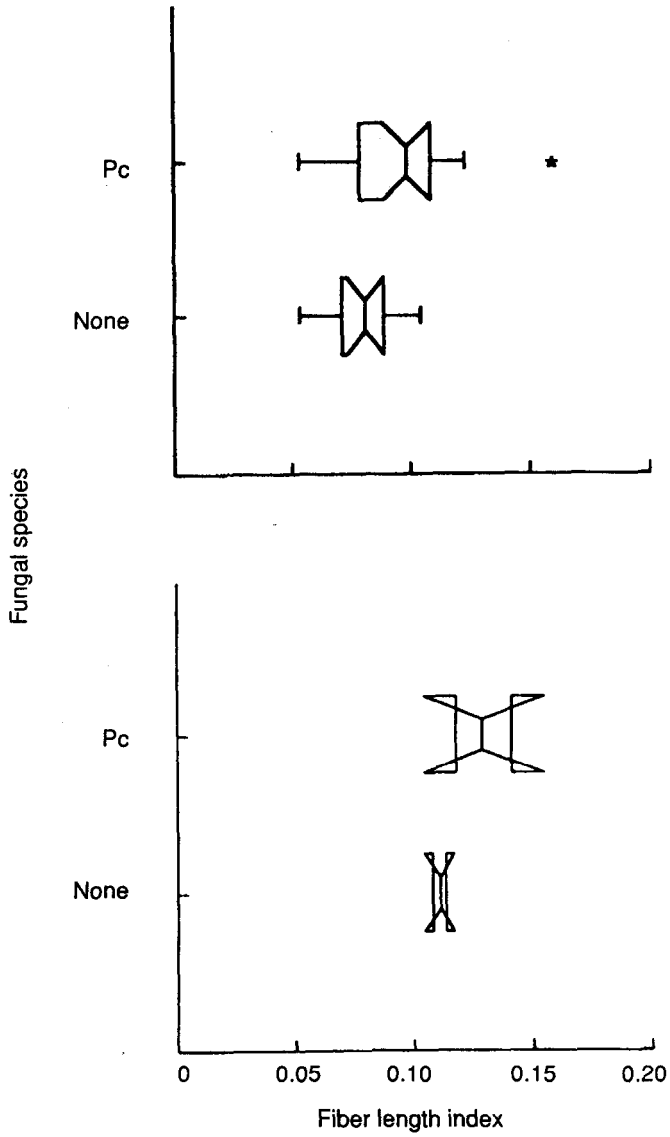


Figure 34—Fiber length index of paper from aspen (top) or pine (bottom) treated with *P. chrysosporium.*

The effect of incubation time on the various properties is shown in Figures 35-47. These plots are for aspen treated with *P. chrysosporium* only. There was no significant difference between 2 and 4 weeks in terms of energy savings (Fig. 35). The two values at 3 weeks are high but when compared with their specific control runs, which included the top three control outliers, they also showed a reduction in energy.

Figure 36 shows that weight loss exhibited an almost linear relationship with incubation time. Taken together, results suggest that there was little relationship between energy savings and weight loss (Figs. 35 and 36).

Klason lignin decreased with incubation time (Fig. 37). There did not appear to be a trend between density and incubation time (Fig. 38).

Strength properties, except for tear index, improved during the first 2 weeks of incubation. Improvements for burst, tensile, and TEA indexes are shown in Figures 39-41. Elongation significantly increased after 2 weeks but then decreased after 4 weeks (Fig. 42). Tear index (Fig. 43) increased with time at least up to 4 weeks. There was no difference in zero span tensile index (Fig. 44), although the single value at 6 weeks was low.

Brightness (Fig. 45) and scattering coefficient (Fig. 46) followed similar patterns, both decreasing with incubation time. There was no obvious trend between opacity and incubation time (Fig. 47).

The effect on energy consumption using pine and *C. subvermispora* with respect to inoculum age is shown in Figure 48. Data suggest that inoculum age was not a significant factor in energy savings.

The results in Figure 49 indicate that spore suspensions might be more effective than colonized chips as inoculum; this deserves further study.

For aspen treated with *P. chrysosporium,* the effects of inoculum age or level were not significant (Figs. 50 and 51). This is not surprising, because *P. chrysosporium* under the right conditions is a fast-growing fungus.

For aspen treated with *C. subvermispora,* the use of colonized chips or mycelium suspension was equally effective (Fig. 52). Inoculum age was again not a factor (Fig. 53). However, there was a significant positive effect of inoculum level on energy savings with this fungus (Fig. 54); as the inoculum level increased, the energy savings increased. No trends were seen in the effect of inoculum level on the other properties (data not shown).

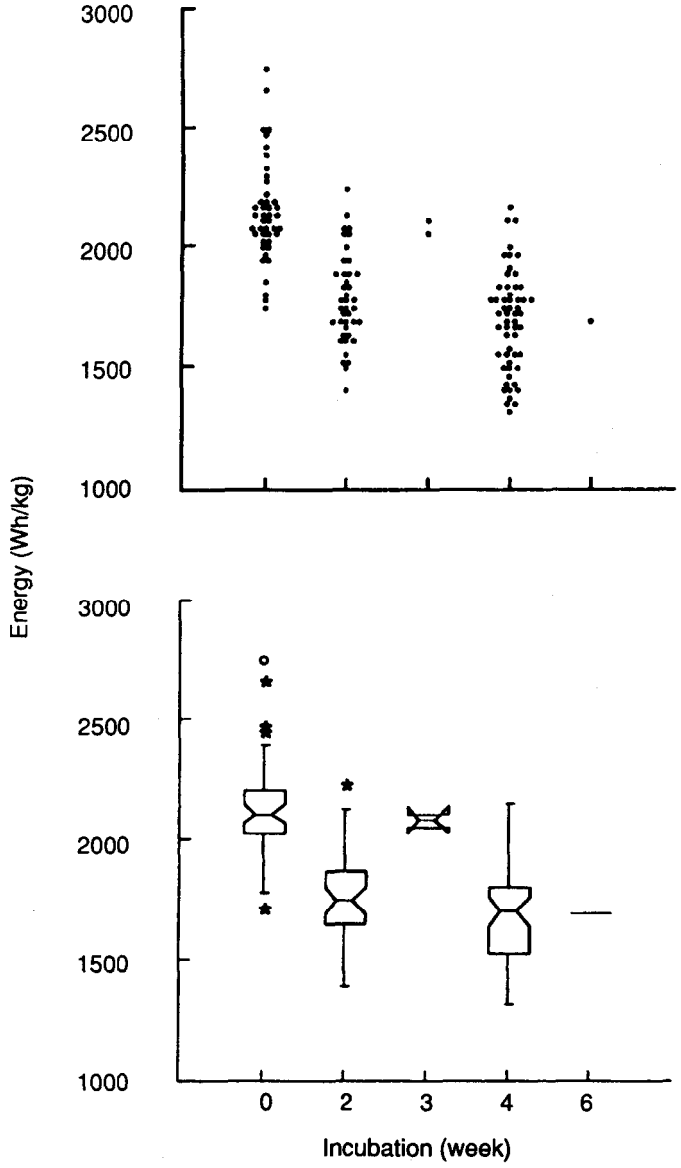


Figure 35—Refining energy as a function of incubation time for aspen treated with *P. chrysosporium.*

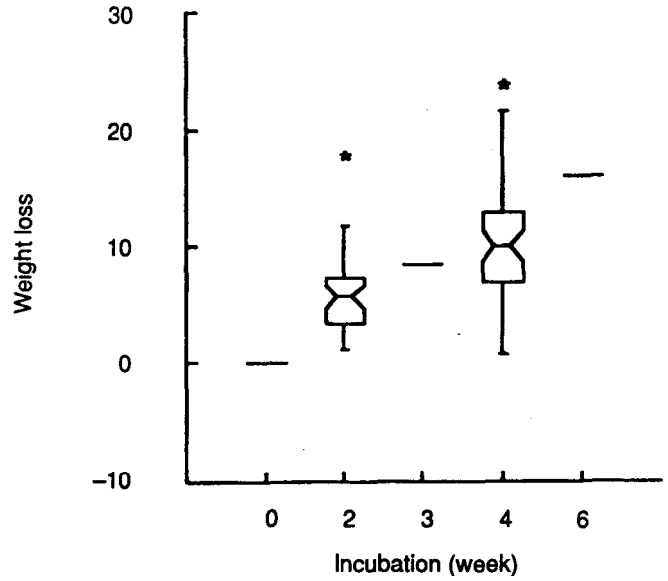


Figure 36—Weight loss as a function of incubation time for aspen treated with *P. chrysosporium.*

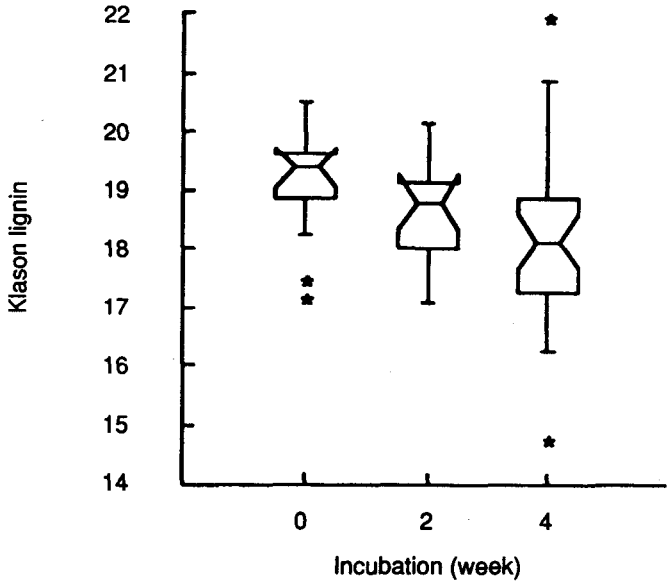


Figure 37—Klason lignin content of aspen chips as a function of incubation time with *P. chrysosporium.*

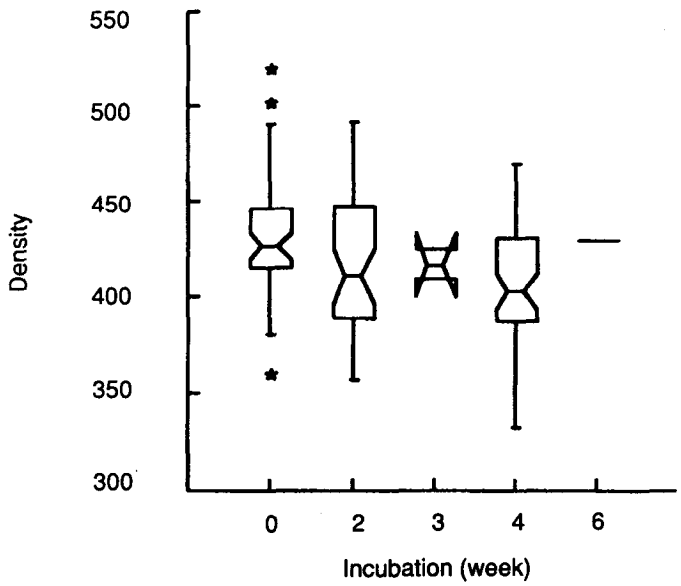


Figure 38—Handsheet density as a function of incubation time for aspen treated with *P. chrysosporium.*

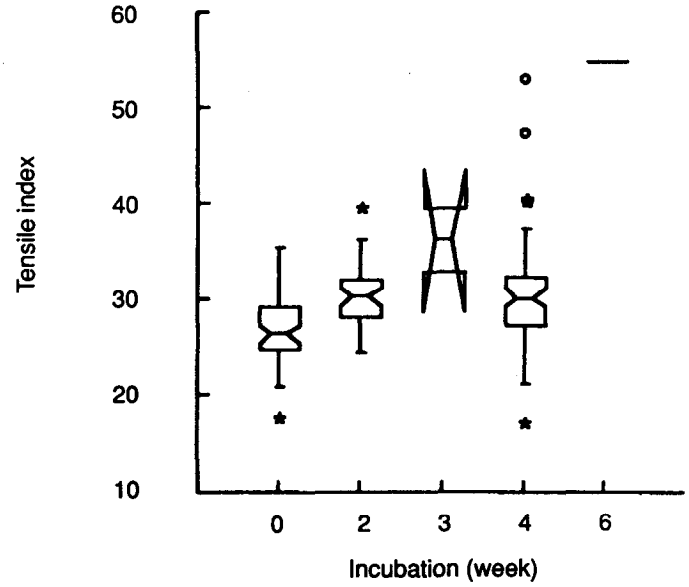


Figure 40—Tensile index of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

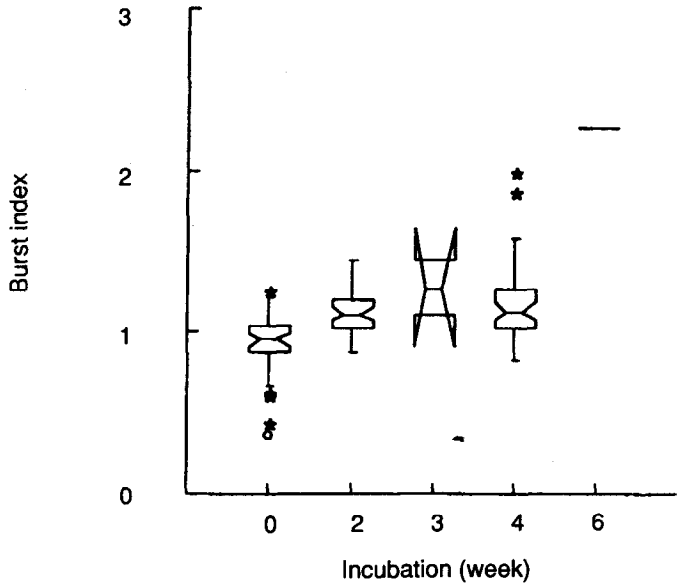


Figure 39—Burst index of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

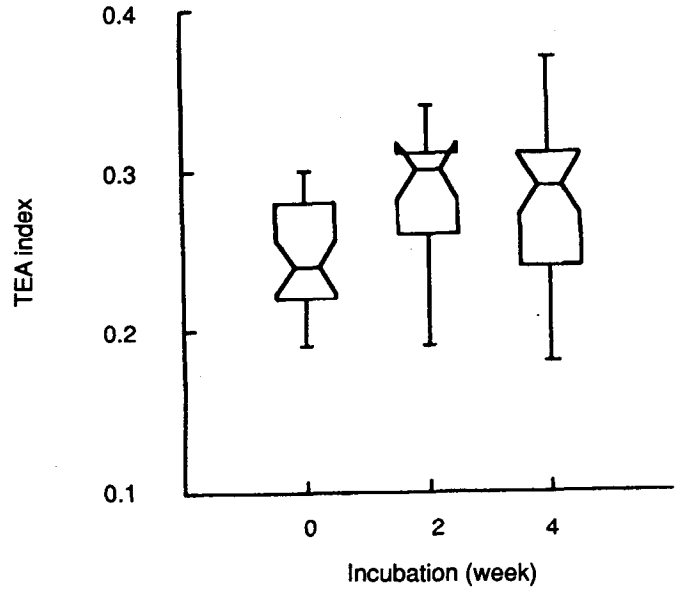


Figure 41—TEA index of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

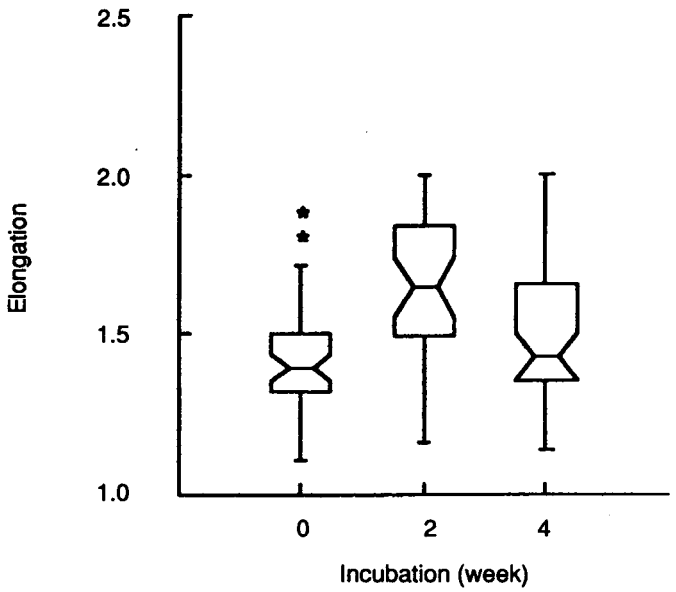


Figure 42—Elongation of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

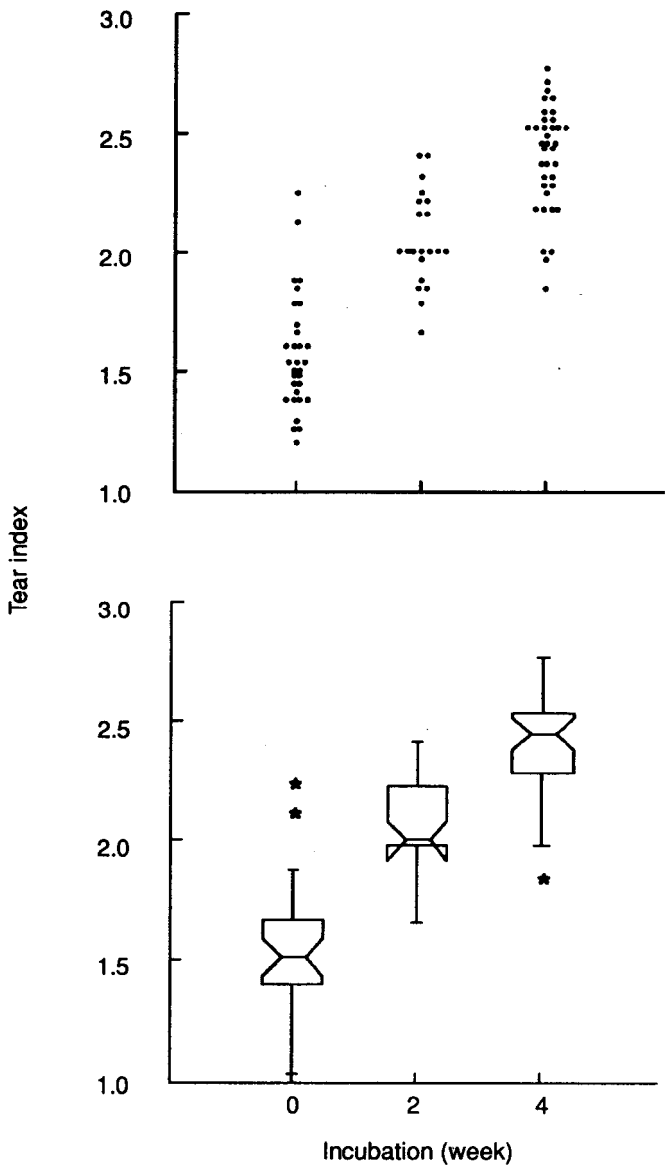


Figure 43—Tear index (single-ply tests) of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

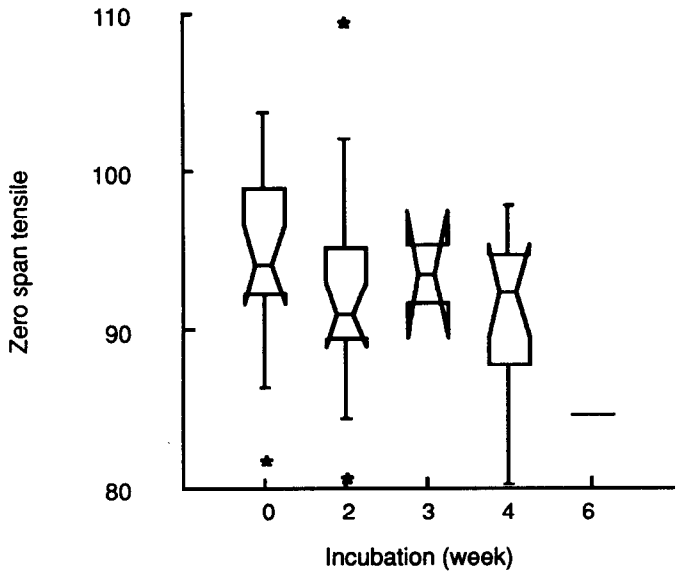


Figure 44—Zero span tensile index of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

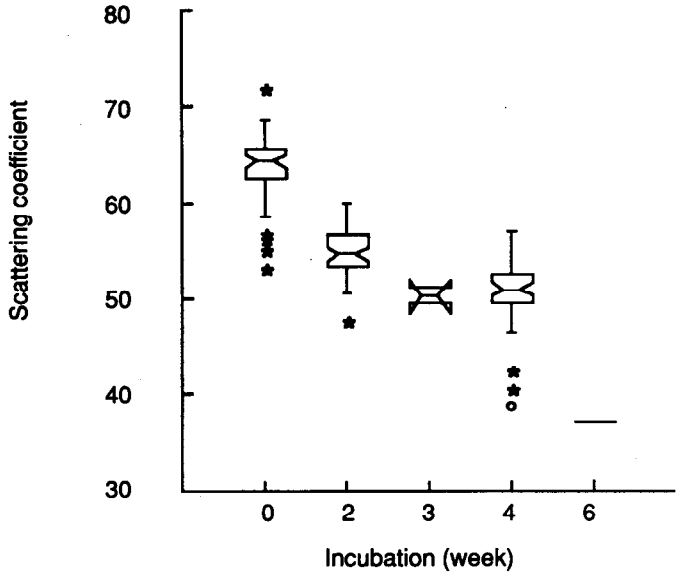


Figure 46—Scattering coefficient of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

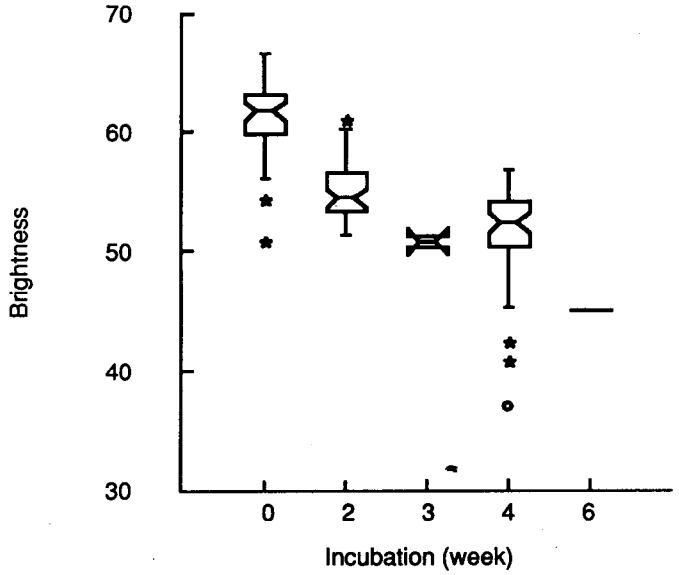


Figure 45—Brightness of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

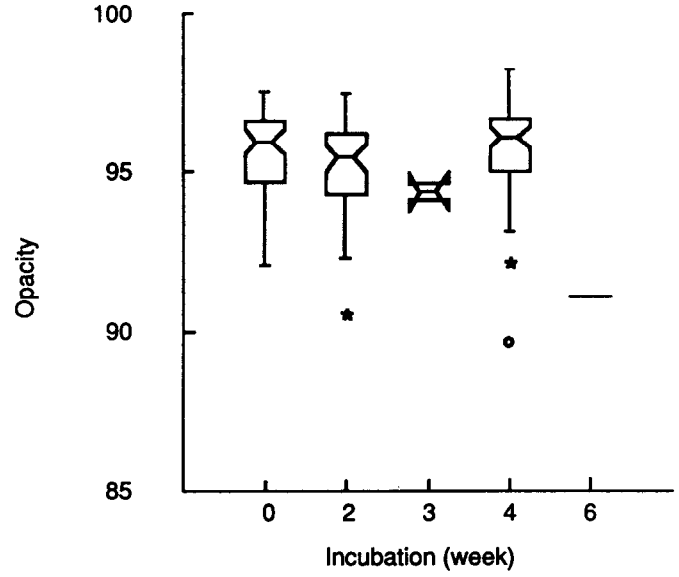


Figure 47—Opacity of paper from aspen treated with *P. chrysosporium* as a function of incubation time.

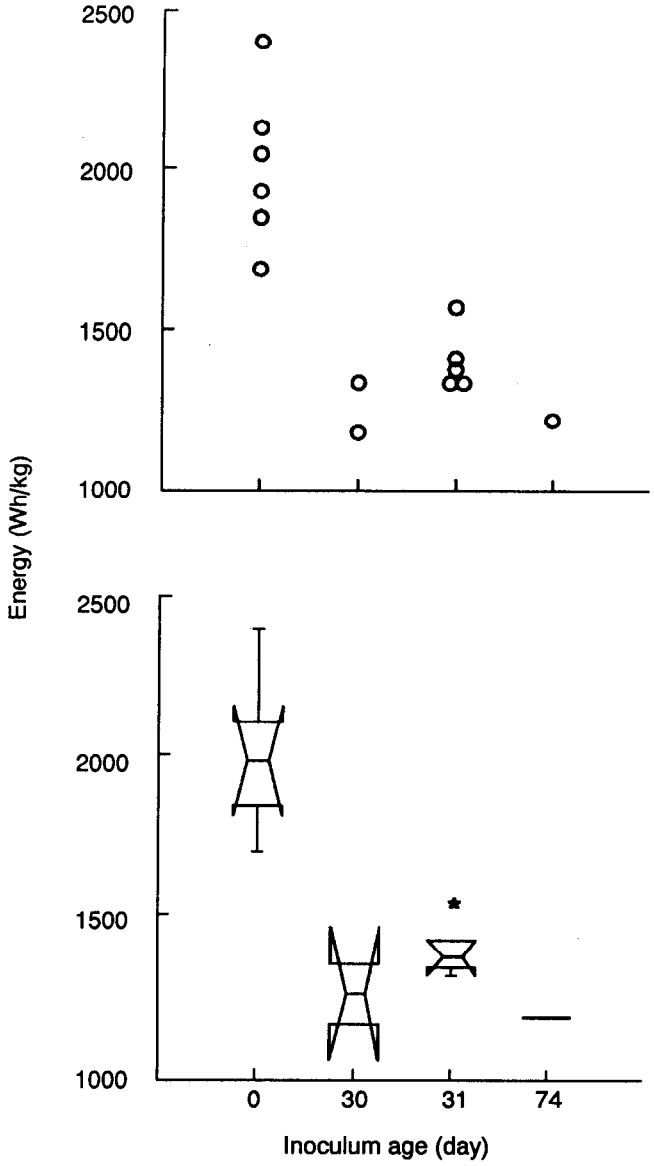


Figure 48—Refining energy as a function of inoculum age for pine treated with *C. subvermispora.*

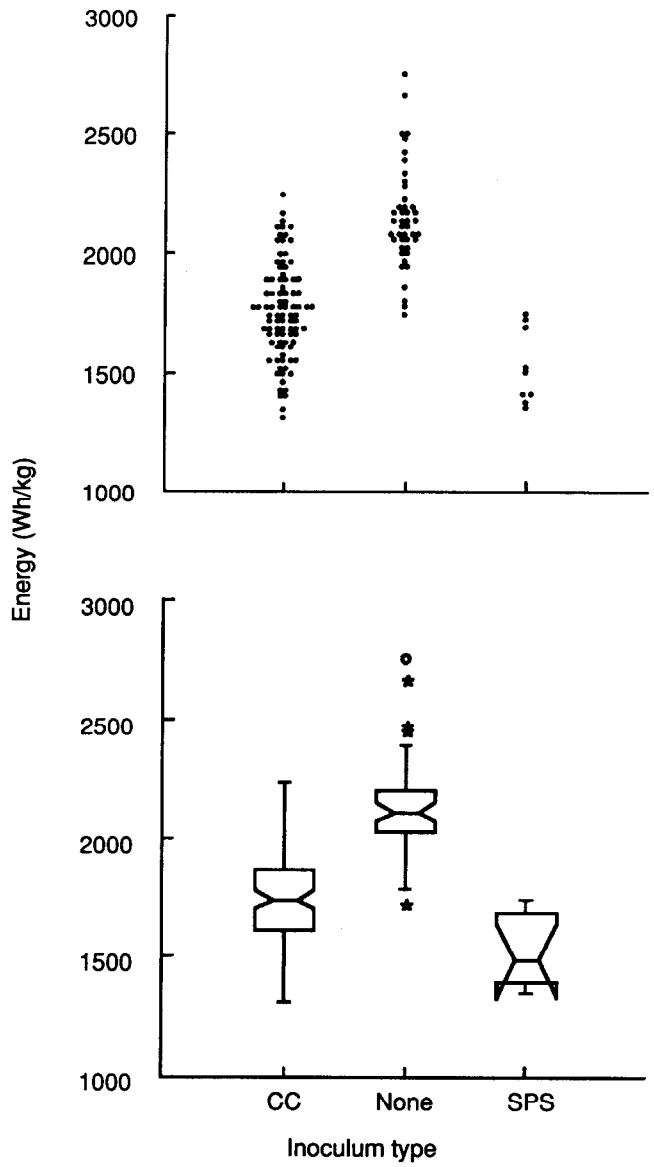


Figure 49—Refining energy as a function of inoculum type for aspen treated with *P. chrysosporium.* CC = colonized chips; SPS = spore suspension. (Spore suspension was prepared by adding a small amount of sterile 0.1% Tween-20 to the surface of PDA plate cultures (5-day old) and dislodging the spores. Spore suspension was then filtered through sterile glasswool to get rid of fungal hyphae; 5 x 10^8 viable spores/ kg of chips (dry weight basis) were used.)

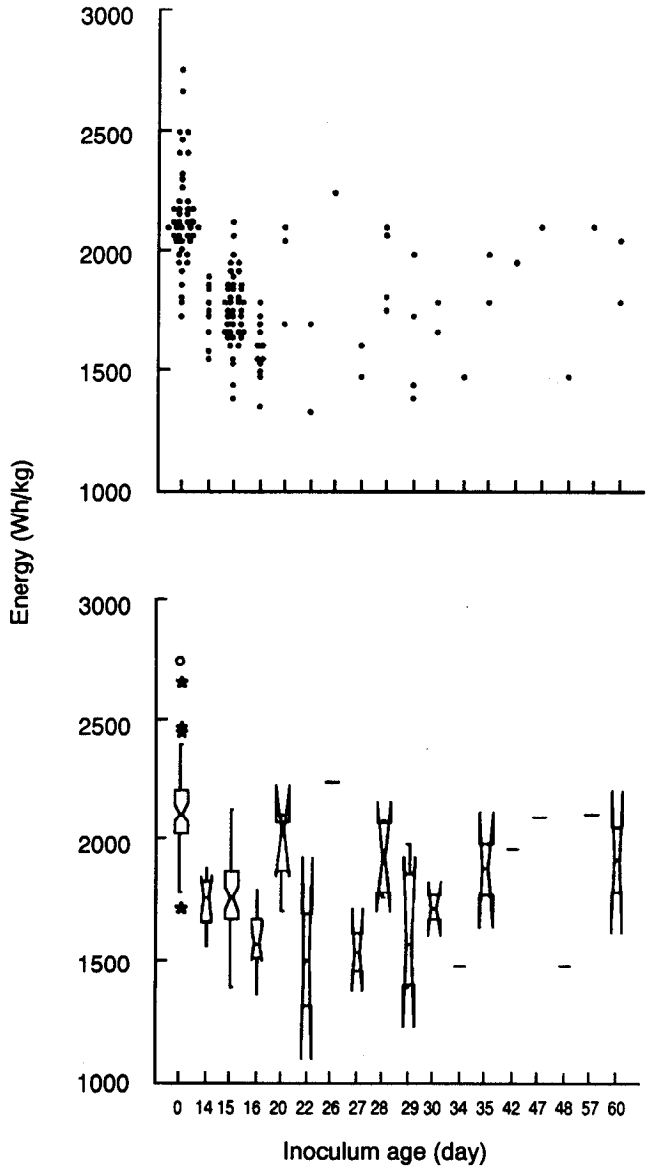


Figure 50—Refining energy as a function of inoculum age for aspen treated with *P. chrysosporium.*

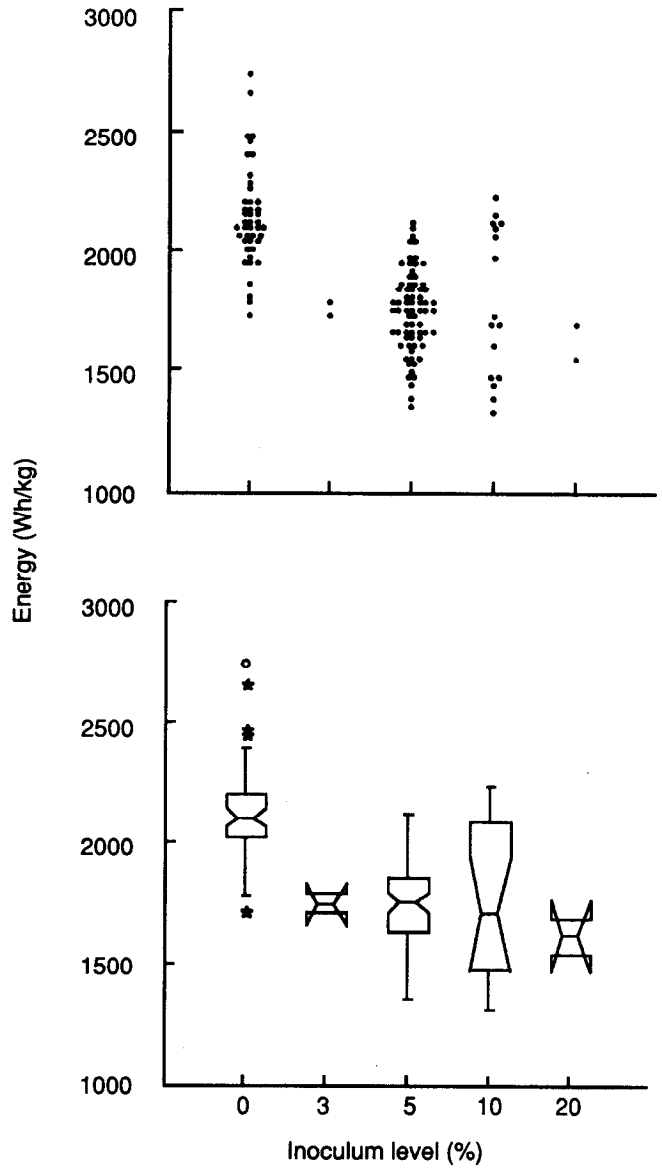


Figure 51—Refining energy as a function of inoculum level for aspen treated with *P. chrysosporium.*

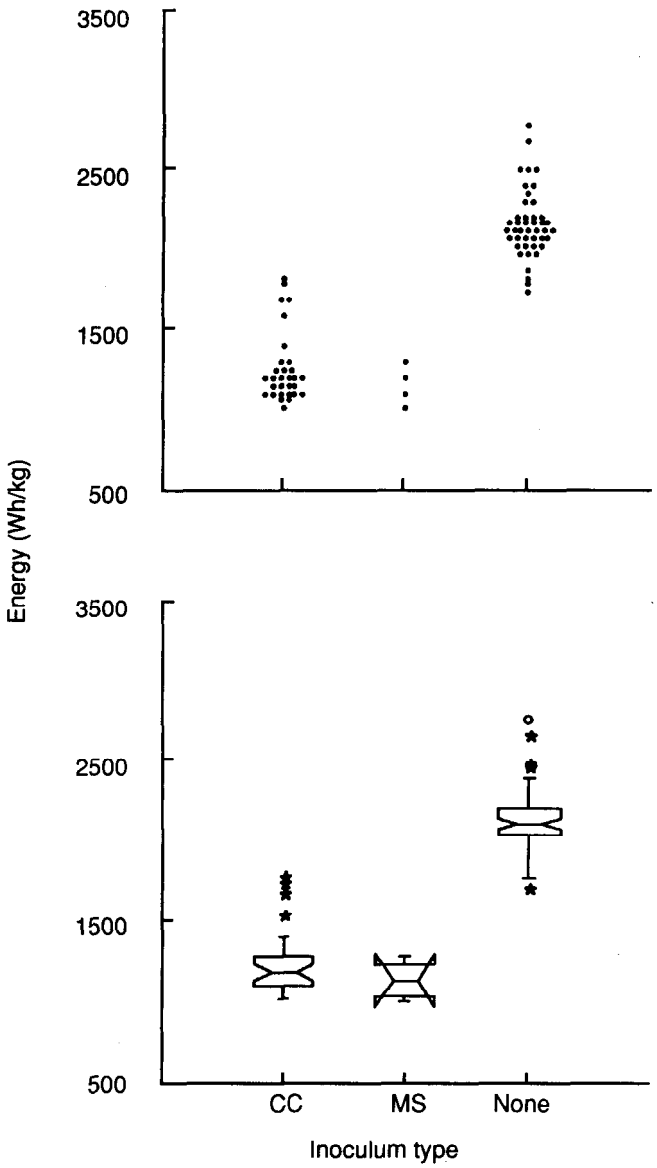


Figure 52—Refining energy as a function of inoculum type for aspen treated with *C. subvermispora.* CC q colonized chips; MS = mycelial suspension. (The mycelium was grown in potato dextrose broth, 100 ml in seven 1-L flasks. Each flask was inoculated with mycelium-covered agar plugs and incubated at 27 ± 1°C without agitation. The spent medium was then decanted, the mycelium washed with sterile distilled water, and then blended aseptically in a Waring blender. Sterile distilled water was added to the suspension to a total volume 300 ml. This liquid (100 ml) suspension (1.7 g fungus on a dry weight basis) was added to each bioreactor containing 1,500 g of chips (ovendry basis).)

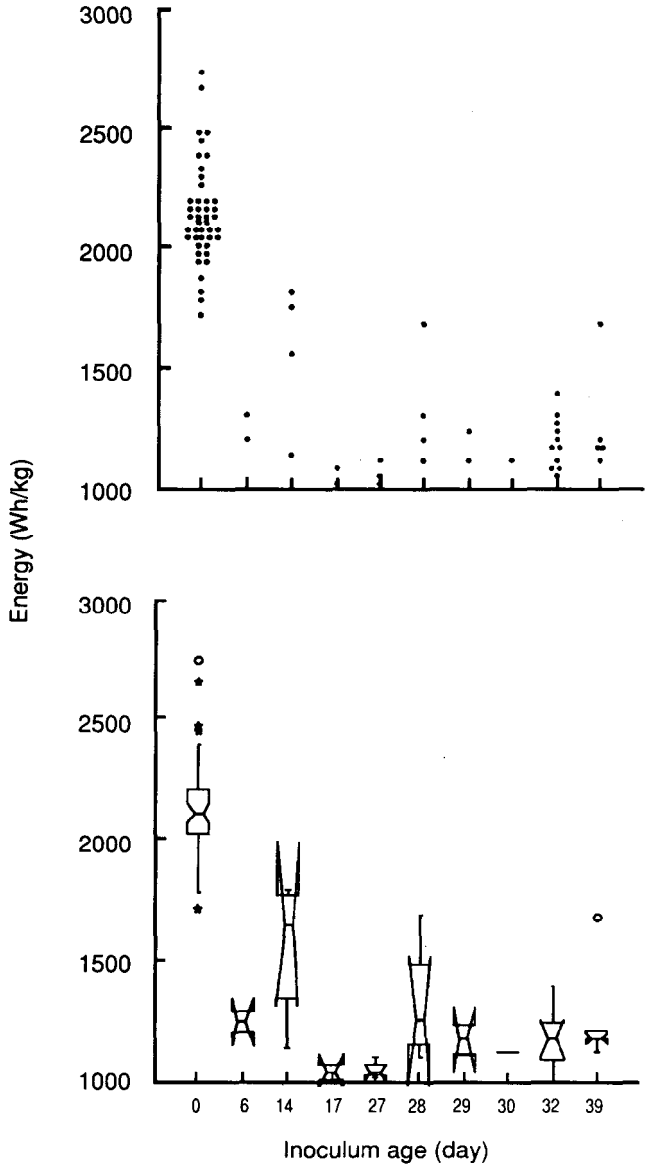


Figure 53—Refining energy as a function of inoculum age for aspen treated with *C. subvermispora.*

Specific Biopulping Experiments

In the following descriptions, numbers refer to the runs comprising the individual experiments. Data for the runs are found in Appendix B. Energy results are given graphically in connection with the descriptions of the following experiments.

Changes in optical properties and density are not detailed for the various experiments because the changes, or lack thereof, were essentially the same for a given wood and fungus combination, regardless of treatment.

Screening of Fungi on Aspen Chips

In early experiments, several white-rot fungi were screened for their biopulping performance using aspen wood chips (Myers and others 1988, Leatham and Myers 1990, and Leatham and others 1990a,b). Based on energy savings (Fig. 17) and improvements in paper strength properties, six fungi were selected for further study: *Phlebia tremellosa* (PRL-2845), *P. subserialis* (RLG-6074-sp. TON-427), *P. brevispora* (HHB-7099), *Dichomitus squalens* (TON-427), *Phanerochaete chrysosporium* (BKM-F-1767), and *Poria medulla-panis* (RAB-825). Emphasis was given to

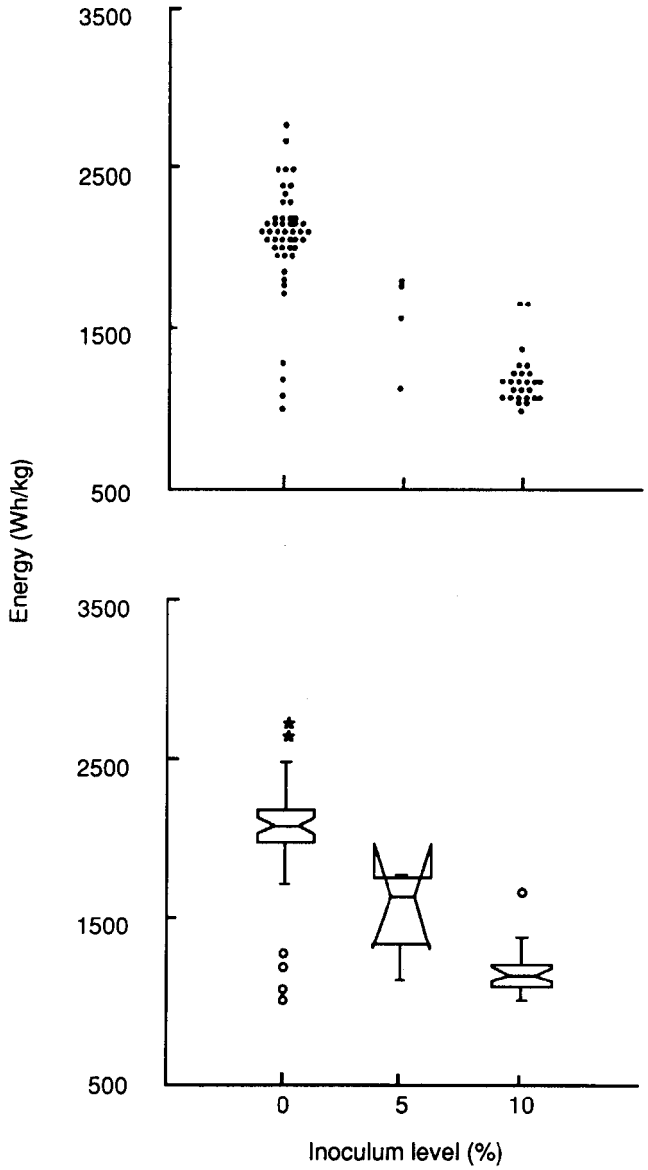


Figure 54—Refining energy as a function of inoculum level for aspen treated with C. *subvermispora.*

P. chrysosporium because it is by far the most studied white-rot fungus, and it competes well with indigenous microorganisms. Based on this early work, *P. chrysosporium* was chosen for most of the ensuing studies, as described in the foregoing section. From time to time, additional fungi identified in the screening were also selected for further evaluation, one was *C. subvermispora.*

As described in the next section, our initial screening (Fig. 18) of fungi on pine indicated that *C. subvermispora* is superior (Leatham and others 1990a,b), and it was chosen for the subsequent work. It was of interest also to determine the biopulping performance of this fungus on aspen wood chips. Three strains, FP-90031-sp, L-6133, and CZ-3 (runs 177-182), were selected for this study based on their greater lignin selectivity compared to the other strains (Blanchette and others 1992). Aspen wood chips were treated in aerated static-bed bioreactors, and the experiment was performed in duplicate. All three strains caused 4% to 10% loss in weight of the chips (dry weight basis). All three strains saved electrical energy (41% to 48%) when compared to the control. The burst, tear, and tensile indices for the biopulped chips were significantly greater than those of the controls.

Screening of Fungi on Pine Chips

After our initial screening of fungi for their biopulping efficacy on aspen wood chips, we extended our studies to include pine.

Seven white-rot fungi were selected for this study based on their ability to selectively remove lignin from small loblolly pine blocks (Otjen and others 1987, Blanchette and others 1988). Fungi selected were *Phlebia tremellosa* (PRL-2845), *Phanerochaete chrysosporium* (BKM-F-1767), *Dichomitus squalens* (TON-427), *Hypodontia setulosa* (FP-106976-sp), *Phlebia brevispora* (HHB-7099-sp), *Ceriporiopsis subvermispora* (FP-90031-sp), and *Phlebia subserialis* (RLG-6074-sp). Pine chips were treated for 4 weeks in either rotating drum or stationary-tray bioreactors.

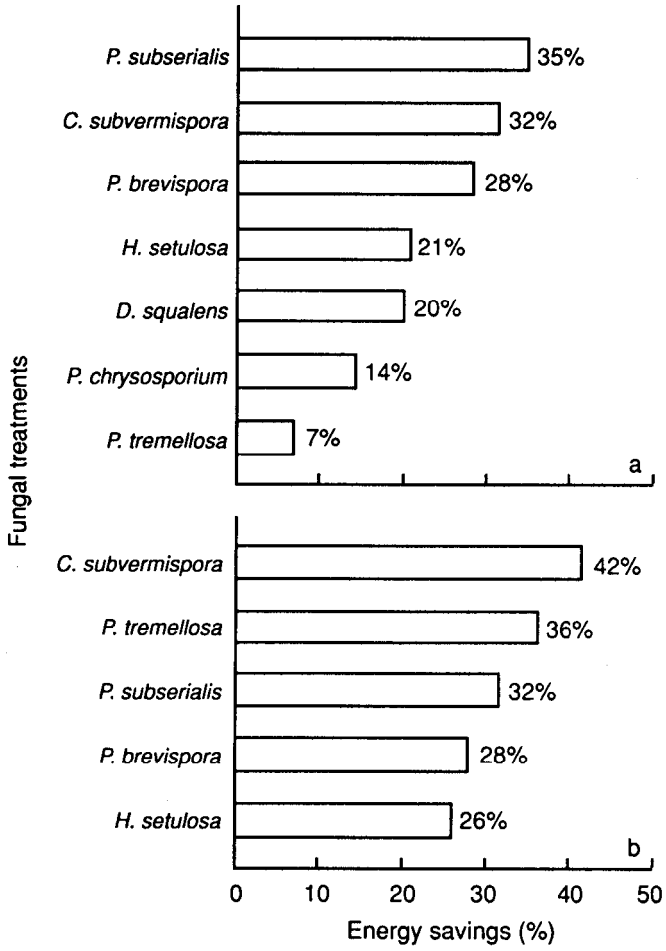


Figure 55—Energy savings for refining pine after treatment with selected white-rot fungi in rotating drum (a) or stationary-tray (b) bioreactors.

Table 3—Comparison of fungal species used to treat loblolly pine

Bioreactor/fungus	Strain	Run	Improvement (%) Burst index	Tear index	Tensile index
Rotating drum					
Dichomitus squalens	TON-427	38	6	33[a]	9
Phlebia subserialis	RLG-6074-sp	39	6	23[a]	15[a]
Phlebia tremellosa	PRL-2845	42	3	19	11
Ceriporiopsis subvermispora	FP-90031-sp	79	29[a]	71[a]	7
Hypodontia setulosa	FP-106976-sp	100	53[a]	74[a]	23[a]
Phlebia brevispora	HHB-7030-sp	101	30[a]	58[a]	15[a]
Stationary tray					
Phanerochaete chrysosporium	BKM-F-1767	36	14	1	19[a]
Phanerochaete chrysosporium	BKM-F-1767	37	35[a]	52[a]	20[a]
Phlebia tremellosa	BRI-67	57	-18[b]	12	-17[b]
Phlebia subserialis	RLG-6074-sp	58	-29[b]	9	-36[b]
Phlebia brevispora	HHB-7030-sp	67	-4	21[a]	-9
Hypodontia setulosa	FP-106976	68	12	32[a]	-12
Ceriporiopsis subvermispora	FP-90031-sp	80	32[a]	67[a]	-1

[a] Increases in property exceeds overlap of 95% confidence interval.
[b] Decreases in property exceeds overlap of 95% confidence interval.

During fungal treatment, weight losses from the chips ranged from 1% to 7% when incubated in the rotating drum bioreactors, and from 4% to 6% when incubated in stationary-tray bioreactors.

All fungal treatments applied to the pine chips saved electrical energy, regardless of bioreactor configuration, when compared to untreated controls (Fig. 55). Using the rotating *drum* and *P. tremellosa* (PRL-2845), the energy saving was only 7%. Using the stationary tray and *P. tremellosa* (BRI-67), the energy saving was 36%. It is not clear whether the difference was due to fungus strain or bioreactor type, but based on our experience overall, it was probably due to the differences between the strains.

Changes in strength and other properties of handsheets prepared from biomechanical pulps are summarized in Table 3. Tear index generally increased as a result of fungal pretreatment. *Hypodontia setulosa*-treated chips incubated in a rotating drum bioreactor had the greatest impact on tear index when compared with handsheets prepared from control pulps (74% increase). Pretreatment with *C. subvermispora,* incubated in either a rotating drum or stationary bioreactor, also resulted in a considerable increase in tear index (71% and 67% improvement, respectively). Tear index was not adversely affected by any fungal pretreatment.

Burst index also increased most by pretreatment with *H. setulosa* incubated in a rotating drum bioreactor. Increases in burst index were also observed following pretreatment with *P. brevispora* in a rotating drum bioreactor, with *C. subvermispora,* incubated in either bioreactor type, and with *P. chrysosporium* incubated in a stationary-tray bioreactor. Pretreatment with *P. tremellosa* and *P. subserialis* in stationary bioreactors had an adverse impact on burst index (18% and 29% reductions, respectively).

Tensile index was most significantly improved by *H. setulosa* when incubated in a rotating drum bioreactor. Other fungi that favorably affected tensile index were *P. chrysosporium, P. brevispora,* and *P. subserialis,* all in rotating drum bioreactors.

When incubation occurred in a rotating drum bioreactor, strength properties appeared to improve considerably. Unfortunately, there were insufficient comparisons of most species to draw conclusions about the impact of chip movement and bioreactor type on strength properties. The combination that yielded the greatest improvements in strength properties was *H. setulosa* incubated in the rotating drum bioreactor. This biopulping run (run 100) showed the greatest increases in all strength properties evaluated in these experiments. Differences observed in the two *P. chrysosporium* runs suggest variability as well as potential.

Based on energy savings and improvements in strength properties using both stationary-tray and rotating drum bioreactors, we concluded that *C. subvermispora* appeared to be superior to other fungi evaluated (Akhtar and others 1993).

In further studies (runs 123-127), five strains of *C. subvermispora* were evaluated. Choice of these strains was based on their lignin-degrading ability (Blanchette and others 1992). Pine chips were treated with these strains in stationary-tray bioreactors.

Weight losses of the chips during fungal treatments ranged from 4% to 7%. Figure 56 shows that pulping energy savings ranged from 37% for strain FP-90031-sp to 21% for strain FP-104027. Strains FP-105752, L-14807, and L-15225 gave similar energy savings of 27% to 31%.

Burst index increased by 10% to 15% after treatment with four of the five strains of *C. subvermispora;* tear index also increased significantly (approximately 45%) for all strains. Tensile index was not affected significantly, although the values were generally greater than for the controls. Elongation and TEA index were not significantly changed.

Based on energy savings and improvements in paper strength properties, we found strain FP-90031-sp superior to the other strains evaluated. This strain was isolated from oak house timbers from Beltsville, Maryland, by R. W. Davidson, R.L. Gilbertson, and Ed Haschayla. These results clearly indicate that strains of the same fungus can differ significantly in their biopulping efficacy.

Toward Optimization of Fungal Treatments

The number of variables in biopulping is large. In our initial work, we simply made best guesses based on the published literature, knowledge of fungal growth, and past experience. The opportunity to increase the effectiveness and efficiency and decrease the cost of biopulping through optimization of variables is great, as in any industrial microbial process. Consequently, we selected certain variables to begin optimization studies, which are described in the following sections.

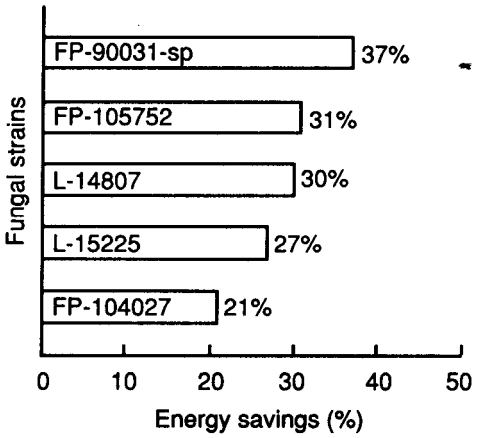


Figure 56—Energy savings for refining pine after treatment with different strains of *C. subvermispora.*

Post-Chipping Treatment of Chips

Runs 128-130 were conducted to determine whether the physical condition of chips (frozen, fresh, or room temperature dried) has an effect on biopulping performance. Aspen chips receiving these different physical treatments were inoculated with 5% chip inoculum (2 weeks old) of *P. chrysosporium* and incubated in aerated static-bed bioreactors in the usual way for 4 weeks. All chips showed comparable weight losses of 10% to 13%. Regardless of the chip conditions, energy savings ranged from 20% to 22%.

The three chip batches had similar burst and tensile indices. These were not changed significantly by fungal treatment in this experiment. In contrast, tear index increased significantly (about 50%) by fungal treatment. All chip batches gave the same results. The TEA index and elongation were similar for all samples, controls, and fungal-treated chips. The results suggest that biopulping is forgiving of chip handling procedures.

Effect of Shaking Bioreactors During Fungal Treatment

In previous experiments, fungus sensitivity to bioreactor type and chip movement was observed in comparisons of stationary-tray and rotating drum bioreactors (Leatham and others 1990a, Myers and others 1988). Chip movement during incubation in the rotating drums affected the extent of chip degradation, energy consumption on refining, and paper strength properties (Leatham and others 1990a).

To further evaluate the effect of movement of the chips during the runs, a few runs with aspen wood chips were made in which the aerated static-bed bioreactors were or were not shaken (runs 189-191). In all runs prior to 189, the bioreactors were shaken manually once during each of the first 2 weeks with the purpose of maintaining uniformity throughout the bioreactor.

Shaking the bioreactors had no effect on energy savings or paper strength properties. *Ceriporiopsis subvermispora* had the usual beneficial effects on energy consumption (52% and 53% savings), and on burst, tear, and tensile indices.

Nitrogen Addition to Inoculum Chips

This experiment (*P. chrysosporium* on aspen, runs 115-122, control F') was conducted with an idea that adding nutrient nitrogen to the inoculum would help build fungal biomass and vigor, which in turn would improve biopulping performance of the fungus. L-glutamic acid at two levels (500 or 5,000 ppm nitrogen, ovendry basis) was added to the inoculum prior to introducing the fungus. The inoculated chips were then incubated for 2 weeks. This inoculum was used at the 5% level with aerated static-bed bioreactors that received 4 or 40 g/kg glucose (ovendry basis). Additional nitrogen was not added to the chips in the bioreactors; consequently, at inoculation, the nitrogen with the inoculum

was diluted out to 25 or 250 ppm nitrogen. Bioreactors were incubated for 2 or 4 weeks.

Adding a high level of nitrogen to the inoculum caused additional weight loss, irrespective of the incubation time. The treatment high nitrogen/high carbon (glucose) resulted in the maximum weight loss of 9% in 2 weeks and 16% in 4 weeks. Energy savings were found for all conditions, with the high-nitrogen inoculum giving the most savings (15% and 20% at 2 weeks; 25% and 26% at 4 weeks); the high carbon condition was also beneficial, but the effect of nitrogen was greater (Fig. 57).

The 2-week runs showed increased burst strength; however, it was significant only with the high-nitrogen samples. Tear index increased in all cases from approximately 10% with low nitrogen/low carbon to approximately 35% with high nitrogen/high carbon. Tensile index increased significantly only in the high nitrogen/high carbon sample. Elongation and TEA index were unchanged from controls.

In the 4-week runs, burst and tensile indices were not significantly changed, but tear index increased, as it had in the 2-week samples. Again, elongation and TEA index were not affected by the fungal treatment.

Overall, these results suggest that increased inoculum nitrogen can have beneficial effects. However, the increased weight loss caused by the high nitrogen probably offsets the benefits. If the high inoculum nitrogen is in fact manifested as increased vigor, then other ways of increasing vigor should also be beneficial.

Nitrogen Addition to the Bioreactor Chips

Other experiments (runs 91-109) demonstrated that adding the nutrient nitrogen to the chips in the bioreactor rather than to the inoculum chips resulted in essentially the same results as shown in Figure 57. Further study showed that

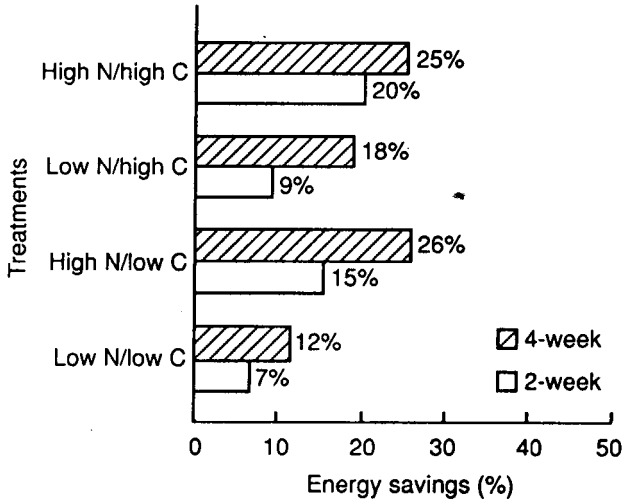


Figure 57—Energy savings for refining aspen after treatment with *P. chrysosporium.* Chips for inoculum were amended with high or low nitrogen (glutamic acid) and high or low carbon (glucose).

ammonium tartrate gave slightly better energy savings and improvements in paper strength properties than glutamate (runs 81-88).

Results With Nonchemically Defined Medium

In all previous runs, MCDM was used (Table 1). In this study, a nonchemically defined medium was employed. Yeast extract and lactose were used as nitrogen and carbon sources, respectively. Two fungi, *P. chrysosporium* and *C. subvermispora,* were used with aspen chips. With *P. chrysosporium,* two levels of nitrogen (108 or 324 ppm N on ovendried chip basis) with a uniform level of 40 g lactose per kg wood were used. With *C. subvermispora,* three levels of nitrogen (108, 324, or 976 ppm N) with a uniform level of 4 g lactose per kg wood were used. In both sets, aerated static-bed bioreactors were employed. *P. chrysosporium*-treated chips were incubated for 2 weeks, and *C. subvermispora*-treated chips were incubated for 4 weeks.

With *P. chrysosporium,* weight losses were 3% to 5% (runs 89 and 90). Savings in energy were twice as high for the higher level of yeast extract (32% compared to 14%). The tear and tensile indices were greater for the treatments than for the controls. Tear index increased with increasing nitrogen addition. The increase was 109% for 108 ppm N and 127% for 324 ppm N. The burst index was not significantly greater than the control. (No control was run with this set, so an average value for other controls was used.) The energy savings of 32% after 2 weeks with a weight loss of only 5% was one of the best results achieved with *P. chrysosporium.* Use of nonchemically defined medium, therefore, needs further study.

With *C. subvermispora* (runs 110-113), energy savings (Fig. 58) and weight loss (5% to 7%) also increased with nitrogen content. The energy savings for the highest nitrogen level (976 ppm) was better than average for this fungus on aspen. The tear index was significantly greater than that of the control for all treatments. Tear improvements ranged from 72% to 86%; differences between levels of nitrogen were not significant. Tensile and burst indices and other strength properties were not statistically different from the control.

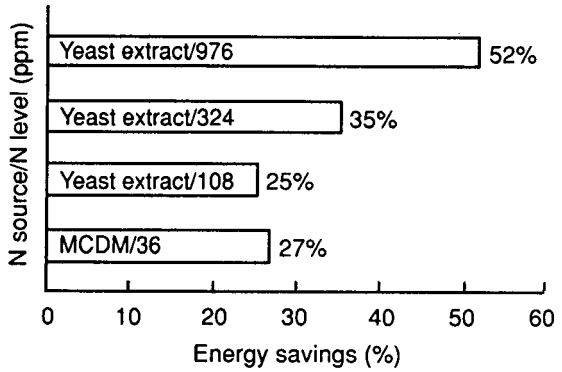


Figure 58—Refining energy savings with chips amended with yeast extract and lactose (aspen, *C. subvermispora*).

Aeration

Solid substrate fermentations are known to be affected markedly by aeration. In addition, the ligninolytic activity of fungi depends strongly on oxygen availability. Consequently, the influence of three airflow rates on biopulping efficacy was evaluated: low (0.001 L/L/min), medium (0.022 L/L/min), and high (0.100 L/L/min). The low flow rate was achieved by intermittent aeration (1 L/L/min for 1 h/day). Batches of chips were inoculated in aerated static-bed bioreactors with 5%, 2-week-old chip inoculum of *C. subvermispora.* The experiment was conducted in duplicate (runs 143-154; controls N' and O').

With 2-week incubation, all flow rates resulted in 3% to 4% weight loss. With 4-week incubation, medium and high flow rates showed 10% to 12% weight losses, whereas the low flow rates showed only a 6% weight loss.

As expected, the energy savings were greater with 4-week incubation than with 2-week incubation. Values were comparable to those obtained in other experiments with this fungus. Irrespective of incubation time, medium and high flow rates gave almost equal results, showing greater energy savings than the low flow rate (Fig. 59).

At both 2 and 4 weeks, all treatments showed significant increases in tear index over controls. At 2 weeks, two of the six treatments showed significant increases over the low flow rate treatments. Increases ranged from 24% to 48%. At 4 weeks, both replicates at high flow rate showed a significantly greater tear index than the low flow rate; increases ranged from 57% to 83%. At 2 weeks, there was no significant difference in burst index between treatments. At 4 weeks, there was no significant improvement in burst value when compared to the control. At both 2 and 4 weeks, there were no significant differences in the other strength properties compared to the controls.

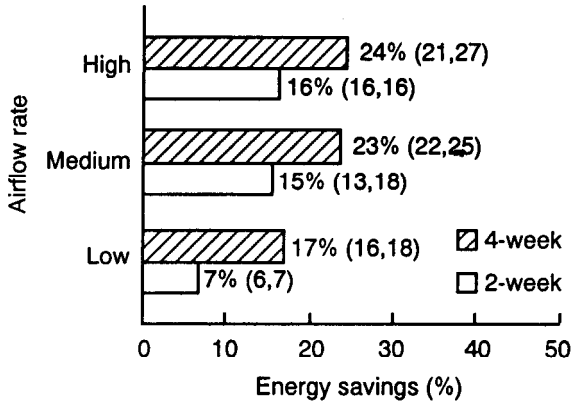


Figure 59—Refining energy savings as a result of different airflow rates during fungal treatment (aspen, *C. subvermispora*). (Numbers in parentheses are actual values for duplicate runs.)

Overall, the experiment showed that the medium and high flow rates gave comparable energy savings and had similar effects on strength properties and that the low flow rate was suboptimal.

Medium Sterilization Experiments

Phanerochaete chrysosporium on Aspen—As described in Materials and Methods, nutrient media were added to batches of chips and the amended chips autoclaved for 90 min. The question was asked whether autoclaving chips with medium adversely affected the biopulping performance. Autoclaving certain media has been reported to have deleterious effects on fungal growth including extending lag times. Therefore, the effects of medium and autoclaving on biopulping of aspen with *P. chrysosporium* were studied (runs 199-202). The four treatments were autoclaved chips with MCDM autoclaved separately, autoclaved chips without MCDM, nonautoclaved chips with autoclaved MCDM. and nonautoclaved chips. All treatments were at a final moisture content of 55% and were inoculated with a spore suspension (1.8×10^5 spores/g dry weight chips) and incubated in aerated static-bed bioreactors for 4 weeks. Three controls were used: autoclaved, nonautoclaved, and nonautoclaved with MCDM. All chips were adjusted to 55% final moisture content.

For the autoclaved medium treatments, weight losses were less (2% and 2.5%) than is usual for *P. chrysosporium* on aspen. The nonautoclaved chips showed weight losses of 4.5% with medium and 11% without medium.

Energy savings were best (33%) for the nonautoclaved *P. chrysosporium* inoculated chips without MCDM. The other inoculated chips showed similar energy savings (21% to 23%). Surprisingly, both nonautoclaved controls showed energy savings compared to the autoclaved control.

All fungus treatments and the nonautoclaved controls showed significant increases in tear index when compared to the autoclaved control, from 39% to 59%, and 25% and 32% for the nonautoclaved controls. The burst index of the two autoclaved treatments was significantly greater than the controls. The other treatments and nonautoclaved controls were not significantly different from the autoclaved control in the other strength properties.

It was of interest to examine the microflora in the nonautoclaved chips. Chip samples were removed periodically and plated onto PDA plates. In all cases, most growth from the chips was fungal. About half the fungal mass was *P. chrysosporium* in the case of the inoculated chips; other fungi were not identified. From the noninoculated control chips, only the unidentified fungi grew. As expected, chips supplemented with MCDM gave rise to a greater mass of contaminant growth than did nonsupplemented chips.

Results showed that even without added nutrients and autoclaving, *P. chrysosporium* is effective with aspen wood. Surprisingly, nonautoclaved controls also showed energy savings and increases in tear index. Autoclaving the medium was without significant effect. (We did not conduct further experiments with the "contaminant" fungi.)

***Ceriporiopsis subvermispora* on Aspen**—Another experiment was set up using *C. subvermispora (runs* 194-198). We compared chips autoclaved for 90 min with and without MCDM (filter-sterilized MCDM was added at the time of inoculation) with chips to which sterilized water was added after autoclaving. This last treatment was included to determine whether the medium was critical for the biopulping performance of the fungus. For comparison, three separate controls were treated in the same way, except they were not inoculated. Incubation was 4 weeks in aerated static-bed bioreactors with 10% wood chip inoculum.

Chips with MCDM lost 3% to 7% weight, whereas those with no medium lost only 2% weight. No clear effect of autoclaving the medium was determined.

Energy savings were comparable (44% to 45%) for chips with autoclaved and filter-sterilized medium but were much lower for chips receiving no medium (19%).

For all treatments, tear and burst indices were significantly greater than the control values. The treatment with no added medium showed significantly lower burst and tear indices than the other treatments. The increases in burst index ranged from 20% to 31% for the treatments with medium and was 14% for the treatment with no medium. The increases in tear index ranged from 102% to 121% for the treatments with medium and 52% for the treatment with no medium.

We conclude that autoclaving the chips with medium does not appear to affect energy savings or paper properties with *C. subvermispora.* Addition of medium has a substantial beneficial effect on energy savings and burst and tear indices. However, energy savings and changes in paper properties were significant even without added nutrients.

Light and Electron Microscopy Studies

The objectives of the light and electron microscopy studies were to explore at the microscopic level the growth patterns of the fungi in wood, the effects of the fungi on wood cell walls, and the appearance of biomechanical paper in comparison to other papers. The following summarizes the studies aimed at these objectives. Most results have been summarized in publications, cited in the following.

Ceriporiopsis subvermispora and *P. chrysosporium* colonized aspen wood chips by rapid proliferation in vessels and ray cells. After 2 weeks of growth, the fungi had grown over the surface of the chips (Fig. 60) and within vessels and rays. The fiber cells immediately adjacent to the vessels and ray cells appeared to become altered before other fibers. Wood cells fixed with $KMnO_4$ stained evenly as a diffuse electron dense stain through the secondary wall. The compound middle lamellae appeared darkest, with intense staining in the cell comer regions and the middle lamella between cells. As *P. chrysosporium* or *C. subvermispora* colonized, the wood cells started to lose electron density at the edge of the secondary wall exposed to the lumina. After 4 weeks of fungal growth, the ray parenchyma cells were disrupted and adjacent cells became less electron-dense. These changes demonstrated localized zones of delignification in cells adjacent to vessels and rays. If wood were incubated for additional weeks, delignification became substantial throughout the wood. Our studies demonstrated that during 2 to 4 weeks of fungal pretreatment, significant changes occurred in some wood cells. The progressive sequence of cell wall alteration by the fungi was underway before the second week of fungal growth.

Scanning electron microscopy was also used to observe growth in and degradation of nutrient-supplemented aspen chips after a 3-week treatment with *P. chrysosporium.* The fungus grew well across the chip surfaces and penetrated wood vessels and fiber cells as well as spreading through natural pits and fungal bore holes. Partial degradation of the cell lumen walls by fungal enzymes was evident. Erosion troughs and localized wall fragmentation or thinning were clearly visible, as was a generalized swelling and relaxing of the normally rigid wood cell wall structure (Fig. 61). Our observations suggest that the physical basis for biopulping efficacy of the fungal treatment might involve the overall enzymatic softening and swelling of the wood cell wall fibers, as well as thinning and fragmentation of the wood cell walls in localized areas (Sachs and others 1989).

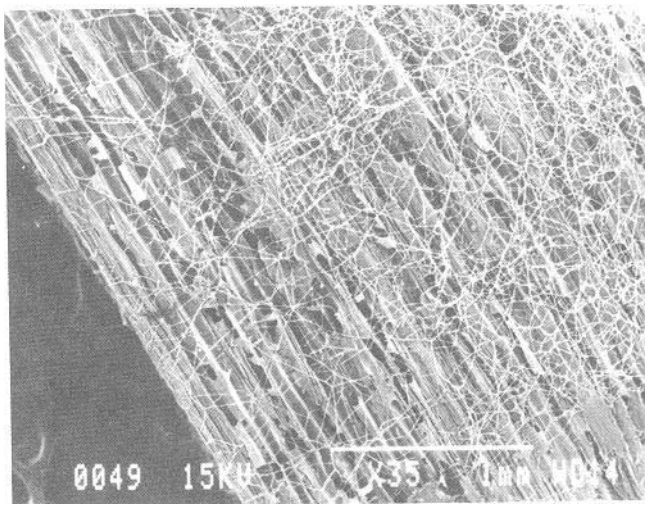


Figure 60—Web-like hyphal network of *P. chrysosporium* on the surface of a nutrient-supplemented aspen wood chip (bar = 1 mm).

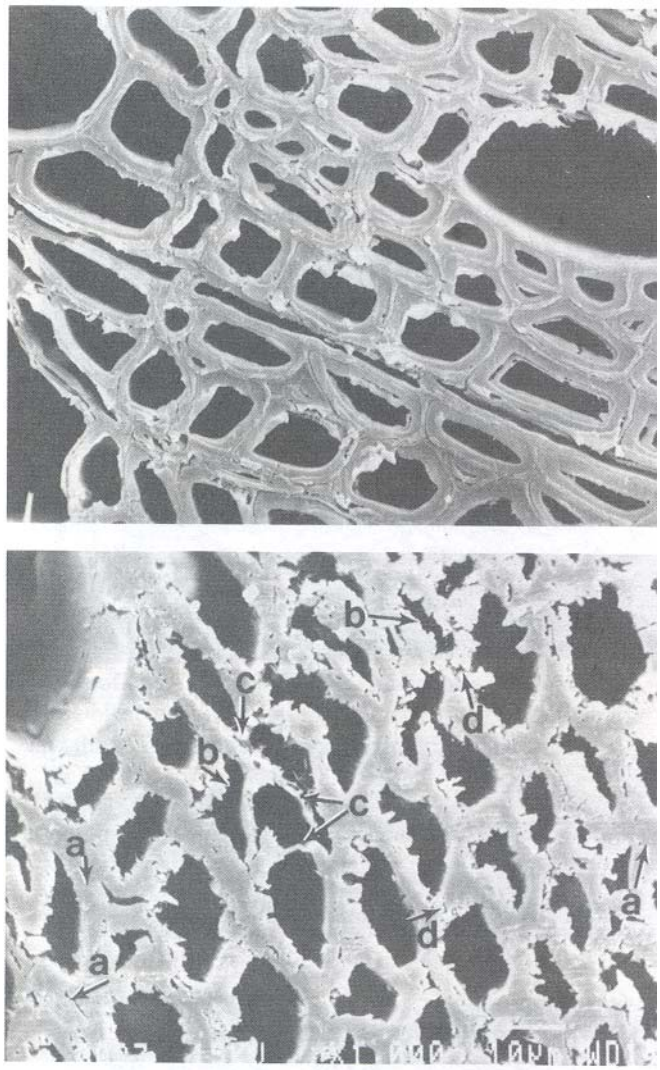


Figure 61—The normally rigid wood cell wall structure (top) within an aspen chip was modified (bottom) by a 3-week fungal treatment *P. chrysosporium.* Modifications included (a) cell wall swelling, (b) softening or relaxing resulting in the partial collapse of the tube-like cell structure, and (c) localized areas of wall thinning or (d) fragmentation (bar = 10 μ).

Another study evaluated the effect of wood particle size on the growth pattern of the biopulping fungus. We used standard industrial 6- and 19-mm chips and coarse refiner mechanical pulp, all from aspen. Scanning electron microscopy revealed a slight increase in the number of hyphae in the 19-mm chips when compared to that in the 6-mm chips, but no major morphological differences. Dense aerial hyphal growth occurred. The fungus eroded the chip cell walls primarily from the cell lumens outward. After only 3 weeks of fungal treatment, both chips and coarse pulp showed marked localized cell wall thinning and fragmentation as well as generalized swelling and relaxing of the normally rigid cell-wall structure. We conclude that particle size has a negligible effect on fungal growth on wood under conditions likely to be used in a commercial biopulping process (Sachs and others 1991).

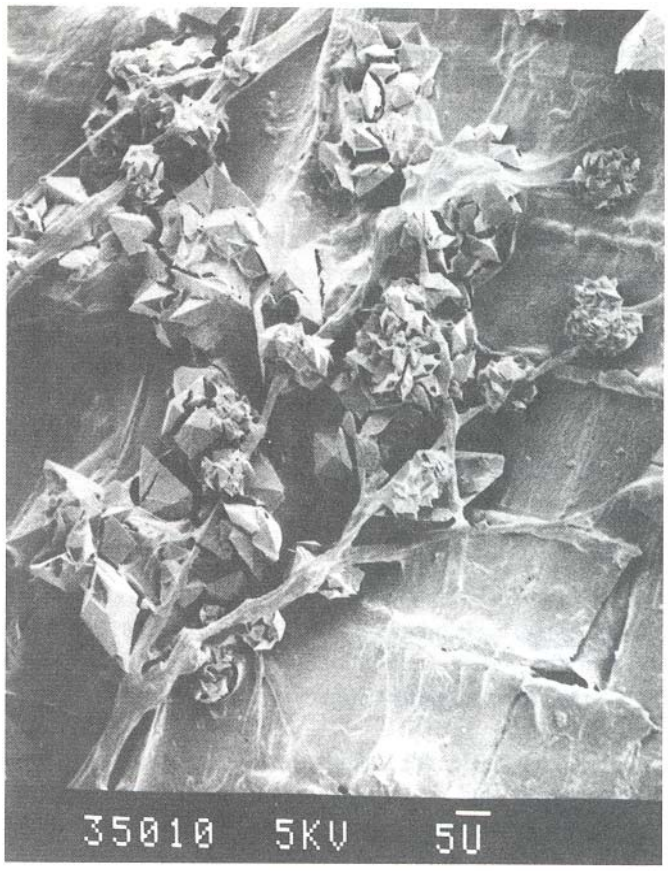


Figure 62—Calcium oxalate crystals on the hyphae of *C. subvermispora* (bar = 5μ).

Scanning electron microscopy of wood chips that had been treated with *C. subvermispora* showed that this fungus grows first as tightly packed hyphae within the ray cells. Microscopy revealed large quantities of calcium oxalate crystals on the surfaces of hyphae (Fig. 62). These crystals were most common on the mycelium covering the surface of the wood but were often also observed on hyphae within the lumens (Sachs and others 1989). The role of calcium during wood degradation by *C. subvermispora* could be significant.

In another investigation, we compared the microscopic appearance of bio-refiner mechanical pulp (BRMP) with that of refiner mechanical pulp (RMP), stone ground wood (SGW) pulp, thermomechanical pulp (TMP), chemithermomechanical pulp (CTMP), neutral sulfite semichemical pulp (NSSC), and kraft pulp. The CTMP was prepared in a sodium sulfite process.

Compared to control RMP, BRMP appeared "woolier," looser, and bulkier, with fibers less variable in length and with abundant fibrillation. In contrast to BRMP, RMP fibers were not as wide, appeared stiffer, were of different lengths, and had only moderate fibrillation. The SGW pulp fibers showed even less fibrillation, contained debris and included stiff fibers of various lengths. The TMP and CTMP pulp

fibers were of various lengths, longer than RMP, and had moderate fibrillation; they appeared to be stiff. These fibers were more twisted than the BRMP fibers. The NSSC pulp fibers, for the most part, exhibited fewer stiff fibers of various lengths, with more compressibility and conformability, when compared to the mechanically processed pulps. Compared to BRMP, NSSC pulp fibers were not as compressed and were more variable in length. Kraft pulping produced more uniform, separated, and collapsed fibers with abundant fibrillation. Overall, the BRMP pulp appeared similar to the kraft pulp.

To visually assess how the fiber morphology in these pulps contributes to sheet strength properties, we examined cross sections of handsheets (Fig. 63). Handsheets made from the mechanically processed pulps showed uncollapsed fibers leading to poor conformability and reduced bonding. The NSSC- and kraft-processed pulps gave handsheets that exhibited fibers of enhanced compressibility and conformability. Handsheets prepared from BRMP visually resembled the kraft handsheets, exhibiting good compressibility and conformability of the fibers (Sachs and others 1990).

To obtain a better understanding of the relationship between lignin removal and biopulping benefits, several studies were completed. Immunological techniques (Blanchette and others 1989) and bromination studies (Blanchette and others 1987, Otjen and others 1987) were used to characterize cell wall alterations in fungus-pretreated wood chips. Antibodies to lignin peroxidase were used to detect lignin peroxidase in wood cell walls treated with *P. chrysosporium.* Thin sections observed with transmission electron microscopy did not show the enzyme within the cell walls.

Another method involving the use of bromine to locate and quantify lignin did not show significant lignin loss within the cell wall layers (Blanchette and others 1987). Samples were treated with bromine and observed with energy dispersive x-ray microanalyses. Bromine reacts with lignin and the x-ray detection points of bromine demonstrate the location of lignin. The greatest concentrations are observed in the compound middle lamellae. When fungus-pretreated wood chips were observed, there was a general reduction in lignin content near the cell lumens, but the remaining secondary wall did not show significant lignin losses.

The results of these studies demonstrated the need to evaluate additional techniques to monitor the early cell wall changes that occur in wood chips treated with *P. chrysosporium* or *C. subvermispora.* Selective histological stains were used and excellent results obtained with Simons stain. The results from these studies provided information on the characteristics of the pulp fibers made from fungus-pretreated wood chips. The technique provided a good mechanism to evaluate cell wall alterations and might provide a rapid screening method for optimizing conditions for biopulping (see Screening Methods).

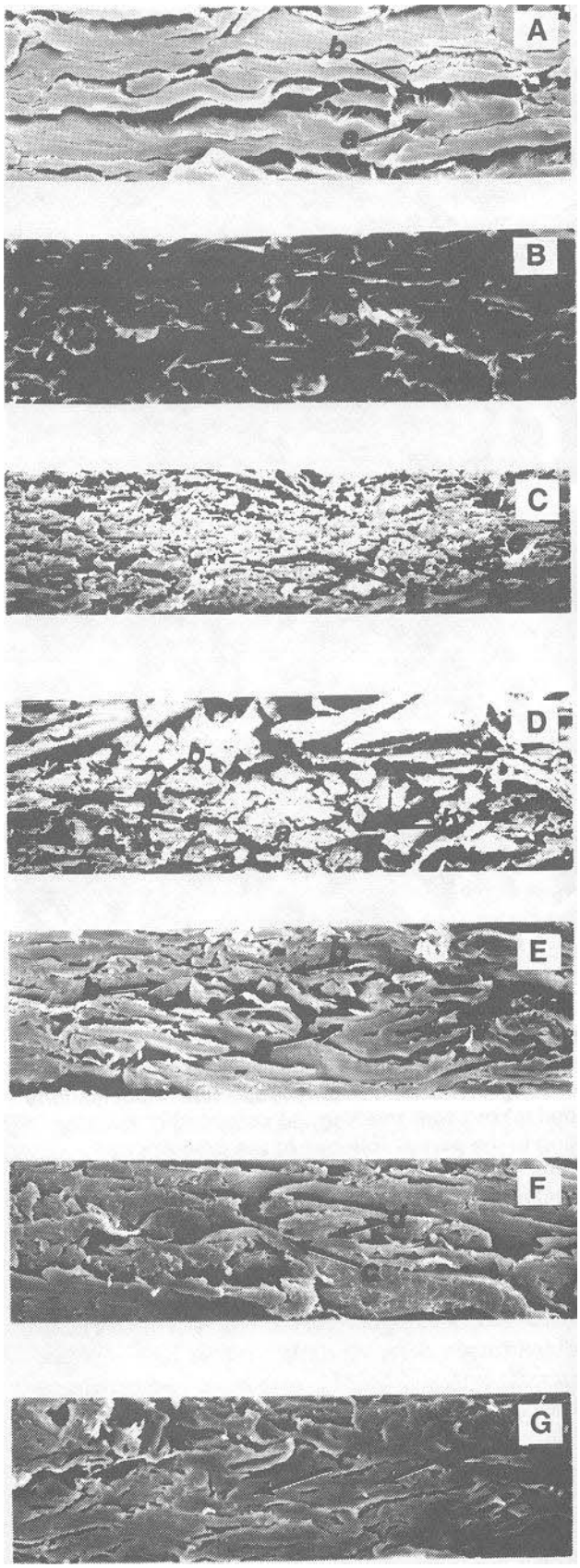


Figure 63—Cross sections of handsheets viewed by scanning electron microscopy (Sachs and others 1990). A, RMP; B, TMP; C, SGW; D, CTMP; E, NSSC; F, Kraft; G, BRMP (200x except "a", x100).

Exploratory Bleaching Experiments

Fungal treatment of wood chips prior to mechanical refining reduces the brightness of the resulting pulps (BRMP) by as much as 15 Elrepho brightness points. To be considered a viable pulping alternative, it is essential that biomechanical pulps be able to be bleached to high brightness levels. Implicit in bleaching high yield mechanical pulps is brightness stability upon exposure to heat or sunlight (Rapson and others 1989).

The bleachability and brightness stability of *P. chrysosporium*/aspen biomechanical pulp were examined and compared with those of aspen controls that were autoclaved with nutrient media and incubated for the same duration as their respective biopulps. These results were subsequently compared with the bleachability and stability of other traditional high-yield aspen pulps. Both alkaline hydrogen peroxide and sodium hydrosulfite, typical lignin-preserving bleach chemicals, were used to brighten aspen BRMP, RMP, SGW, TMP, and CTMP to nominal Elrepho brightness levels of 60%, 70%, and 80%. Handsheets prepared from these bleached pulps were subjected to accelerated photo- and thermal-aging tests to compare brightness stability.

The *P. chrysosporium*/aspen BRMP was responsive to both hydrogen peroxide and sodium hydrosulfite and could be bleached to 80% with 2-step H_2O_2 (run 75) (Fig. 64) and into newsprint (60% brightness) range brightness with 1% $Na_2S_2O_4$. The brightness of BRMP when subjected to accelerated aging was slightly less stable than that of RMP (Figs. 65 and 66).

Additional bleaching was done with *C. subvermispora* BRMP. *Ceriporiopsis subvermispora*/aspen BRMP was just as responsive to hydrogen peroxide bleaching as was *P. chrysosporium*/aspen BRMP (runs 189-193). Pine has a naturally low brightness (45% compared to 60% for aspen) and is not as responsive to peroxide bleaching as aspen because of the high resin content (Andrews and Singh 1979).

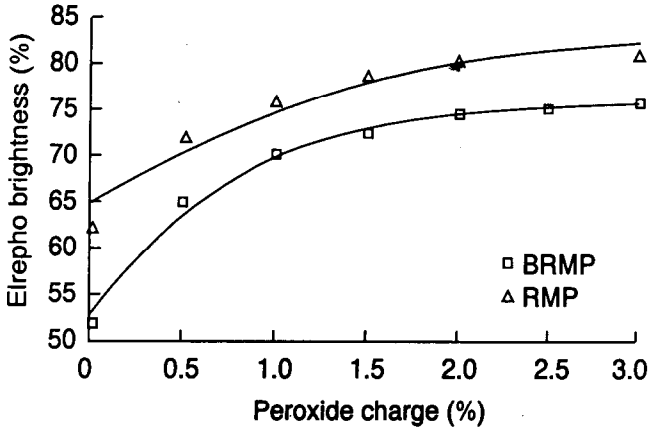


Figure 64—Peroxide bleach response: aspen, *P. chrysosporium* (run 75).

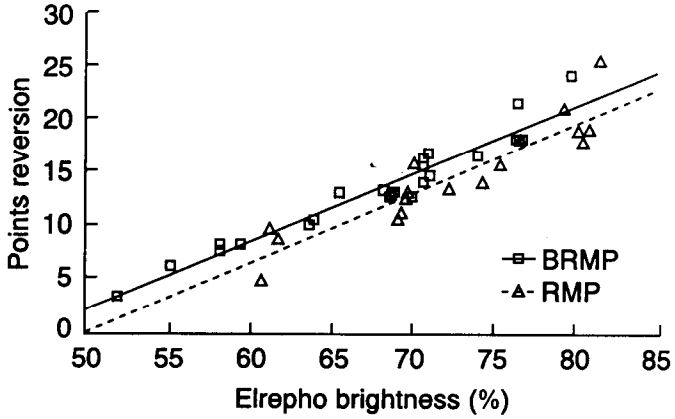


Figure 65—Thermal reversion of BRMP handsheet brightness (aspen, *P. chrysosporium*).

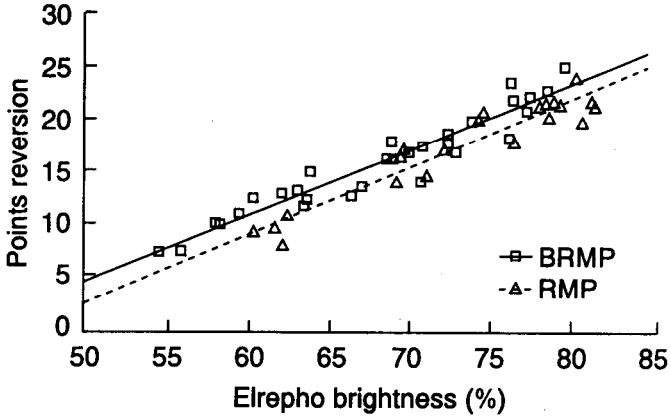


Figure 66—Photoreversion of BRMP handsheets (aspen, *P. chrysosporium*).

Bleach trials on pine using hydrogen peroxide or sodium hydrosulfite failed to achieve high brightness on either the control or biopulp (Table 4). A 4% H_2O_2 charge raised the brightness of pine BRMP (with an initial brightness of approximately 35% Elrepho brightness) only to a value approaching newsprint range (58%) (run 44). If high brightness is required with pine BRMP, some delignification, probably with an alternate bleach chemical, will be necessary; alternatively, a bleach pretreatment to remove resinous material could enhance peroxide bleaching (Dodson and Bohn 1988).

At the brightness levels at which aspen BRMPs initially were produced, a two-step bleach was required to attain the 80% brightness target (e.g., run 75). Either hydrogen peroxide or sodium hydrosulfite was used in the second step; peroxide was more effective in achieving high brightness and has the added benefit of slightly better brightness stability and paper strength enhancement. When optimization of some pulping process variables (shortened incubation, alternate methods of asepsis, bisulfite addition) improved the brightness of aspen biopulps to an initial brightness in the 50% to 55% brightness range, it was possible to achieve high brightness with a single-step 3% to 4% peroxide charge.

Table 4—Bleaching response of pulps (pine, *C. subvermispora*) (run 44)

Treatment	Elrepho brightness (%)	
	Control	Biopulp
Initial	42	32
1% $Na_2S_2O_4$	49	36
3% H_2O_2	60	51
4% H_2O_2	--	58

In later bleach trials using *C. subvermispora*/aspen BRMP (run 194). brightness levels exceeding 80% (up to 81.6%) were achieved with 4% alkaline peroxide by maintaining optimum bleaching pH and extending the retention time. Increasing the consistency or temperature should also produce higher brightness levels.

The hydrogen peroxide bleach responses of other aspen mechanical pulps-CTMP, SGW, and TMP-are shown in Figure 67. Groundwood pulp had a high initial brightness and readily brightened to 80% with 1.5% hydrogen peroxide. Both the ease of bleaching and the excellent stability of aspen SGW compared with the RMP in this study (Fig. 67) can be attributed in part to the fact that the SGW had not been autoclaved or incubated as had the RMP.

Results of 144 h of accelerated aging of the bleached SGW, CTMP, and TMP are compared in Figure 68. SGW was the most stable of the pulps compared, and CTMP the least stable. The thermal stability of BRMP was similar to that of CTMP (Fig. 65).

No established TAPPI standard exits for measuring photo-reversion. Our accelerated photo-reversion testing was performed in a Rayonet photo-reactor chamber composed of a bank of 300 to 400 nm lamps (to simulate the long-wave ultraviolet) surrounding a rotating sample rack. Results of brightness loss after a 4-h exposure of bleached CTMP, TMP, and SGW are shown in Figure 69. BRMP was more stable than CTMP to photoaging.

It may be concluded that chromophores created by autoclaving wood chips with nutrient media and by fungal metabolism during the biopulping process are readily bleached with either alkaline hydrogen peroxide or sodium hydrosulfite. Heat- and photo- reversions are similar to those seen with TMP and CTMP.

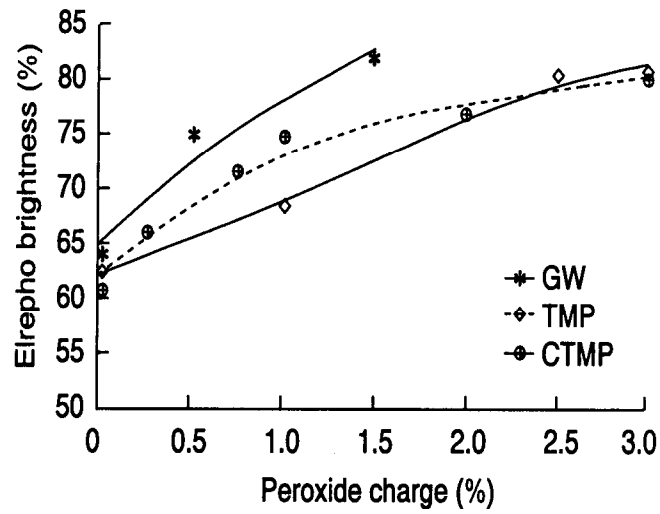


Figure 67—Peroxide bleach response of CTMP, SGW, and TMP.

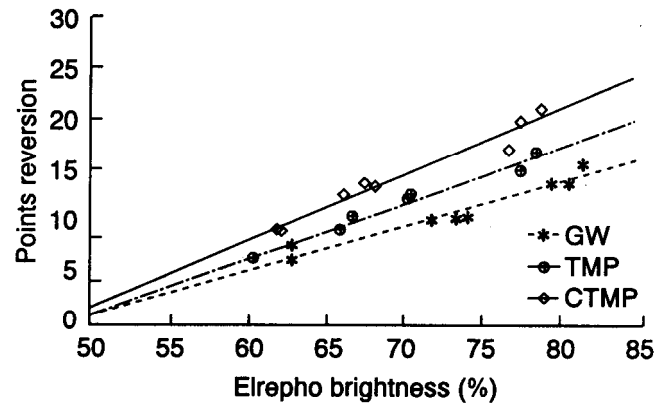


Figure 68—Thermal reversion of pulp brightness (105°C, 144 h).

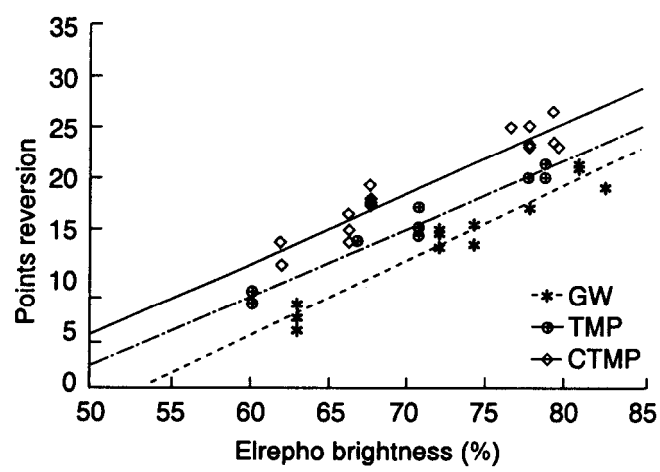


Figure 69—Photo-reversion of pulp brightness (ultraviolet 300-400 nm, 4 h).

Effluent Analyses

The environmental impact of a new pulping process is a critical factor in assessing its viability. One question about biopulping is whether effluents are more detrimental to the environment than effluents produced by traditional mechanical refining. Specifically, do fungal metabolites or fungal degradation products of wood introduce additional toxicity to the effluent or significantly alter the BOD/COD load?

Effluents of commercial pulp mills are now monitored for 100 individual potentially toxic compounds. Because our effluents contain unknown compounds, a "general" toxicity test was selected as the most efficient and appropriate way to evaluate them. The Microtox method of analysis has been used satisfactorily as a rapid screening method in the evaluation of acute toxicity of pulp mill effluents. As mill effluents become more complex, a toxicity-based consent for mill effluents has been suggested as an appropriate alternative to the chemical-specific consent now in place (Johnson and Butler 1991).

The Microtox assay uses luminescent bacteria to measure acute toxicity. This system, based on the half life of the bacteria, correlates well with established bioassays for toxicity. Microtox has proven to be more accurate than the rainbow trout assay (acute), but not as sensitive as the *Ceriodaphnia* (chronic) assay (Firth and Backman 1990).

Effluents from aspen biopulps using either P. *chrysosporium* or *C. subvermispora* were analyzed. The runs that we sampled were chosen to determine the impact on effluents of several biopulping process variables. Methods of chip sterilization and the addition of nutrient medium were investigated. We found that the raw aspen control produced the most toxic effluent. Results demonstrated that fungal pretreatments reduce effluent toxicity (Figs. 70-72).

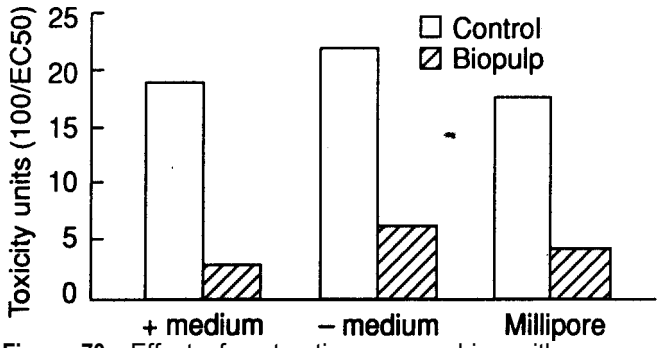


Figure 70—Effect of pretreating aspen chips with *C. subvermispora* on refiner effluent toxicity (Microtox assay). This experiment compared effluents from sterile chips amended with nutrient medium sterilized by autoclaving ("+ medium") or by filtration ("Millipore"); a third run had sterile water only ("- medium"). Runs 195, 196, 198, BB, DD, CC.

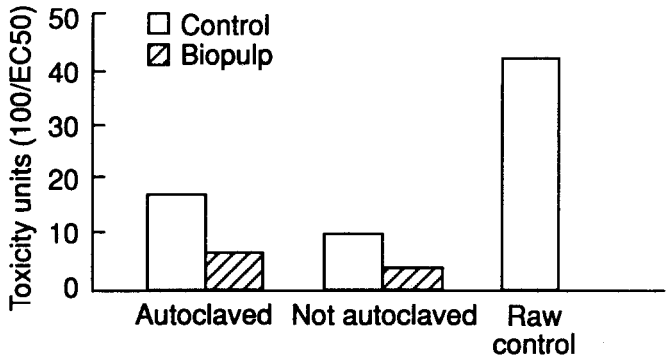


Figure 71—Effect of pretreating aspen chips with *C. subvermispora* on refiner effluent toxicity (Microtox assay). This experiment compared runs with sterile and non-sterile chips and included nonincubated raw control chips. All chips had added nutrient medium. Runs 204, 206, JJ, KK.

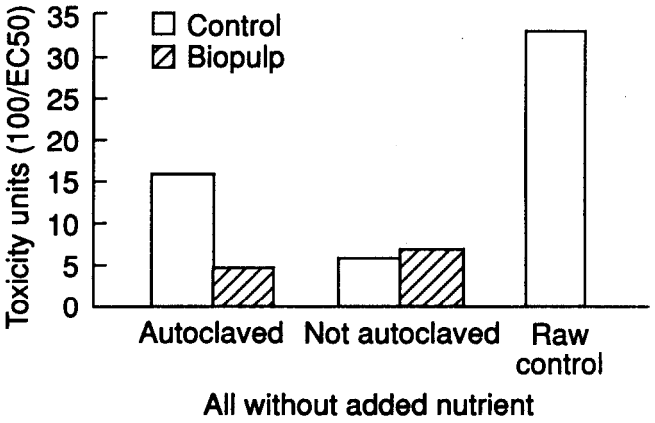
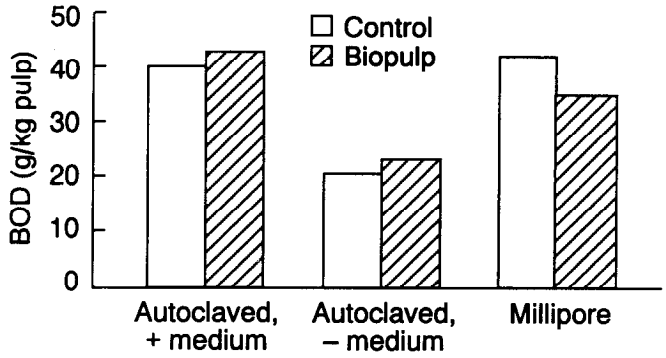
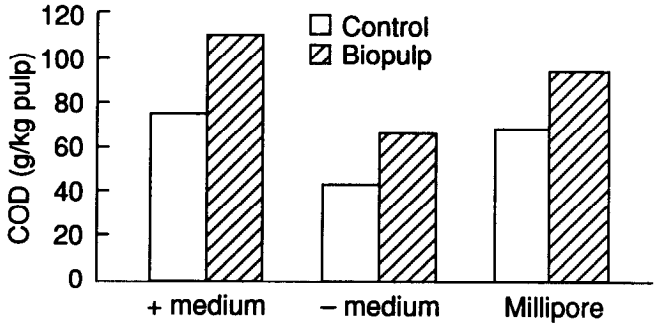


Figure 72—Effect of pretreating aspen chips with *C. subvermispora* on refiner effluent toxicity (Microtox assay). This experiment compared runs with sterile and non-sterile chips and included nonincubated raw control chips. Runs 217, 218, NN, PP.

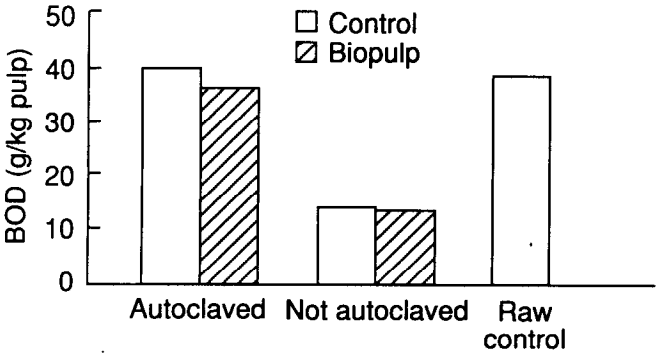
As expected, addition of nutrient medium to aspen control chips increased both BOD and COD loads in the refiner effluents (Figs. 73-78). Therefore, an important factor in process optimization-from the viewpoint of effluent quality-is minimizing nutrient addition to the level required to assure vigorous fungal growth. In aspen runs with *C. subvermispora,* biopulping did not substantially alter the BOD load (Figs. 73-75). Evidently, utilization of the added nutrients by the fungus was offset by release of BOD-raising byproducts. The COD load increased as a result of fungal treatment, perhaps reflecting production of lignin degradation products (Figs. 7678).



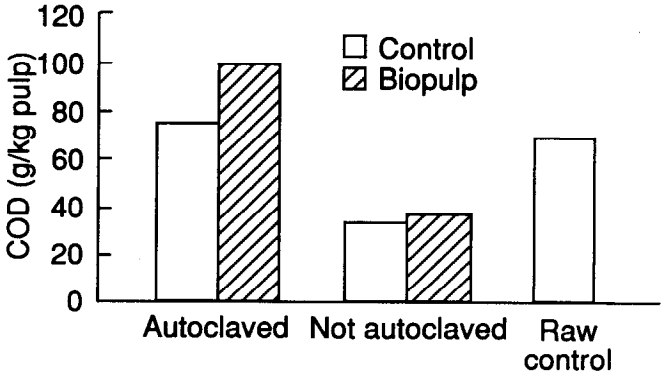
Figures 73—Effluent BOD levels resulting from alternate sterilization methods (aspen, *C. subvermispora*). Runs 195, 196, 198, BB, DD, CC.



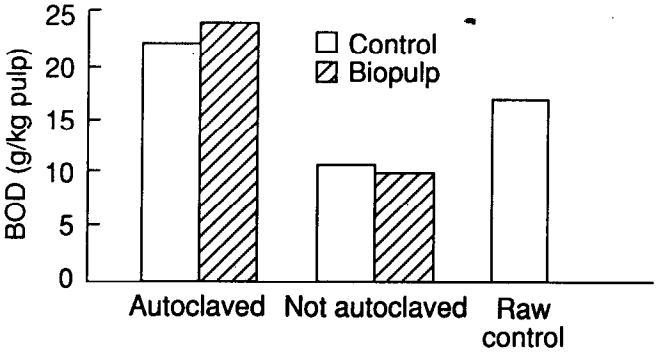
Figures 76—Effluent COD levels resulting from alternate sterilization methods (see Fig. 4). Runs 195, 198, 196, BB, DD, CC.



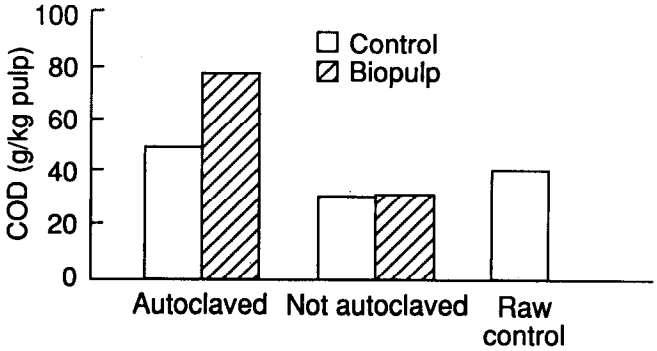
Figures 74—Effluent BOD levels comparing sterile and nonsterile runs-all with nutrient added (aspen, *C. subvermispora*). Runs 204, 206, JJ, KK.



Figures 77—Effluent COD levels comparing sterile and nonsterile runs-all with nutrient added (aspen, *C. subvermispora*). Runs 204, 206, JJ, KK.



Figures 75—Effluent BOD levels comparing sterile and nonsterile runs-all without nutrient (aspen, *C. subvermispora*). Runs 217, 218, NN, PP.



Figures 78—Effluent COD levels comparing sterile and nonsterile runs-ail without nutrient (aspen, *C. subvermispora*). Runs 217, 218, NN, PP.

Data collected from nonsterilized chips displayed uniformly low BOD/COD loads when compared with those using sterilized chips (data not shown). Incubation without sterilization permitted unknown contaminants to thrive, reducing BOD and COD levels.

Preliminary work with *P. chrysosporium* on aspen indicated that it decreases both the BOD and COD loads.

Preliminary work with *C. subvermispora* on pine indicated a slight increase in the COD; BOD was not determined. Microtox assays also indicated a slight reduction in toxicity caused by fungal treatment.

Ultraviolet spectra of both aspen and biopulp effluents displayed increased absorbance, in comparison to the control effluents, in the 280-mm region. This suggests the release (as expected) of lignin-related compounds by fungal action (data not shown).

The effluent data that we gathered indicated that in all runs sampled, biopulping decreases toxicity, does not substantially alter the BOD load, and slightly increases COD when compared with control RMPs. Note that most data represent single observations. Our method for sampling raw loads is reproducible, and our results for raw aspen are within the range of published values from generic wood species in TMP mills. We can assume the usual effluent processing that is in place in TMP mills will be able to handle biopulp effluents. The effluent load from biopulping should be lower and more benign than effluents currently produced by commercial CTMP mills. One commercial aspen CTMP mill reports a BOD load of 45 kg BOD/t pulp (air-dried) or 52 g/kg pulp (ovendried), almost double that seen here with BRMPs (Figs. 73-75).

Economics and Engineering

The economics and engineering approach to eventual scale-up involved an iterative process including process simulation, and laboratory-scale studies. Laboratory-scale studies were used to obtain data required for process simulation and to gain a better understanding of process variables that affect biopulping efficacy. Process simulation was used to integrate information determined experimentally and to make predictions concerning operation at laboratory scale.

Data

Engineering design requires a large amount of process information. Data currently available for the biopulping process include stoichiometric and thermodynamic data, the results of laboratory-scale biopulping experiments, and preliminary economic information.

The biopulping process is essentially the result of two major oxidation reactions, of lignin and of wood polysaccharides

$$\text{lignin (s)} + \text{oxygen (g)} \rightarrow \text{water } (\ell) + \text{carbon dioxide (g)}$$

$$C_{46}H_{48}O_{15} + 50.5\ O_2 \rightarrow 24\ H_2O + 46\ CO_2;\ 5{,}545\ \text{cal/g}$$

$$\text{cellulose(s)} + \text{oxygen (g)} \rightarrow \text{water } (\ell) + \text{carbon dioxide (g)}$$

$$C_6H_{10}O_5 + 6\ O_2 \rightarrow 5\ H_2O + 6\ CO_2;\ 4135\ \text{cal/g}$$

$$\text{glucose(s)} + \text{oxygen (g)} \rightarrow \text{water } (\ell) + \text{carbon dioxide (g)}$$

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ H_2O + 6\ CO_2;\ 4179\ \text{cal/g}$$

Figure 79—Stoichiometry and heats of reaction at 25°C.

(cellulose and hemicelluloses). The stoichiometry and enthalpies of these reactions are shown in Figure 79. The production of cell mass, extracellular polysaccharide, extracellular protein, and soluble byproducts is expected to be small compared to carbon dioxide production. Therefore, heat production can be calculated from dry weight loss and wood composition changes. If nutrient addition is required, a third reaction, the oxidation of the carbon source (e.g., glucose in Fig. 79), must be considered. The glucose equation can be easily replaced if a more practical nutrient supplement is chosen over glucose.

As described in the foregoing, more than 200 laboratory-scale biopulping runs were performed. These runs involved two species of wood: aspen and lobolly pine. Several species and strains of white-rot fungi were tested on each wood species. Two species were chosen for further process development: (1) *P. chrysosporium,* chosen for its rapid growth, ability to compete against indigenous microorganisms, and widespread use as a model organism for studying the biochemistry, physiology, and genetics of lignin degradation; *(2) C. subvermispora,* chosen for its superior energy savings and paper strength improvements on both hardwoods and softwoods in biopulping runs. Because of the large amount of data available, the engineering analysis focused mainly on the biopulping of aspen by *P. chrysosporium.*

The economics of biopulping based on a thermomechanical process model were evaluated (Harpole and others 1989). Results indicated that a 40% reduction in pulping energy by fungal pretreatment would save US$33/air-dried ton (adt) of pulp. The savings were capitalized to allow US$26.40/adt for increased operating costs for the fungal pretreatment and US$6.60/adt or US$10 million for capital investment (Wall 1990). Later, an economic model based on mass and energy balances in a controlled solid substrate fermentation process was constructed. The largest operating cost was found to be electricity (58% of the total), and the largest capital cost was the bioreactor (60% of the total). The return on investment was 14.9%, suggesting that a low-technology alternative would be desirable. A rough calculation was made for the other extreme-an uncontrolled chip pile, which suggested a return on investment of more than 100%. Thus, it may be possible for biopulping to be commercially viable.

Process Flowsheet

The biopulping process involves wood harvesting, debarking, and chipping. If necessary, the chips are mixed with nutrients and/or steamed. Then, the chips are mixed with inoculum and incubated.

All design decisions are strongly dependent on the choice of bioreactor. Two major options exist: aerated static-bed bioreactor (Fig. 80) or a chip pile-based system (Fig. 81). Systems between these two extremes can also be considered. For each bioreactor type, different options and constraints influence the other design decisions important for biopulping scale-up. The key design decisions include choice of organism, degree of asepsis, size and type of inoculum, physical conditions such as temperature, aeration, and moisture content, and if necessary, type and amount of added nutrients.

Aerated Static-Bed Bioreactor

The aerated static-bed bioreactor envisaged for the biopulping process is a bed of wood chips with controlled airflow. Both tunnel and silo bioreactors can be considered. Aerated static-bed bioreactors allow better control of process conditions, such as aeration rate, gas concentration, moisture delivery, temperature, and exposure to contaminants, than do chip pile-based systems. The drawback to these bioreactors is the much greater capital expenditure and increased operating costs compared to a chip pile-based system. However, current composting and malting processes use aerated static-bed reactors to produce products with a value close to wood pulp. This suggests that if processing times could be decreased and process efficacy increased, aerated static-bed bioreactors might be practical. A static-bed bioreactor will be practical only if its design and operation are extremely simplified.

Because of the greater control of operating conditions possible with a static-bed bioreactor, use of most biopulping organisms should be feasible.

Steaming the chips can be easily performed in a static-bed bioreactor. A steaming step would most likely be necessary for *C. subvermispora* and might be useful for *P. chrysosporium.* A two-stage steaming process with a holding period between the stages to allow for the germination of heat-resistant spores is probably not necessary. In the laboratory, all contamination problems were due to molds that should be killed by a single-steaming step. The use of steaming as a decontamination method must be tested experimentally.

Likely sources of inoculum include spores, disrupted mycelia, and colonized chips or other solid inoculum. *Phanerochaete chryosporium* produces abundant conidiospores that have potential for use as a commercial inoculum. Unless methods for increasing sporulation of *C. subvermispora* are discovered, spore inoculum is not an option with this organism. The use of spores offers greater reproducibility and the ability to accurately determine inoculum size. In addition, spores have greater stability and are easier to package than other inoculum forms. Mycelial fragments might have a shorter lag time and be less expensive than spores, but they are not as easily stored or quantified. Solid inocula on wood chips or other substrates might have short lag times, but they are difficult to quantify and are likely to be expensive.

Increased control of temperature, aeration, and moisture delivery are among the major advantages of an aerated static-bed bioreactor. Maintaining the bioreactor close to the organism's optimal growth temperature or optimal biopulping temperature (these may be different) decreases treatment time, and in the case of mixed cultures, should give the desired organism a competitive edge. Reduction of channeling or uneven air distribution may be easier in an aerated static-bed bioreactor than in chip piles. Control of moisture content is also crucial. At high moisture levels, gas exchange with the chip interior is likely to be severely hindered, and at low moisture levels, growth and biopulping are likely to be limited.

Based on limited data, the use of the MCDM does not appear to offer significant energy or strength benefits compared to unsupplemented, moisture-adjusted wood for biopulping runs with *P. chrysosporium.* These experiments should be replicated before firm conclusions can be made. The MCDM does, however, increase energy savings and paper strength properties when used with *C. subvermispora.* Once again, firm conclusions cannot be made until these data are verified. If nutrient addition is necessary, a less expensive nutrient mixture must be developed.

Chip Pile-Based System

A chip pile-based system is defined as an industrial-size chip pile modified to increase temperature and moisture control. Possible modifications include cooling and aeration by forced or free convection, turning to decrease pile heterogeneity, and sprinklers or forced convection of humidified air to supply moisture. The advantage of the chip pile is reduced cost; the disadvantage is reduced process control. To determine what degree of environmental control is necessary, simulation and laboratory-scale biopulping studies must be performed. Based on these results, chip pile experiments can be designed with the goal of reliable process scale up.

Chip pile-based systems should be feasible for *P. chrysosporium* and may be possible for *C. subvermispora.* With *C. subvermispora,* steamed chips and protection from airborne contaminants should be adopted to give it a competitive edge over indigenous organisms. Some environmental control may be necessary for temperature and possibly moisture content. With *P. chrysosporium,* steaming may not be necessary, but preliminary results suggest that some environmental control will be necessary, particularly in cooler climates.

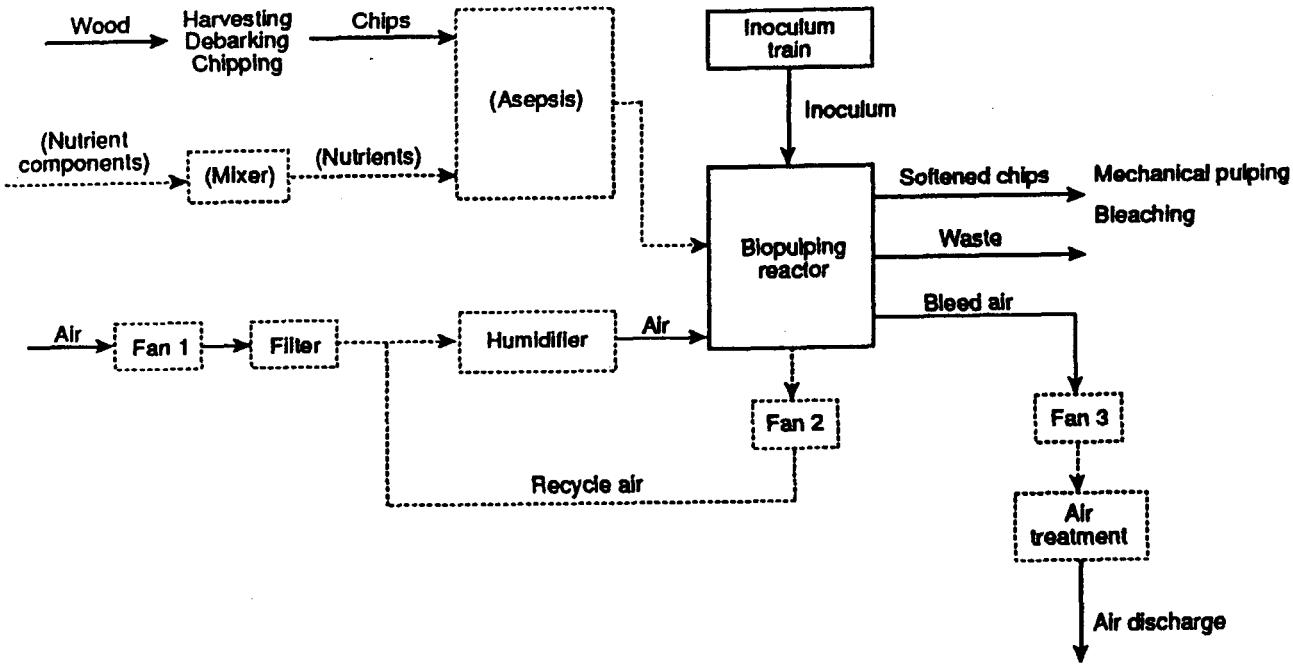


Figure 80—A aerated static-bed process flowsheet, ( ) = optional.

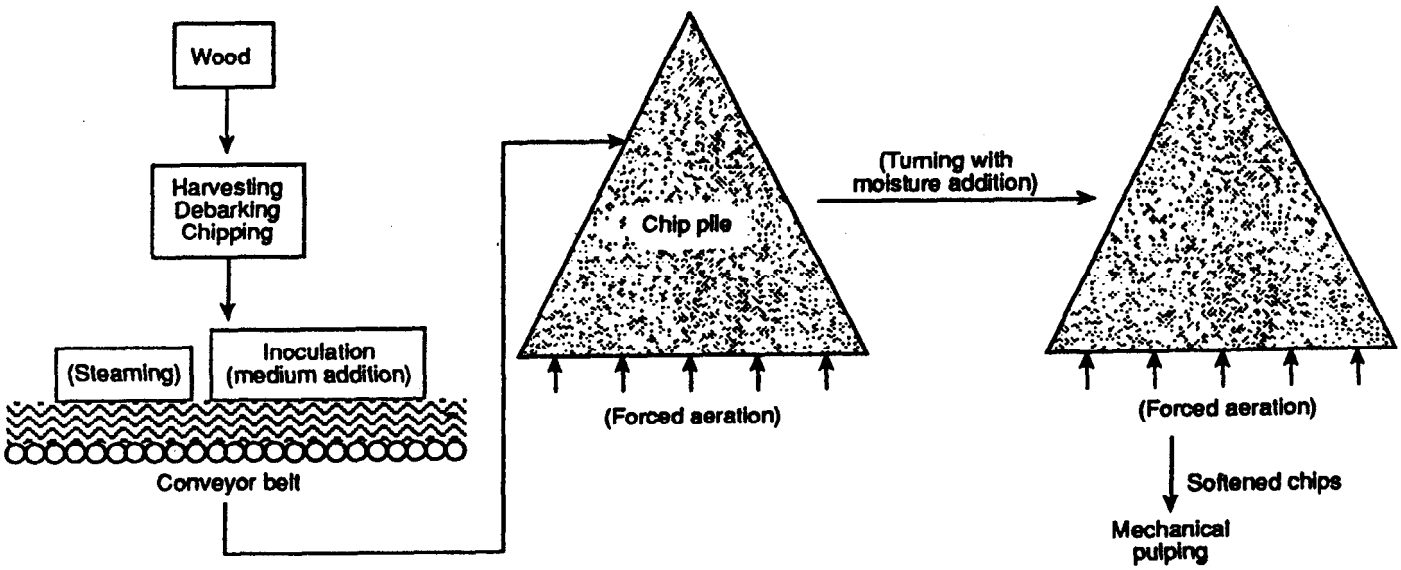


Figure 81—Chip pile-based system process flowsheet, ( ) = optional.

If necessary, the chips would be steamed on the conveyor (Fig. 81) and cooled prior to inoculation. Inoculation could also occur on the conveyor. Inoculum concerns are similar to those discussed for an aerated static-bed bioreactor.

Several methods are available to provide partial control of environmental conditions such as temperature, aeration, and moisture content. If the temperature of the pile rises above the ambient, free convection will provide cooling and gas exchange with the possible disadvantage of moisture stripping. If cooling by free convection is insufficient, forced aeration with humidified air could be provided. If moisture loss is a problem, sprinkler systems could be added or moisture could be provided as the piles are turned. Turning may be used to provide moisture and reduce heterogeneity. Covering the pile and placing coarse filters at air inlets are possible methods to reduce airborne contamination. Covering the pile, forced convection of heated, humidified air, or inoculating the chips soon after steaming are methods to bring the pile temperature to the range required for growth.

If necessary, addition of nutrients could occur on the conveyor concurrently with inoculation.

Process Monitoring Techniques

Experiments were performed to study the changes taking place in chips colonized by *P. chrysosporium* over time. Methods of monitoring dry weight loss, moisture content, and growth rate were developed. Glucose uptake rate was also monitored for glucose-supplemented chips.

The experimental protocol (previously described) was used with the following modifications. All experiments used a spore suspension of *P. chrysosporium* BKM-F-1767. The bioreactors were sampled periodically by lifting the lid and removing samples aseptically. The bioreactors were shaken prior to sampling. In all cases, aerated static-bed bioreactors were used.

Dry Weight Loss

Knowledge of the wood dry weight loss as a function of time enables the determination of lignin, cellulose, and hemicellulose losses as a function of time from the composition of chip samples taken.

Dry weight loss cannot be directly measured at each time point without running a large number of bioreactors in parallel and sacrificing one at each time point. This method is time-consuming and expensive and decreases the reproducibility of the results.

One method used to estimate dry weight loss was to place preweighed mesh bags of chips in the bioreactor; they were removed at different times and weight loss determined. Data obtained using this method showed a large amount of scatter. This might have been due to variation in moisture content or blockage of mass transfer between the bulk bioreactor and the bags. *Phanerochaete chrysosporium* had a tendency to grow on the bags, blocking the mesh. Addition of the bags might have also caused channeling of the air through the bioreactor.

Another method of estimating dry weight loss is to determine the moisture content of samples taken from the bioreactor at intervals. From the moisture content of the sample and the wet weight of the bioreactor, the dry weight loss is estimated.

Dry weight loss can also be determined by performing a mass balance on the carbon in the system using carbon dioxide production data. The assumed reaction stoichiometry is shown in Figure 79. We assumed that the flow rate of air out of the bioreactor was the same as the flow of air into the bioreactor and that the inlet air was water-saturated. Breakdown of wood components to soluble products was not viewed as dry weight loss. We also assumed that any added glucose was depleted before wood components were broken down.

This method was tested for a biopulping run using aspen chips inoculated with *P. chrysosporium.* Chip composition data were determined for samples taken at intervals. There was little change in chip composition on a percentage basis. The results for the carbon balance and the moisture content method are compared in Figure 82. The actual dry weight loss could be experimentally determined only for the final data point. The value was slightly lower than that determined by the carbon balance. The fluctuation in dry weight loss calculations by the moisture content method was probably due to errors in moisture content measurement.

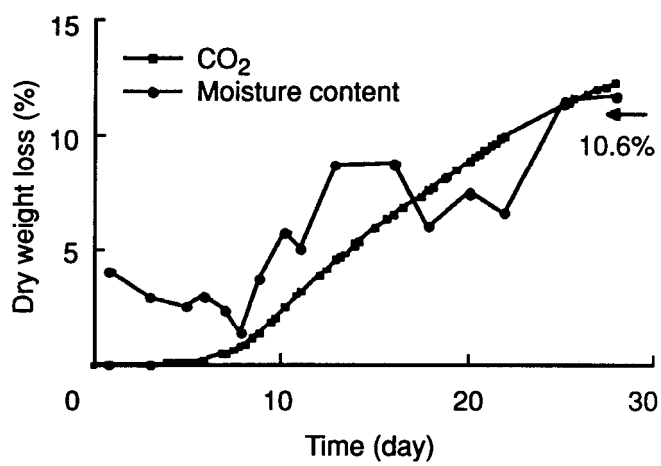


Figure 82—Comparison of dry weight estimation methods.

Moisture Content

Chip moisture content was determined both by sampling the bioreactor and performing a mass balance on the bioreactor. The results from the two methods are compared in Figure 83. The results agreed within the limits of sampling error for the growth stage of the fungal pretreatment.

Growth Estimation

Another method to monitor the biopulping process is estimating fungal growth. This could also lead to a better understanding of the mechanism of biopulping and would be useful to standardize the use of colonized chips as inoculum. Determining fungal levels in a complex substrate such as wood is not a trivial matter, and various methods have been attempted (Table 5).

We decided to focus on the development of the carbon dioxide and ergosterol-based techniques. Carbon dioxide has the advantages of easy, continuous, nondestructive measurement. Also, sampling outlet gas gives an average over the whole bioreactor, reducing the problem of sampling error. However, although carbon dioxide production is indicative of the rate of cell growth during the exponential growth phase, without a good estimate of the initial biomass and carbon yield, absolute biomass levels cannot be determined. During nonexponential growth, carbon dioxide production cannot be directly related to cell mass. Ergosterol has the advantages of a well-developed procedure with good sensitivity.

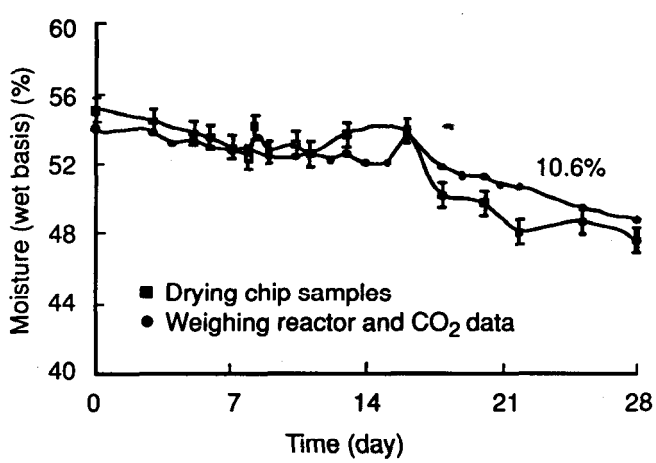


Figure 83—Comparison of moisture content estimation methods.

Carbon dioxide is produced both by cell growth and by endogenous metabolism:

$$\frac{dC_{CO_2}}{dt} = Y_{CO_2/X}(\mu_{max}X) + k_e X \qquad (1)$$

where

C_{CO_2} = carbon dioxide concentration (g/L)

$Y_{CO_2/X}$ = yield of carbon dioxide on cells (dimensionless)

μ_{max} = maximum specific growth rate (h^{-1})

X = dry cell concentration (g/L)

k_e = rate of endogenous metabolism (g/g•L)

During the exponential growth phase, cell concentration is expressed

$$X = X_0 e^{\mu_{max} t} \qquad (2)$$

where

X_0 = initial dry cell concentration (g/L)

By substituting Equation (3) into Equation (2) and integrating, carbon dioxide concentration as a function of time is obtained

$$C_{CO_2} = \frac{(\mu_{max} Y_{CO_2/X} + k_e)}{\mu_{max}} X_0 e^{\mu_{max} t} \qquad (3)$$

Thus, the maximum specific growth rate, μ_{max} is obtained as the slope when $\ln[CO_2]$ is plotted as a function of time, assuming that the yield of carbon dioxide on cells and the rate of endogenous metabolism are constant during the exponential growth phase.

If an accurate value of cell concentration were available for one time point, Equation (3) could be used to calculate cell concentrations during the exponential phase. This method might reduce the number of samples that must be analyzed using the more laborious, destructive techniques such as ergosterol. It is also useful to determine whether changes in environmental and developmental conditions affect the maximum specific growth rate or the lag time. Figure 84 shows $\ln[CO_2]$ for aspen chips supplemented with MCDM and treated with *P. chrysosporium.* The line is linear between day 3 and day 10, with a slope of 0.017 h^{-1}.

Ergosterol, the predominant sterol of most fungi, is rarely found outside the fungal kingdom and has a characteristic ultraviolet absorption pattern that differs from that of common plant sterols. Procedures for the extraction and quantification of ergosterol from colonized wood samples were developed by Davis and Lamar (1992). Biopulping runs

Table 5—Comparison of growth estimation methods

Method	Description	Type	Sensitivity	Advantages	Disadvantages
Glucosamine	Fungal cell wall component (chitin)	Cell concentration	Approximately 3,000 ppm biomass in wood (Johnson and McGill 1990)	Well-documented procedure	Glucosamine content of fungus varies with growth conditions; wood components interfere with calorimetric assay; lengthy procedure
Ergosterol	Fungal cell membrane component	Cell concentration	50 ppm (Matcham and others 1984)	Well-documented procedure; easy to analyze many samples simultaneously; fairly simple procedure; little or no interference from wood components	Ergosterol content of fungus may vary with growth conditions
Kjeldahl	Organic nitrogen	Cell concentration		Well-documented procedure	Organic nitrogen in media interferes; nitrogen content of fungus varies with growth conditions
ELISA	Cellular components	Cell concentration	0.25 µg fungus/ml liquid (Breuil and others 1988)	Simple procedure; easy to analyze many samples simultaneously	Inhibition by wood components reduces sensitivity; species specificity and variation with culture and developmental conditions; dependent on antibody used.
Carbon dioxide	Growth associated product	Growth rate		Continuous measurement; average over entire reactor	Difficult to relate to cell concentration
ATP	High energy metabolite	Cell viability	187 ppm fungus in soil	Quantitative	Samples must be freeze-dried; lengthy procedure; specialized equipment
FDA (fluorescein diacetate)	Converted to fluorescent compound by metabolically active hyphae	Cell viability		Ability to localize metabolically active hyphae	Not quantitative

that showed greater dry weight loss (indicative of increased fungal biomass) had increased ergosterol content. Further work is required to correlate ergosterol biomass values with carbon dioxide production data and to assess the stability of ergosterol under various biopulping conditions.

Glucose Uptake

Determining sugar uptake rates is useful in studying the effect of varying physiological and physical conditions. In most biopulping runs, glucose was used as an initial source of carbon and energy. Glucose concentrations were determined either enzymatically using glucose oxidase or by high-performance liquid chromatography, the preferred method because a large number of sugars can be measured using this technique. Glucose concentrations as a function of time are shown in Figure 85 for aspen chips supplemented with MCDM treated with *P. chrysosporium.*

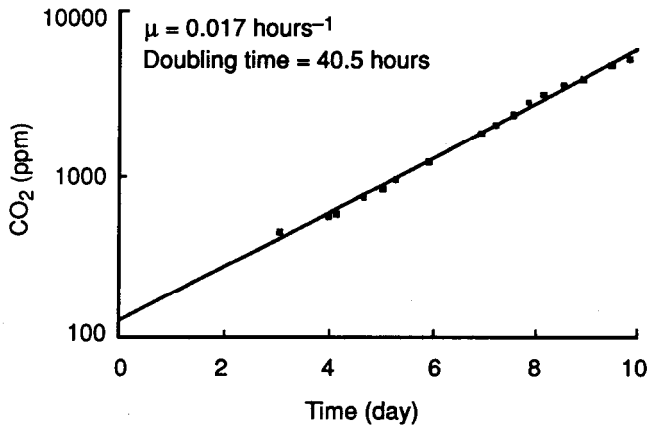


Figure 84—Specific growth rate (μ) determined from carbon dioxide production, *P. chrysosporium.*

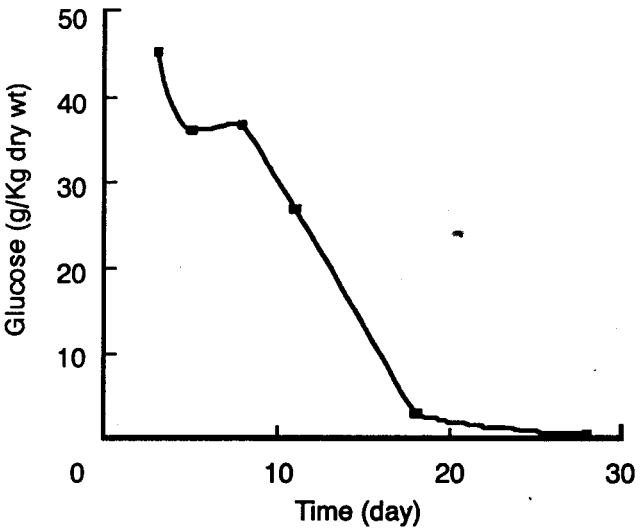


Figure 85—Glucose uptake.

Bioreactor Design and Construction

We completed the design and construction of a bioreactor system (Fig. 86) with computer data acquisition. The computer continuously monitored the bioreactor temperatures, the air inlet and outlet temperatures, relative humidities, mass flow rates, and carbon dioxide concentrations of six 21 L (= 0.02 m^3) aerated static-bed bioreactors. This bioreactor system was used to determine the effect of varying temperature, moisture level, and carbon and nitrogen supplements on growth rate and biopulping efficacy.

With this approach, process information can be obtained. As discussed from the carbon dioxide production data, the specific growth rate can be calculated and dry weight loss and moisture content can be followed with time. Regular sampling of the bioreactors gives information on sugar uptake, pH, chip composition, and possibly organism content using the ergosterol assay.

The aerated static-bed bioreactors were very similar to those described in Figure 3. The tops were sealed with silicon caulk and closed with a specially constructed stainless steel clamp. These modifications ma& air leakage negligible. Thermistors were inserted half-way between the top and bottom of the bioreactors. A sampling port was placed directly opposite the thermistor to eliminate the necessity of opening the bioreactor tops.

The incubator had refrigeration and heating capacity to give a practical operating range from 5°C to 60°C. The temperature/relative humidity probes (Vaisala, HMD30YB, Waburn, Massachusetts) were from -5°C to 55°C (±0.2°C) and had a relative humidity range from 0% to 100% (±3% > 90%; ±2% < 90%). The thermistors ranged from 0°C to 100°C and had an accuracy of ±0.1°C. The mass flow meter (Unit Instruments, UFM1100, San Jose, California) had a range of 0 to 2 standard L/min (±0.02 standard L/min). The IR carbon dioxide analyzer (Horiba, APBA210, Irvine, California) had dual ranges of 0 to 2,000 ppm and 0 to 5,000 ppm. Data acquisition was performed using an IBM computer with software developed by the FPL instrumentation group.

Process Design

Goals and Optimization Criteria

The goal of biopulping process design is to determine operating conditions that enable economical, industrial-scale fungal pretreatment. The process must be optimized based on biopulping performance. Important parameters include organism, decontamination treatment, added nutrients, inoculum size and type, and physical and environmental conditions.

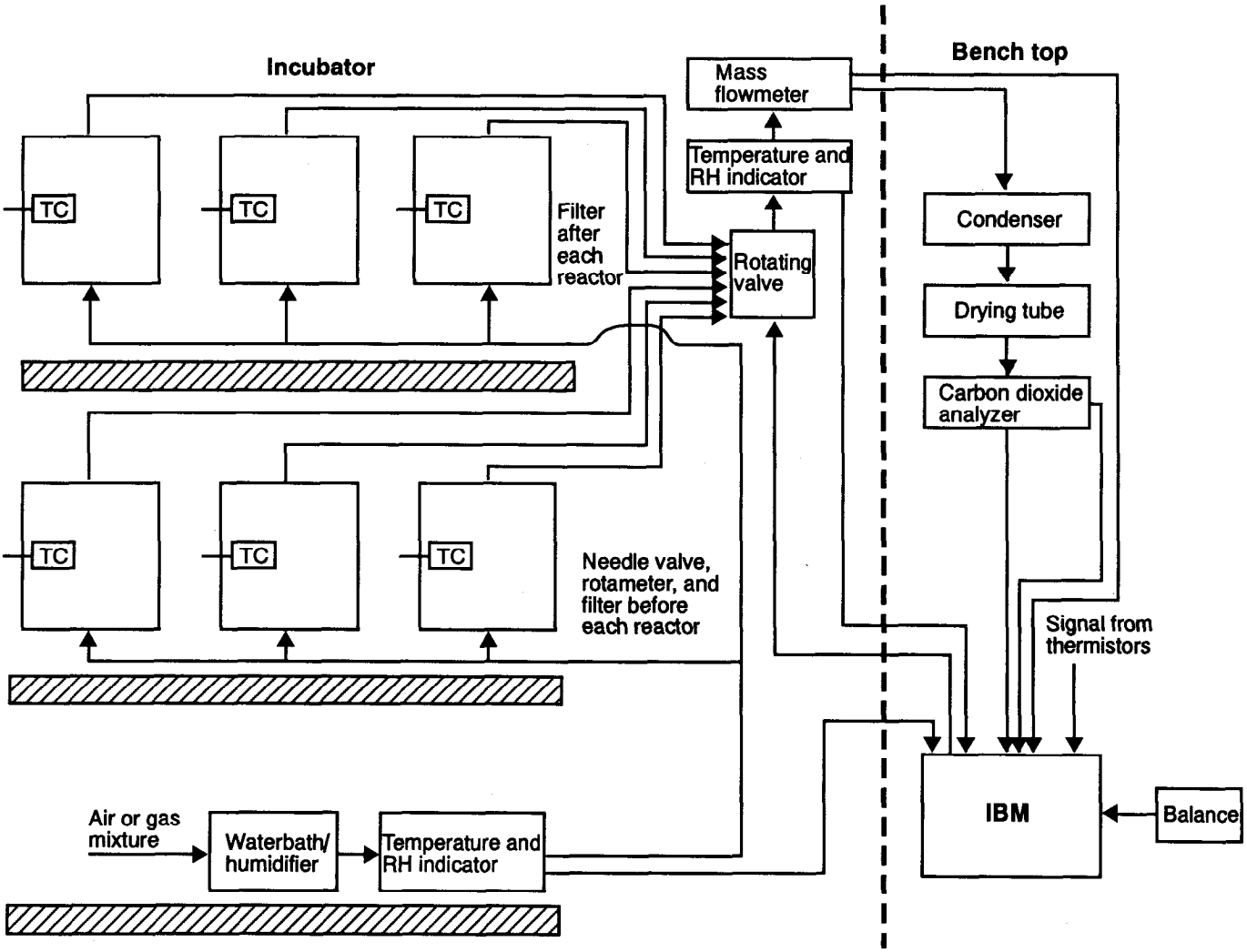


Figure 86—Laboratory-scale biopulplng bioreactor system.

Process Models

As an aid in scale up, initial work was done to develop a model to predict biopulping efficacy and economic feasibility under various operating conditions. The model is composed of three components: an economic model (not yet addresssed), a macroscopic model, and a dynamic model. In addition, calculations were made to determine the likelihood of gaseous mass transfer limitations.

Mass Transfer Within Chip Lumens—The rate of gaseous mass transfer in a chip was estimated to predict whether cell growth is limited by mass transfer. In these calculations, the resistance to diffusion of oxygen in the lumens was assumed to be much greater than the resistance to diffusion in the boundary layer surrounding the chips. Oxygen transport was assumed to occur only across the transverse surfaces of the chip, and although the cell wall was accessible to oxygen, oxygen transfer through the wood cell wall was assumed to be insignificant.

Two cases were considered: diffusion through lumens completely accessible to air and diffusion through lumens completely filled with water. In both cases, a zero-order dependence on oxygen was assumed. A Monod-type equation was shown to give a better fit to experimental data than the zero order equation, but the predictions of Monod kinetics and zero-order kinetics were fairly close. Also, a zero order dependence should predict the likelihood of oxygen limitation on growth. A shell balance integrated with the boundary conditions that $C = C_0$ at $x = \pm L$ yields

$$\frac{C}{C_0} = 1 + \frac{Q_{O_2}}{2DC_0}(x^2 - L^2) \qquad (4)$$

where

C_0 = reference concentration (21% w/w)

Q_{O_2} = oxygen uptake rate (mol/L•s)

D = diffusivity of oxygen (0.178 cm^2/s)

L = length of chips (1.95 cm)

x = length

C = concentration (w/w)

For our system, the oxygen uptake rate, Q_{O_2}, was estimated as 1.369 x 10^{-8} mol/L•s. Because of the uncertainties in this estimation, Equation (4) was evaluated with values of the oxygen utilization rate one order of magnitude greater than and less than the calculated value. The results are shown in Figure 87. This analysis shows that even at oxygen utilization rates much larger than those expected, diffusion limitations are not significant in air-filled lumens.

For the case of a water-filled pore, Equation (4) remains valid with the parameters: D = 2.5 x 10^{-5} cm^2/s and C_0 = 8 mg/L. In this case, oxygen transfer is extremely limited and the oxygen penetration length (L_c), the maximum distance from the chip surface where oxygen can be detected, can be calculated by setting oxygen concentration equal to zero in Equation (4).

Equation (5) was also evaluated for three values of the oxygen uptake rate (the predicted value and values one order of magnitude greater than and less than the predicted value). Even at a value of oxygen uptake rate 10 times less than the predicted value, oxygen was predicted to penetrate less than 1% of the chip. Unless oxygen transport occurs by another mechanism, such as active transport by fungal hyphae, oxygen concentrations are close to zero in a water-filled lumen.

$$\sqrt{\frac{Q_{O_2} - 2D_{eff}C_0}{Q_{O_2}}} = \frac{L_C}{L} \qquad (5)$$

where

D_{eff} = D/t

t = tortuosity (dimensionless)

Because electron microscopy has shown that hyphae can penetrate to the center of a chip, it is concluded that either at least some lumens are completely accessible to air or these organisms have an active transport mechanism for oxygen. Oxygen transfer limitations may be significant if small pockets of water block otherwise air-filled pores. In this case, the rate at which air diffuses through the water pocket and the percentage of lumens blocked will determine the rate of oxygen transfer to the lumen.

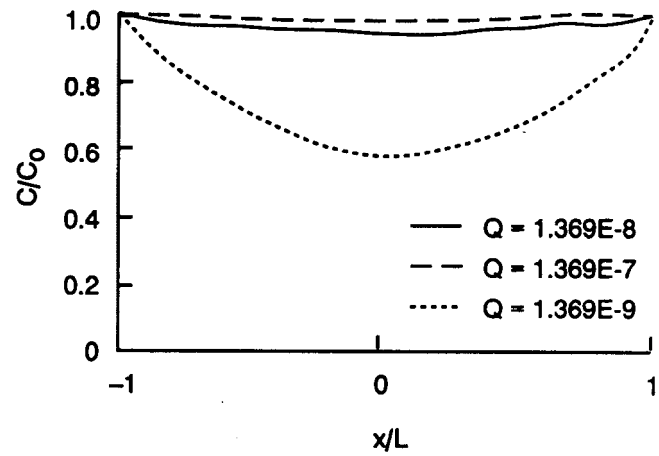


Figure 87—Oxygen distribution in air-accessible chip.

Macroscopic Model—Mass and energy balances were performed on an aerated static bed of wood chips. The calculations dealt with equilibrium, not kinetics, and were applicable to a chip pile-based system with forced or free convection. (To predict the aeration requirements of a chip pile, the model would have to be evaluated with the appropriate values for temperature difference and carbon dioxide production rate.) These calculations were performed using a program developed with the Framework III software program (Ashton-Tate).

Biopulping process conditions are not yet optimized. Thus, the physiological requirements of the organism were not clearly defined. Reasonable first guesses of the required parameters were chosen when performing the mass and energy balances, and the calculation algorithm was flexibly designed to easily obtain results for different operating conditions.

A macroscopic balance over the entire bioreactor was performed; kinetics and mass and heat transfer were not considered. This analysis considered the degradation of wood by fungi to be the result of the oxidation of cellulose, hemicellulose, and lignin (Fig. 79). The program assumed complete conversion of glucose to carbon dioxide and accepted values for total dry weight loss, lignin loss, and treatment time. Carbon dioxide production was assumed linear throughout the biotreatment. This was not actually the case; carbon dioxide production increased with time until maximum growth was achieved and then decreased to a fairly constant value. If the process were operated semicontinuously, the assumption of linear carbon dioxide production would be valid for the system as a whole.

The program assumed a continuous process with a throughput supplied by the user. Batch aerated static-bed bioreactors were envisaged for this process. However, with a treatment time of up to 28 days, operating in a semicontinuous mode should not be difficult. The required bioreactor volume was calculated from the physical characteristics of the wood, throughput, and treatment time. The amount of carbon

dioxide and heat produced were calculated from the reaction stoichiometry and the heats of reaction.

Heat removal was provided through evaporative cooling and sensible heating of the circulating air. The user supplied the temperature rise to the program. The heat removed was calculated for a given airflow rate, temperature, and humidity. Airflow rate was varied until heat removal by aeration balanced heat production by the metabolism of the organism.

Table 6 gives the aeration requirement for two conversions and treatment times. A temperature increase of 2°C and a throughput of 300 t/day were assumed. The amount of water addition required to maintain constant chip moisture content was calculated from the stoichiometry of the water-producing reactions and the amount of water removed from the system by evaporation. Evaporation provided 85% of the cooling.

Aeration rates reported for laboratory-scale solid substrate fermentors (SSF) ranged from 7.54 x 10^{-4} volume per volume per minute (VVM) (Rathbun and Shuler 1983) to 10 VVM (Bajracharya and Mudgett 1980). A pilot-scale SSF designed by Durand and Chereau (1988) for production by SSF single-cell protein from sugar beet pulp operates at 17.9 VVM. Therefore, the aeration requirements calculated (Table 6) seemed reasonable for this type of application.

However, aeration is expected to be a significant portion of the capital and operating costs of a biopulping process, and methods of reducing the required aeration rate should be investigated. Decreasing the treatment time required for an effective biopulping process increases the aeration requirement. The trade-off between bioreactor capacity and aeration capacity influences optimization of the biopulping process.

Decreasing the yield loss would reduce the aeration requirement, which is proportional to the degreee of wood degradation. if the process is not overly sensitive to temperature changes, increasing the temperature rise across the bed will decrease the aeration requirement with the side effect of increasing heterogeneity. The direction of airflow may be changed periodically from upward flow through the bed to downward flow to decrease concentration and temperature gradients in the bed.

Dynamic Model—The dynamic model uses information concerning the effect of parameters such as temperature, moisture content, and nutrient concentrations on fungal growth to predict the distribution of organisms in chip piles and bioreactors under actual operating conditions. In addition, thermodynamic and transport properties are used to model the variation of temperature and moisture within a bed of chips. The multivariable and overlapping dependence of the important parameters-growth rate, moisture content, and temperature-made the development of this model a computational challenge.

We began by deriving the equations required to express the system mathematically. First, an equation must be chosen that expresses the dependence of specific growth rate on temperature. Evaluation of the four parameters used in this equation require biopulping runs at six or more temperatures.

The availability of quantitative data for temperature effects is particularly important in developing chip pile-based systems. Three operating regimes exist: (1) extinction, where low temperatures cause slow growth and environmental conditions do not allow the buildup of heat generated by the organism; (2) balanced growth, where removal of heat balances generation by growth and the temperature remains within the optimum range; and (3) ignition, where rapid growth causes heat accumulation to an extent that the temperature rises above the maximum tolerated by the organism.

Next, the basic equations of change for energy must be evaluated for an isolated chip plug and for a chip plug with one dimensional airflow. Equations can then be developed for forced convection under isothermal and nonisothermal conditions and free convection under nonisothermal conditions. Actual evaluation of these equations requires rate data as a function of temperature. Extension of this analysis to a chip pile requires dividing the chip pile into a matrix, evaluating each cell separately, and compiling the results.

Table 6—Aeration requirement for two conversions and treatment times[a]

Dry weight loss (%)	Lignin loss (%)	Treatment time (days)	Volume/ volume/min	Flow rate (x10^3 ft^3/min)	Water loss (L/min)	Outlet [CO_2] (ppm)	Reactor volume (m^3)
20	22	21	4.77	2,130	241	1,550	12,600
5	8	21	1.71	838	109	1,610	12,600
20	22	14	7.15	2,130	241	1,550	8,400
5	8	14	2.56	838	109	1,610	8,400

[a]Temperature increase of 2% and throughput of 300 t/day.

New Commercial Process

During the course of research by the Biopulping Consortium, one sponsor company developed and commercialized a biotechnological product/process that is similar in many aspects to biopulping. The fact that such a product was developed supports the ultimate practicality of biopulping and deserves mention. Cartapip was developed by the Sandoz Chemical Corporation, with its research subsidiary, Repligen Sandoz Research Corporation. Cartapip is sold as a white powder and is actually inoculum of the fungus *Ophiostoma piliferum.* A dilute slurry of the powder, which contains fungal spores, is sprayed onto wood chips as they are piled for storage prior to being mechanically pulped. The fungus grows in the chip piles, digesting and consuming pitch components within about 10 days; the organism does not degrade the structural components of wood, Partial removal of pitch helps solve several problems associated with pitch (Farrell and others 1992). *Ophiostoma piliferum* is a naturally occurring and ubiquitous "blue stain" fungus; Cartapip is prepared from a strain that is colorless. The process thus resembles the "low technology" biopulping process as discussed.

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Appendix A-Publications

The following are publications arising, wholly or in part from the Biopulping Consortium research.

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Appendix B—Biopulping Runs

This appendix contains data that were collected for the biopulping runs summarized in this report. Abbreviations used in Table 1B are defined at the end of the table.

Table 1 B—Biopulping runs with controls

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	energy watt-hrs. per kg	density kg/m^3	n	s.d.	.95 CI	burst index kN/g	n	s.d.	.95 CI	tear index mN•m^2/g	n	s.d.	.95CI
				*1		*2	*3	*4			*5						*6	*7								
1	slow	white birch	A	Pc	BKM-F1767	A	wood type, CDM	CC	NA	NA	RP	NA	NA	NA	330	10	13.53	9.68	0.27	3	0.08	0.19	1.21	5	0.19	0.24
2	slow	aspen	A	Ds	Ton-429	B,C	fungal species, CDM	CC	NA	NA	RP	NA	NA	NA	372	10	26.74	19.13	1.16	10	0.24	0.17	4.41	5	0.27	0.34
3	slow	aspen	A	Pc	SC-26	B,C	fungal species, CDM	CC	NA	NA	RP	NA	NA	NA	427	10	23.14	16.55	0.89	10	0.11	0.08	2.63	5	0.21	0.27
4	slow	aspen	A	Pc	SC-26	B,C	fungal species, CDM	CC	18	10	RP	28	2.00	NA	397	10	9.25	6.62	0.65	10	0.07	0.05	2.19	5	0.18	0.23
5	slow	aspen	A	Pt	RAB-25/PRL2845	B,C	fungal species, CDM	CC	35	10	RP	27	4.50	NA	412	10	19.02	13.61	0.92	10	0.14	0.10	2.39	5	0.25	0.30
6	slow	aspen	A	Pc	BKM-F-1767	B,C	CDM	CC	18	10	RP	28	1.90	NA	412	10	21.81	15.60	0.91	10	0.11	0.08	2.34	5	0.28	0.35
7	slow	aspen	A	Pc	BKM-F-1767	B,C	CDM	CC	18	10	T	NA	12.80	NA	370	10	15.35	10.98	0.74	10	0.11	0.08	2.72	5	0.21	0.26
8	slow	aspen	B	Pc	SC-26	D,E,F	fungal species, CDM	CC	NA	10	T	28	6.30	NA	449	10	26.49	18.95	1.53	10	0.20	0.14	3.43	5	0.27	0.34
9	slow	aspen	B	Pmp	RAB-82-5	D,E,F	fungal species, CDM	CC	43	10	RP	28	0.70	NA	470	10	23.02	16.47	1.35	10	0.13	0.09	3.16	5	0.33	0.40
10	slow	aspen	B	Pmp	RAB-82-5	D,E,F	fungal species, CDM	CC	46	10	T	28	11.50	NA	410	10	24.02	17.18	1.44	10	0.16	0.11	3.94	5	0.24	0.30
11	slow	aspen	B	Pt	RAB-25/PRL2845	D,E,F	fungal species, CDM	CC	49	10	T	28	10.20	1560	426	10	21.94	15.70	2.14	10	0.26	0.18	6.01	5	0.44	0.54
12	slow	aspen	B	Cv	MAD-697	D,E,F	fungal species, CDM	CC	41	10	RP	28	4.60	2488	450	10	25.27	18.08	1.12	10	0.14	0.10	2.71	5	0.27	0.33
13	slow	aspen	B	Cv	MAD-697	D,E,F	fungal species, CDM	CC	48	10	T	28	5.10	2373	461	10	20.65	14.77	1.28	10	0.12	0.08	3.05	5	0.26	0.32
15	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	CDM	CC	48	10	RS	28	13.70	1477	394	10	5.54	3.96	2.05	10	0.21	0.15	4.53	5	0.27	0.34
16	slow	aspen	B	Pb	HHB-7099	D,E,F	fungal species, CDM	CC	94	10	T	28	6.60	1271	379	10	9.31	6.66	1.64	10	0.13	0.09	4.80	5	0.47	0.59
17	slow	aspen	B	Pm	OKM-2994	D,E,F	fungal species, CDM	CC	101	10	T	28	2.20	1504	389	10	18.82	13.46	1.51	9	0.18	0.14	4.88	5	0.28	0.34
18	slow	aspen	B	Ps	RLG-6074-sp	D,E,F	fungal species, CDM	CC	NA	10	T	28	2.50	1387	399	10	15.48	11.07	1.68	10	0.16	0.11	5.34	5	0.87	1.08
19	slow	aspen	B	Ds	Ton-429	D,E,F	fungal species, CDM	CC	31	10	RS	28	5.30	2219	446	10	14.75	10.55	0.93	9	0.13	0.10	2.92	5	0.31	0.39
20	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	CDM	CC	57	10	T	28	7.80	2103	450	10	29.27	20.94	1.89	10	0.16	0.11	4.49	5	0.30	0.38
21	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	35	10	RP	28	0.40	2587	441	10	18.57	13.28	1.29	10	0.13	0.09	3.54	5	0.30	0.37
22	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	119	10	SS	28	12.80	1880	405	10	18.79	13.44	1.65	10	0.13	0.09	4.30	5	0.27	0.33
23	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	126	10	T	28	2.60	1938	378	10	10.52	7.53	1.63	9	0.12	0.09	4.48	5	0.25	0.32
24	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	20	10	RS	21	8.50	2103	425	10	19.77	14.14	1.45	10	0.12	0.09	3.58	5	0.22	0.27
25	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	26	10	RS	14	5.80	2235	427	10	31.34	22.42	1.46	9	0.18	0.13	3.41	5	0.75	0.93
26	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	22	10	RS	42	16.00	1694	429	10	21.84	15.62	2.27	10	0.22	0.16	5.00	5	0.29	0.36
27	slow	white spruce	B	Pt	PRL-2845	H	wood type, CDM	CC	19	10	T	27	8.20	1808	488	10	17.00	12.16	3.08	10	0.31	0.22	4.56	5	0.45	0.56
28	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	MCDM	CC	NA	10	T	28	24.00	2148	393	10	8.90	6.37	1.51	10	0.12	0.08	4.06	5	0.29	0.36
29	slow	white spruce	A	Pc	BKM-F-1767	H	wood type	CC	21	10	RS	28	10.10	2596	416	10	24.54	17.56	1.74	9	0.15	0.12	4.46	5	0.26	0.32
30	slow	aspen	C	Wc	FP-100604-sp	I,J,M,N,O,	fungal species, CDM	CC	22	10	RS	28	4.10	2046	454	10	57.96	41.46	0.78	6	0.12	0.09	2.03	5	0.17	0.21
31	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	No MCDM	CC	22	10	RS	28	3.80	1317	418	10	17.43	12.47	1.58	10	0.13	0.09	4.11	5	0.34	0.42
32	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	reactor type	CC	29	10	RS	28	4.20	1726	391	10	25.09	17.95	1.13	10	0.11	0.08	3.18	5	0.19	0.23
33	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	incubation time	CC	29	10	RS	28	12.90	1983	383	10	17.82	12.75	0.92	10	0.09	0.07	2.57	5	0.18	0.22
34	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	incubation time	CC	28	10	T	14	NA	2083	413	10	23.16	16.57	1.02	10	0.13	0.09	2.72	5	0.17	0.22
35	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	reactor type	CC	28	10	T	21	NA	2053	410	10	12.90	9.23	1.11	10	0.07	0.05	3.23	5	0.25	0.31
36	slow	loblolly	A	Pc	BKM-F-1767	K,L	wood type	CC	30	10	T	28	7.30	1851	362	10	10.56	7.55	0.71	10	0.06	0.05	2.86	5	0.20	0.25
37	slow	loblolly	A	Pc	BKM-F-1767	K,L	wood type	CC	29	10	T	28	2.90	1577	322	10	9.89	7.08	0.84	10	0.07	0.05	4.32	5	0.23	0.28
38	slow	loblolly	A	Ds	Ton-429	K,L	wood type, fungal species	CC	39	10	RS	28	3.10	1605	313	10	10.81	7.73	0.66	10	0.09	0.06	3.79	5	0.24	0.30
39	slow	loblolly	A	Ps	RLG-6074-sp	K,L	wood type, fungal species	CC	32	10	RS	28	1.00	1304	318	10	5.69	4.07	0.66	10	0.08	0.06	3.49	5	0.12	0.15
40	slow	loblolly	A	Pfa	FP106507	K,L	wood type, fungal species	CC	42	10	RS	28	2.20	NA	365	10	22.00	15.74	0.50	10	0.06	0.04	2.37	5	0.11	0.14
41	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	pulp for bleaching	CC	34	10	RS	28	0.78	1479	390	10	14.65	10.48	1.38	10	0.14	0.10	4.74	5	0.27	0.33
42	slow	loblolly	A	Pt	PRL-2845	K,L	wood type, fungal species	CC	46	10	RS	28	3.30	1862	341	10	12.12	8.67	0.64	10	0.06	0.04	3.39	5	0.29	0.36
51	slow	loblolly	A	Ps	RLG-6074	K,L	fungal species	CC	35	10	T	28	1.93	NA	332	10	13.78	9.86	0.55	10	0.09	0.06	3.50	5	0.17	0.21
53	slow	loblolly	A	Pb	HHB-7099	K,L	wood type, fungal species	CC	34	10	T	28	7.89	1394	338	10	19.87	14.21	0.50	10	0.07	0.05	2.97	5	0.17	0.20
54	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	inoculum preparation	CC	29	10	T	27	8.40	1425	338	10	10.82	7.74	1.01	10	0.10	0.07	3.90	5	0.19	0.24
55	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	inoculum preparation	CC	29	10	T	27	9.10	1391	333	10	13.59	9.72	0.88	10	0.08	0.06	3.41	5	0.15	0.19
56	slow	aspen	C	Pt	PRL-2845	I,J,M,N,O,	fungal species	CC	35	10	T	27	3.93	1213	338	10	21.98	15.72	1.11	9	0.07	0.06	4.53	5	0.23	0.28
57	slow	loblolly	A	Pt	BRI-67	K,L	wood type, fungal species	CC	30	10	T	28	5.71	1272	306	10	15.45	11.05	0.51	10	0.09	0.06	3.18	5	0.24	0.29
58	slow	loblolly	A	Ps	RLG-6074	K,L	wood type, fungal species	CC	30	10	T	28	4.13	1351	320	10	13.46	9.63	0.44	10	0.06	0.04	3.09	5	0.16	0.20
59	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	2.5	T	14	2.40	1710	376	10	10.82	7.74	0.92	10	0.08	0.06	3.26	5	0.18	0.22
60	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	5	T	14	6.20	1735	406	10	14.04	10.04	1.05	10	0.13	0.09	3.01	5	0.18	0.22
61	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	10	T	14	7.80	1613	357	10	11.62	8.31	0.88	10	0.10	0.07	2.79	5	0.18	0.22
62	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	20	T	14	5.80	1690	387	10	26.65	19.07	1.06	10	0.07	0.05	3.18	5	0.18	0.22
63	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	2.5	T	13	7.60	1790	367	10	16.41	11.74	1.11	10	0.06	0.04	3.83	5	0.20	0.25
64	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	5	T	13	7.30	1599	375	10	17.32	12.39	1.09	10	0.09	0.07	4.43	5	0.16	0.20
65	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	10	T	13	7.00	1684	357	10	9.31	6.66	1.02	10	0.08	0.06	3.62	5	0.14	0.17
66	slow	aspen	C.	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	20	T	13	9.50	1552	359	10	17.64	12.62	0.97	10	0.08	0.06	3.55	5	0.15	0.19

Table 1 B—Biopulping runs with control—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	tensile index Nm/g	n	s.d.	.95CI	TEA index J/g	n	s.d.	.95 CI	elong-ation %	n	s.d.	.95 CI	zero span tensile Nm/g	n	s.d.	.95 CI
1	slow	white birch	A	Pc	BKM-F1767	A	wood type, CDM	CC	NA	NA	RP	NA	NA	14.60	6	2.31	2.43	NA				NA				NA			
2	slow	aspen	A	Ds	Ton-429	B,C	fungal species, CDM	CC	NA	NA	RP	NA	NA	35.00	10	2.42	1.73	NA				NA				98.70	10	6.02	4.31
3	slow	aspen	A	Pc	SC-26	B,C	fungal species, CDM	CC	NA	NA	RP	NA	NA	31.30	10	3.40	2.43	NA				NA				111.70	10	6.91	4.94
4	slow	aspen	A	Pc	SC-26	B,C	fungal species, CDM	CC	18	10	RP	28	2.00	29.20	10	1.95	1.40	NA				NA				96.70	10	6.22	4.45
5	slow	aspen	A	Pt	RAB-25/PRL2845	B,C	fungal species, CDM	CC	35	10	RP	27	4.50	34.40	10	1.71	1.22	NA				NA				98.50	10	5.81	4.16
6	slow	aspen	A	Pc	BKM-F-1767	B,C	CDM	CC	18	10	RP	28	1.90	33.70	10	2.55	1.82	NA				NA				94.10	10	4.28	3.06
7	slow	aspen	A	Pc	BKM-F-1767	B,C	CDM	CC	18	10	T	NA	12.80	27.70	9	2.55	1.96	NA				NA				82.30	10	3.84	2.75
8	slow	aspen	B	Pc	SC-26	D,E,F	fungal species, CDM	CC	NA	10	T	28	6.30	45.20	10	2.65	1.90	NA				NA				106.00	10	8.31	5.94
9	slow	aspen	B	Pmp	RAB-82-5	D,E,F	fungal species, CDM	CC	43	10	RP	28	0.70	42.00	10	3.23	2.31	NA				NA				113.90	10	4.99	3.57
10	slow	aspen	B	Pmp	RAB-82-5	D,E,F	fungal species, CDM	CC	46	10	T	28	11.50	40.70	10	2.08	1.49	NA				NA				90.00	10	5.01	3.58
11	slow	aspen	B	Pt	RAB-25/PRL2845	D,E,F	fungal species, CDM	CC	49	10	T	28	10.20	51.90	10	5.55	3.97	NA				NA				94.90	10	5.18	3.71
12	slow	aspen	B	Cv	MAD-697	D,E,F	fungal species, CDM	CC	41	10	RP	28	4.60	37.30	10	3.15	2.25	NA				NA				102.20	10	6.24	4.46
13	slow	aspen	B	Cv	MAD-697	D,E,F	fungal species, CDM	CC	48	10	T	28	5.10	38.30	9	2.03	1.56	NA				NA				103.90	10	4.69	3.36
15	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	CDM	CC	48	10	RS	28	13.70	52.80	10	3.43	2.45	NA				NA				96.70	10	5.30	3.79
16	slow	aspen	B	Pb	HHB-7099	D,E,F	fungal species, CDM	CC	94	10	T	28	6.60	45.40	8	2.80	2.34	NA				NA				88.50	10	5.39	3.86
17	slow	aspen	B	Pm	OKM-2994	D,E,F	fungal species, CDM	CC	101	10	T	28	2.20	41.40	8	2.48	2.07	NA				NA				78.30	9	6.16	4.74
18	slow	aspen	B	Ps	RLG-6074-sp	D,E,F	fungal species, CDM	CC	NA	10	T	28	2.50	44.40	8	2.61	2.18	NA				NA				81.20	10	6.03	4.31
19	slow	aspen	B	Ds	Ton-429	D,E,F	fungal species, CDM	CC	31	10	RS	28	5.30	33.90	8	2.32	1.94	NA				NA				92.80	10	3.70	2.65
20	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	CDM	CC	57	10	T	28	7.80	47.20	8	2.69	2.25	NA				NA				97.70	10	4.10	2.93
21	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	35	10	RP	28	0.40	37.80	8	1.70	1.42	NA				NA				99.90	10	3.98	2.85
22	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	119	10	SS	28	12.80	42.20	8	3.48	2.91	NA				NA				88.20	10	5.01	3.58
23	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	126	10	T	28	2.60	40.80	8	2.41	2.02	NA				NA				84.00	10	8.58	6.14
24	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	20	10	RS	21	8.50	39.40	8	2.93	2.45	NA				NA				95.20	10	4.98	3.56
25	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	26	10	RS	14	5.80	39.80	8	2.11	1.76	NA				NA				93.70	10	5.57	3.98
26	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	22	10	RS	42	16.00	54.70	9	3.69	2.84	NA				NA				84.50	10	7.77	5.56
27	slow	white spruce	B	Pt	PRL-2845	H	wood type, CDM	CC	19	10	T	27	8.20	66.80	10	5.09	3.64	NA				NA				90.30	10	5.12	3.66
28	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	MCDM	CC	NA	10	T	28	24.00	40.50	9	3.51	2.70	NA				NA				92.20	10	4.67	3.34
29	slow	white spruce	A	Pc	BKM-F-1767	H	wood type	CC	cc	10	RS	21	10.10	43.80	9	3.38	2.60	NA				NA				101.20	10	4.94	3.53
30	slow	aspen	C	Wc	FP-100604-sp	I,J,M,N,O,	fungal species, CDM	CC	22	10	RS	28	4.10	27.80	6	1.79	1.88	NA				NA				88.40	10	5.32	3.81
31	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	No MCDM	CC	22	10	RS	28	3.80	37.30	8	4.45	3.72	NA				NA				92.40	10	3.97	2.84
32	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	reactor type	CC	29	10	RS	28	4.20	35.40	10	1.99	1.42	NA				NA				82.50	10	4.06	2.90
33	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	incubation time	CC	29	10	RS	28	12.90	30.20	10	2.05	1.47	NA				NA				82.60	10	4.63	3.31
34	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	incubation time	CC	28	10	T	14	NA	33.50	10	1.68	1.20	NA				NA				90.80	10	4.62	3.31
35	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	reactor type	CC	28	10	T	21	NA	32.80	10	1.48	1.06	NA				NA				91.60	10	4.42	3.16
36	slow	loblolly	A	Pc	BKM-F-1767	K,L	wood type	CC	30	10	T	28	7.30	26.10	10	1.57	1.12	NA				NA				80.90	10	2.96	2.12
37	slow	loblolly	A	Pc	BKM-F-1767	K,L	wood type	CC	29	10	T	28	2.90	26.40	9	1.84	1.41	NA				NA				82.00	10	6.53	4.67
38	slow	loblolly	A	Ds	Ton-429	K,L	wood type, fungal species	CC	39	10	RS	28	3.10	23.90	10	1.38	0.99	NA				NA				64.20	10	4.36	3.12
39	slow	loblolly	A	Ps	RLG-6074-sp	K,L	wood type, fungal species	CC	32	10	RS	28	1.00	25.30	10	1.64	1.17	NA				NA				75.20	10	4.55	3.26
40	slow	loblolly	A	Pfa	FP106507	K,L	wood type, fungal species	CC	42	10	RS	28	2.20	21.80	9	1.23	0.95	NA				NA				78.90	10	3.29	2.35
41	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	pulp for bleaching	CC	34	10	RS	28	0.78	40.30	9	2.15	1.65	NA				NA				87.80	10	6.45	4.61
42	slow	loblolly	A	Pt	PRL-2845	K,L	wood type, fungal species	CC	46	10	RS	28	3.30	24.50	8	1.59	1.33	NA				NA				79.40	10	9.19	6.57
51	slow	loblolly	A	Ps	RLG-6074	K,L	fungal species	CC	35	10	T	28	1.93	20.40	10	1.35	0.97	NA				NA				77.40	10	4.48	3.20
53	slow	loblolly	A	Pb	HHB-7099	K,L	wood type, fungal species	CC	34	10	T	28	7.89	18.70	10	1.03	0.74	NA				NA				76.40	10	4.70	3.36
54	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	inoculum preparation	CC	29	10	T	27	8.40	17.40	10	2.57	1.84	NA				NA				89.20	10	4.57	3.27
55	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	inoculum preparation	CC	29	10	T	27	9.10	27.20	9	1.59	1.22	NA				NA				80.10	10	6.19	4.43
56	slow	aspen	C	Pt	PRL-2845	I,J,M,N,O,	fungal species	CC	35	10	T	27	3.93	27.10	10	1.92	1.37	NA				NA				84.50	10	6.50	4.65
57	slow	loblolly	A	Pt	BRI-67	K,L	wood type, fungal species	CC	30	10	T	28	5.71	18.30	9	2.84	2.18	NA				NA				80.00	10	6.37	4.56
58	slow	loblolly	A	Ps	RLG-6074	K,L	wood type, fungal species	CC	30	10	T	28	4.13	14.10	10	1.94	1.39	NA				NA				71.10	10	3.39	2.43
59	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	2.5	T	14	2.40	25.30	10	2.37	1.70	NA				NA				88.70	10	5.40	3.86
60	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	5	T	14	6.20	25.90	10	2.99	2.14	NA				NA				91.10	10	5.05	3.61
61	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	10	T	14	7.80	26.90	10	1.87	1.34	NA				NA				90.20	10	5.27	3.77
62	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	20	T	14	5.80	24.50	10	3.28	2.35	NA				NA				90.70	10	4.77	3.41
63	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	2.5	T	13	7.60	28.00	10	2.54	1.82	NA				NA				100.00	10	6.22	4.45
64	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	5	T	13	7.30	29.60	9	2.77	2.13	NA				NA				80.80	10	6.05	4.33
65	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	10	T	13	7.00	31.10	10	1.65	1.18	NA				NA				91.30	10	8.53	6.10
66	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	20	T	13	9.50	31.20	10	2.16	1.55	NA				NA				87.70	10	6.00	4.29

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	bright-ness %	n	s.d.	.95 CI	opacity %	n	s.d.	.95 CI	scattering coefficient m^2/kg	n	s.d.	.95 CI	fiber length index mm	klason lignin %	Labra-tory
1	slow	white birch	A	Pc	BKM-F1767	A	wood type, CDM	CC	NA	NA	RP	NA	NA	36.00	5	0.45	0.56	96.80	5			43.80	5			0.06	NA	FPL
2	slow	aspen	A	Ds	Ton-429	B,C	fungal species, CDM	CC	NA	NA	RP	NA	NA	39.40	5	0.39	0.48	97.60	5			47.30	5			0.12	NA	FPL
3	slow	aspen	A	Pc	SC-26	B,C	fungal species, CDM	CC	NA	NA	RP	NA	NA	47.20	5	0.23	0.29	97.10	5			55.70	5			0.09	NA	FPL
4	slow	aspen	A	Pc	SC-26	B,C	fungal species, CDM	CC	18	10	RP	28	2.00	40.60	5	0.23	0.29	98.10	5			52.70	5			0.08	20.94	FPL
5	slow	aspen	A	Pt	RAB-25/PRL2845	B,C	fungal species, CDM	CC	35	10	RP	27	4.50	35.70	5	0.24	0.30	98.80	5			50.40	5			0.08	21.40	FPL
6	slow	aspen	A	Pc	BKM-F-1767	B,C	CDM	CC	18	10	RP	28	1.90	36.90	5	0.19	0.24	95.50	5			51.00	5			0.07	20.86	FPL
7	slow	aspen	A	Pc	BKM-F-1767	B,C	CDM	CC	18	10	T	NA	12.80	42.30	5	0.33	0.41	97.30	5			49.80	5			0.10	19.68	FPL
8	slow	aspen	B	Pc	SC-26	D,E,F	fungal species, CDM	CC	NA	10	T	28	6.30	48.90	5	0.24	0.30	95.30	5			50.40	5			0.10	17.97	FPL
9	slow	aspen	B	Pmp	RAB-82-5	D,E,F	fungal species, CDM	CC	43	10	RP	28	0.70	46.70	5	0.24	0.30	96.60	5			50.60	5			0.09	20.02	FPL
10	slow	aspen	B	Pmp	RAB-82-5	D,E,F	fungal species, CDM	CC	46	10	T	28	11.50	48.70	5	0.32	0.40	94.00	5			47.60	5			0.11	17.49	FPL
11	slow	aspen	B	Pt	RAB-25/PRL2845	D,E,F	fungal species, CDM	CC	49	10	T	28	10.20	42.80	5	0.33	0.41	93.30	5			38.20	5			0.11	15.08	FPL
12	slow	aspen	B	Cv	MAD-697	D,E,F	fungal species, CDM	CC	41	10	RP	28	4.60	48.00	5	0.48	0.60	97.30	5			56.70	5			0.09	19.16	FPL
13	slow	aspen	B	Cv	MAD-697	D,E,F	fungal species, CDM	CC	48	10	T	28	5.10	46.90	5	0.43	0.53	96.90	5			54.90	5			0.09	18.16	FPL
15	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	CDM	CC	48	10	RS	28	13.70	41.00	5	0.90	1.12	94.90	5			40.70	5			0.12	14.76	FPL
16	slow	aspen	B	Pb	HHB-7099	D,E,F	fungal species, CDM	CC	94	10	T	28	6.60	46.90	5	0.62	0.77	93.00	5			41.30	5			0.13	13.24	FPL
17	slow	aspen	B	Pm	OKM-2994	D,E,F	fungal species, CDM	CC	101	10	T	28	2.20	46.20	5	0.25	0.31	91.45	5			32.30	5			0.13	17.03	FPL
18	slow	aspen	B	Ps	RLG-6074-sp	D,E,F	fungal species, CDM	CC	NA	10	T	28	2.50	47.50	5	0.29	0.36	91.30	5			39.90	5			0.13	14.24	FPL
19	slow	aspen	B	Ds	Ton-429	D,E,F	fungal species, CDM	CC	31	10	RS	28	5.30	47.40	5	0.35	0.43	97.10	5			56.30	5			0.08	13.18	FPL
20	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	CDM	CC	57	10	T	28	7.80	48.20	5	0.18	0.22	98.20	5			46.90	5			0.12	19.66	FPL
21	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	35	10	RP	28	0.40	49.00	5	0.23	0.29	95.30	5			52.80	5			0.08	17.96	FPL
22	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	119	10	SS	28	12.80	49.90	5	0.21	0.26	93.50	5			48.40	5			0.13	18.40	FPL
23	slow	aspen	B	Ds	Ton-429	D,E,F	reactor type, CDM	CC	126	10	T	28	2.60	48.80	5	0.39	0.48	94.40	5			48.70	5			0.11	17.15	FPL
24	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	20	10	RS	21	8.50	50.20	5	0.35	0.43	94.60	5			51.10	5			0.10	NA	FPL
25	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	26	10	RS	14	5.80	51.70	5	0.24	0.30	96.50	5			53.90	5			0.09	NA	FPL
26	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	incubation time, CDM	CC	22	10	RS	42	16.00	44.90	5	0.30	0.37	91.00	5			37.00	5			0.11	NA	FPL
27	slow	white spruce	B	Pt	PRL-2845	H	wood type, CDM	CC	19	10	T	27	8.20	31.10	5	0.32	0.40	95.20	5			32.60	5			0.14	NA	FPL
28	slow	aspen	B	Pc	BKM-F-1767	D,E,F,	MCDM	CC	NA	10	T	28	24.00	54.20	5	0.28	0.35	94.70	5			54.20	5			0.12	17.86	FPL
29	slow	white spruce	A	Pc	BKM-F-1767	H	wood type	CC	21	10	RS	28	10.10	40.80	5	0.21	0.26	97.30	5			48.60	5			0.12	NA	FPL
30	slow	aspen	C	Wc	FP-100604-sp	I,J,M,N,O,	fungal species, CDM	CC	22	10	RS	28	4.10	47.90	5	0.29	0.36	97.40	5			54.90	5			0.08	NA	FPL
31	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	No MCDM	CC	22	10	RS	28	3.80	45.10	5	0.52	0.65	93.50	5			42.70	5			0.11	NA	FPL
32	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	reactor type	CC	29	10	RS	28	4.20	46.20	5	0.32	0.40	94.30	5			47.30	5			0.10	18.59	FPL
33	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	incubation time	CC	29	10	RS	28	12.90	50.40	5	0.76	0.94	94.20	5			53.70	5			0.08	18.69	FPL
34	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	incubation time	CC	28	10	T	14	NA	57.30	5	0.29	0.36	93.20	5			54.70	5			0.08	19.10	FPL
35	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	reactor type	CC	28	10	T	21	NA	51.20	5	0.36	0.45	94.10	5			49.50	5			0.09	NA	FPL
36	slow	loblolly	A	Pc	BKM-F-1767	K,L	wood type	CC	30	10	T	28	7.30	36.10	5	0.30	0.37	94.80	5			40.40	5			0.12	30.84	FPL
37	slow	loblolly	A	Pc	BKM-F-1767	K,L	wood type	CC	29	10	T	28	2.90	35.00	5	0.41	0.51	88.50	5			32.70	5			0.14	29.35	FPL
38	slow	loblolly	A	Ds	Ton-429	K,L	wood type, fungal species	CC	39	10	RS	28	3.10	35.40	5	0.32	0.40	91.80	5			34.40	5			0.12	31.30	FPL
39	slow	loblolly	A	Ps	RLG-6074-sp	K,L	wood type, fungal species	CC	32	10	RS	28	1.00	31.90	5	0.42	0.52	91.60	5			33.30	5			0.12	29.08	FPL
40	slow	loblolly	A	Pfa	FP106507	K,L	wood type, fungal species	CC	42	10	RS	28	2.20	39.40	5	0.43	0.53	95.10	5			44.90	5			0.12	31.36	FPL
41	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	pulp for bleaching	CC	34	10	RS	28	0.78	42.50	5	0.40	0.50	89.60	5			38.80	5			NA	16.25	FPL
42	slow	loblolly	A	Pt	PRL-2845	K,L	wood type, fungal species	CC	46	10	RS	28	3.30	34.70	5	0.16	0.20	92.80	5			36.50	5			0.11	28.80	FPL
51	slow	loblolly	A	Ps	RLG-6074	K,L	fungal species	CC	35	10	T	28	1.93	32.10	5	0.12	0.15	93.10	5			31.90	5			0.10	NA	FPL
53	slow	loblolly	A	Pb	HHB-7099	K,L	wood type, fungal species	CC	34	10	T	28	7.89	36.80	5	0.21	0.26	89.00	5			35.00	5			0.11	NA	FPL
54	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	inoculum preparation	CC	29	10	T	27	8.40	48.90	5	0.34	0.42	93.70	5			46.60	5			0.05	NA	FPL
55	slow	aspen	C	Pc	BKM-F-1767	I,J,M,N,O	inoculum preparation	CC	29	10	T	27	9.10	50.80	5	0.26	0.32	92.20	5			46.80	5			0.08	NA	FPL
56	slow	aspen	C	Pt	PRL-2845	I,J,M,N,O,	fungal species	CC	35	10	T	27	3.93	48.80	5	0.24	0.30	93.10	5			42.50	5			0.07	NA	FPL
57	slow	loblolly	A	Pt	BRI-67	K,L	wood type, fungal species	CC	30	10	T	28	5.71	34.80	5	0.19	0.24	89.40	5			31.20	5			0.13	28.01	FPL
58	slow	loblolly	A	Ps	RLG-6074	K,L	wood type, fungal species	CC	30	10	T	28	4.13	33.00	5	0.11	0.14	90.30	5			30.30	5			0.11	NA	FPL
59	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	2.5	T	14	2.40	56.40	5	0.19	0.24	93.70	5			54.50	5			0.07	NA	FPL
60	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	5	T	14	6.20	54.60	5	0.21	0.26	94.60	5			53.90	5			0.08	NA	FPL
61	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	10	T	14	7.80	54.40	5	0.15	0.19	93.80	5			53.50	5			0.07	NA	FPL
62	slow	aspen	C	Pc	BKM-F-1767	P	inoculum level - Rep1	CC	15	20	T	14	5.80	53.10	5	0.21	0.26	94.30	5			53.00	5			0.08	NA	FPL
63	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	2.5	T	13	7.60	53.60	5	0.20	0.25	92.30	5			51.30	5			0.10	NA	FPL
64	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	5	T	13	7.30	56.10	5	0.26	0.32	93.80	5			52.50	5			0.16	NA	FPL
65	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	10	T	13	7.00	53.70	5	0.46	0.57	93.30	5			51.00	5			0.12	NA	FPL
66	slow	aspen	C	Pc	BKM-F-1767	Q	inoculum level - Rep 2	CC	16	20	T	13	9.50	52.50	5	0.19	0.24	90.60	5			47.90	5			0.11	NA	FPL

Table 1 B—Blopulping runs with control—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	energy watt-hrs. per kg	density kg/m^3	n	s.d.	.95 CI	burst index kN/g	n	s.d.	.95 CI	tear index mN-m^2/g	n	s.d.	.95CI
				*1		*2	*3	*4			*5						*6	*7								
67	slow	loblolly	A	Pb	HHB-7030-sp	K,L,R	wood type, fungal species	CC	26	26	T	26	4.64	1432	328	10	9.03	6.46	0.60	10	0.07	0.05	3.43	5	0.29	0.35
68	slow	loblolly	A	Hs	FP-106976-sp	K,L,R	wood type, fungal species	CC	26	26	T	26	5.07	1470	353	10	20.16	14.42	0.70	10	0.08	0.06	3.74	5	0.19	0.23
73	slow	aspen	C	Pc	BKM-F-1767	S	aspen C vs D	CC	16	5	T	14	3.00	1525	397	10	25.11	17.96	1.16	10	0.08	0.06	3.41	5	0.13	0.16
74	slow	aspen	D	Pc	BKM-F-1767	T	aspen C vs D	CC	16	5	T	14	3.40	1508	389	10	11.89	8.51	1.17	10	0.07	0.05	3.38	5	0.19	0.23
75	slow	aspen	C	Pc	BKM-F-1767	S	aspen C vs D	CC	16	5	A	14	7.40	1475	406	10	28.10	20.10	1.37	10	0.12	0.08	3.84	5	0.13	0.16
76	slow	aspen	D	Pc	BKM-F-1767	T	aspen C vs D	CC	16	5	A	14	4.40	1605	390	10	19.08	13.65	1.13	10	0.09	0.07	3.47	5	0.13	0.17
78	slow	aspen	D	Cs	FP-90031-sp	U	fungal species	CC	30	10	T	28	3.50	1122	389	10	15.69	11.22	1.56	10	0.09	0.07	4.25	5	0.21	0.26
79	slow	loblolly	A	Cs	FP-90031-sp	V	wood type, fungal species	CC	30	10	RS	28	2.50	1353	347	10	11.72	8.38	0.80	10	0.08	0.05	4.85	5	0.28	0.34
80	slow	loblolly	A	Cs	FP-90031-sp	V	wood type, fungal species	CC	30	10	T	28	7.10	1167	328	10	10.27	7.35	0.82	10	0.07	0.05	4.75	5	0.24	0.30
81	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-0 mM N	CC	15	5	A	14	1.50	1875	402	10	11.50	8.23	1.09	10	0.08	0.06	3.14	5	0.27	0.33
82	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-1.7 mM N	CC	15	5	A	14	2.50	1772	378	10	16.57	11.85	0.99	10	0.10	0.07	3.19	5	0.14	0.18
83	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-5.1mM N	CC	15	5	A	14	7.20	1670	380	10	23.51	16.82	1.06	10	0.08	0.06	3.50	5	0.28	0.35
84	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-15.3mM N	CC	15	5	A	14	9.20	1615	406	10	21.56	15.42	1.06	10	0.08	0.06	3.39	5	0.20	0.24
85	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-0 mM N	CC	15	5	A	26	3.90	1968	389	10	20.20	14.45	1.04	10	0.11	0.08	3.37	5	0.18	0.22
86	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-1.7 mM N	CC	15	5	A	26	8.20	1879	382	10	16.07	11.50	1.12	10	0.09	0.06	3.56	5	0.21	0.25
87	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-5.1mM N	CC	15	5	A	26	7.30	1954	379	10	14.33	10.25	1.03	10	0.07	0.05	3.24	5	0.18	0.23
88	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-15.3mM N	CC	15	5	A	26	13.80	1741	362	10	15.35	10.98	1.07	10	0.09	0.06	3.42	5	0.23	0.28
89	slow	aspen	D	Pc	BKM-F-1767	No control	No MCDM YE/L 5.1mM N	CC	15	5	A	14	3.05	1757	395	10	28.05	20.07	1.05	10	0.10	0.07	3.31	5	0.17	0.21
90	slow	aspen	D	Pc	BKM-F-1767	No control	No MCDM YE/L 15.3mM N	CC	15	5	A	14	4.94	1394	370	10	12.28	8.79	1.03	10	0.07	0.05	3.59	5	0.22	0.27
91	slow	aspen	D	Pc	BKM-F-1767	Z	lowN/lowC -Rep1	CC	15	5	A	14	6.56	1934	433	8	4.51	3.77	1.15	10	0.08	0.06	2.00	10	0.12	0.08
92	slow	aspen	D	Pc	BKM-F-1767	Z	lowN/highC -Rep1	CC	15	5	A	14	10.56	1814	420	8	17.41	14.56	1.15	10	0.09	0.06	2.31	10	0.16	0.11
93	slow	aspen	D	Pc	BKM-F-1767	Z	highN/lowC -Rep1	CC	15	5	A	14	11.82	1647	409	8	12.03	10.06	1.15	10	0.11	0.08	2.41	10	0.19	0.14
94	slow	aspen	D	Pc	BKM-F-1767	Z	highN/highC -Rep1	CC	15	5	A	14	17.99	1752	418	8	7.91	6.62	1.18	10	0.10	0.07	2.39	10	0.15	0.10
95	slow	aspen	D	Pc	BKM-F-1767	A'	lowN/lowC -Rep1	CC	16	5	A	28	11.24	1719	401	8	22.72	19.00	1.27	10	0.15	0.11	2.20	10	0.15	0.10
96	slow	aspen	D	Pc	BKM-F-1767	A'	lowN/highC -Rep1	CC	16	5	A	28	11.27	1666	411	8	14.05	11.75	1.22	10	0.10	0.07	2.52	10	0.30	0.21
97	slow	aspen	D	Pc	BKM-F-1767	A'	highN/lowC -Rep1	CC	16	5	A	28	19.44	1360	413	8	22.10	18.48	1.18	10	0.13	0.09	2.51	10	0.13	0.09
98	slow	aspen	D	Pc	BKM-F-1767	A'	highN/highC -Rep1	CC	16	5	A	28	21.65	1554	408	8	19.25	16.10	1.28	10	0.12	0.09	2.58	10	0.16	0.12
100	slow	loblolly	A	Hs	FP-106976-sp	K,L,R,V	wood type, fungal species	CC	29	10	RS	28	5.60	1586	340	10	23.53	16.83	0.95	10	0.14	0.10	4.95	5	0.27	0.33
101	slow	loblolly	A	Pb	HHB-7030-sp	K,L,R,V	wood type, fungal species	CC	29	10	RS	28	4.70	1430	324	10	26.08	18.66	0.81	10	0.10	0.07	4.48	5	0.33	0.41
102	slow	aspen	D	Pc	BKM-F-1767	C'	lowN/lowC - Rep 2	CC	14	5	A	14	3.68	1884	411	8	7.75	6.48	0.90	10	0.12	0.09	1.84	10	0.12	0.09
103	slow	aspen	D	Pc	BKM-F-1767	C'	lowN/highC - Rep 2	CC	14	5	A	14	5.80	1874	420	8	9.41	7.87	0.96	10	0.09	0.07	2.02	10	0.17	0.12
104	slow	aspen	D	Pc	BKM-F-1767	C'	highN/lowC - Rep 2	CC	14	5	A	14	8.01	1717	417	8	24.93	20.85	0.93	10	0.07	0.05	2.07	10	0.12	0.09
105	slow	aspen	D	Pc	BKM-F-1767	C'	highN/highC - Rep 2	CC	14	5	A	14	4.33	1776	410	8	25.46	21.29	0.97	10	0.11	0.08	2.09	10	0.16	0.12
106	slow	aspen	D	Pc	BKM-F-1767	D'	lowN/lowC - Rep 2	CC	15	5	A	28	12.58	1820	432	8	7.71	6.45	1.13	10	0.14	0.10	2.56	10	0.18	0.13
107	slow	aspen	D	Pc	BKM-F-1767	D'	lowN/highC - Rep 2	CC	15	5	A	28	12.59	1770	388	8	15.91	13.31	1.09	10	0.10	0.07	2.68	10	0.16	0.11
108	slow	aspen	D	Pc	BKM-F-1767	D'	highN/lowC - Rep 2	CC	15	5	A	28	20.30	1445	387	8	8.13	6.80	1.09	10	0.08	0.06	2.77	10	0.27	0.19
109	slow	aspen	D	Pc	BKM-F-1767	D'	highN/highC - Rep 2	CC	15	5	A	28	19.29	1628	391	8	9.29	7.77	1.04	10	0.10	0.07	2.54	10	0.21	0.15
110	slow	aspen	D	Cs	FP-90031-sp	E'	MCDM	CC	14	5	A	28	5.74	1751	379	10	17.40	12.45	1.18	10	0.10	0.07	3.94	4	0.21	0.33
111	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 5.1 mM N (YE)	CC	14	5	A	28	3.22	1797	386	10	7.62	5.45	1.21	10	0.12	0.09	4.10	4	0.31	0.49
112	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 15.3 mM N (YE)	CC	14	5	A	28	4.87	1557	372	10	26.03	18.62	1.30	10	0.15	0.11	4.16	5	0.83	1.03
113	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 45.9 mM N (YE)	CC	14	5	A	28	7.20	1144	352	10	14.42	10.32	1.19	10	0.17	0.12	4.24	4	0.33	0.53
115	slow	aspen	D	Pc	BKM-F-1767	F'	lowC - LowN inoculum	CC	15	5	A	14	4.18	2121	457	8	8.90	7.45	1.19	10	0.10	0.07	1.66	10	0.14	0.10
116	slow	aspen	D	Pc	BKM-F-1767	F'	lowC - HighN inoculum	CC	15	5	A	14	6.42	1935	481	8	10.52	8.80	1.22	10	0.12	0.09	1.87	10	0.15	0.10
117	slow	aspen	D	Pc	BKM-F-1767	F'	highC - LowN inoculum	CC	15	5	A	14	1.27	2073	492	8	7.48	6.25	1.26	10	0.11	0.08	1.98	10	0.12	0.09
118	slow	aspen	D	Pc	BKM-F-1767	F'	highC - HighN inoculum	CC	15	5	A	14	8.69	1831	449	8	7.15	5.98	1.29	10	0.10	0.07	2.12	10	0.14	0.10
119	slow	aspen	D	Pc	BKM-F-1767	G'	lowC - LowN inoculum	CC	15	5	A	28	4.78	1821	470	8	6.14	5.14	1.23	10	0.11	0.08	1.86	10	0.11	0.08
120	slow	aspen	D	Pc	BKM-F-1767	G'	lowC - HighN inoculum	CC	15	5	A	28	14.35	1534	470	8	5.49	4.59	1.30	10	0.12	0.08	2.45	10	0.33	0.23
121	slow	aspen	D	Pc	BKM-F-1767	G'	highC - LowN inoculum	CC	15	5	A	28	8.07	1694	459	8	11.90	9.95	1.40	10	0.10	0.07	2.29	10	0.21	0.15
122	slow	aspen	D	Pc	BKM-F-1767	G'	highC - HighN inoculum	CC	15	5	A	28	16.09	1542	422	8	11.03	9.23	1.27	10	0.09	0.07	2.57	10	0.18	0.13
123	slow	loblolly	A	Cs	L-14807	H'	strain comparison	CC	31	10	T	25	4.87	1375	378	8	8.38	7.00	0.95	10	0.07	0.05	3.46	10	0.26	0.19
124	slow	loblolly	A	Cs	L-15225	H'	strain comparison	CC	31	10	T	25	6.12	1427	376	8	4.52	3.78	0.88	10	0.07	0.05	3.33	10	0.21	0.15
125	slow	loblolly	A	Cs	FP-104027	H'	strain comparison	CC	31	10	T	25	3.42	1552	389	8	4.95	4.14	0.96	10	0.06	0.05	3.21	10	0.21	0.15
126	slow	loblolly	A	Cs	FP-105752	H'	strain comparison	CC	31	10	T	25	7.26	1347	382	8	12.36	10.34	0.91	10	0.08	0.05	3.48	10	0.18	0.13
127	slow	loblolly	A	Cs	FP-90031-sp	H'	strain comparison	CC	31	10	T	25	4.51	1321	383	8	6.52	5.45	0.93	10	0.08	0.06	3.36	10	0.17	0.12
128	slow	aspen	E	Pc	BKM-F-1767	I'	frozen	CC	14	5	A	28	12.96	1570	442	8	16.18	13.53	1.37	10	0.16	0.11	2.43	10	0.24	0.17
129	slow	aspen	E	Pc	BKM-F-1767	J'	fresh	CC	14	5	A	28	12.99	1555	441	8	11.78	9.85	1.31	10	0.14	0.10	2.31	10	0.22	0.16

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	tensile index Nm/g	n	s.d.	.95CI	TEA index J/g	n	s.d.	.95 CI	elong-ation %	n	s.d.	.95 CI	zero span tensile Nm/g	n	s.d.	.95 CI
67	slow	loblolly	A	Pb	HHB-7030-sp	K,L,R	wood type, fungal species	CC	26	26	T	26	4.64	20.00	10	2.39	1.71	NA				NA				80.80	10	4.76	3.41
68	slow	loblolly	A	Hs	FP-106976-sp	K,L,R	wood type, fungal species	CC	26	26	T	26	5.07	19.40	10	2.14	1.53	NA				NA				84.10	10	4.70	3.36
73	slow	aspen	C	Pc	BKM-F-1767	S	aspen C vs D	CC	16	5	T	14	3.00	35.00	8	2.33	1.95	NA				1.48	8	0.14	0.12	93.70	10	7.08	5.07
74	slow	aspen	D	Pc	BKM-F-1767	T	aspen C vs D	CC	16	5	T	14	3.40	34.60	9	2.91	2.24	NA				1.64	9	0.17	0.13	96.30	10	4.68	3.35
75	slow	aspen	C	Pc	BKM-F-1767	S	aspen C vs D	CC	16	5	A	14	7.40	36.20	7	2.26	2.09	NA				1.56	6	0.21	0.22	102.00	10	3.54	2.53
76	slow	aspen	D	Pc	BKM-F-1767	T	aspen C vs D	CC	16	5	A	14	4.40	31.80	7	1.10	1.02	NA				1.47	7	0.28	0.26	109.50	10	3.87	2.77
78	slow	aspen	D	Cs	FP-90031-sp	U	fungal species	CC	30	10	T	28	3.50	35.60	9	3.67	2.82	NA				1.87	9	0.27	0.21	91.92	10	4.30	3.08
79	slow	loblolly	A	Cs	FP-90031-sp	V	wood type, fungal species	CC	30	10	RS	28	2.50	23.60	7	1.55	1.43	NA				1.48	7	0.17	0.15	79.00	10	3.58	2.56
80	slow	loblolly	A	Cs	FP-90031-sp	V	wood type, fungal species	CC	30	10	T	28	7.10	21.80	10	2.61	1.87	NA				1.43	10	0.23	0.17	79.80	10	4.44	3.18
81	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-0 mM N	CC	15	5	A	14	1.50	31.80	5	2.36	2.93	NA				1.49	5	0.19	0.23	96.30	10	4.51	3.23
82	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-1.7 mM N	CC	15	5	A	14	2.50	29.60	10	1.67	1.19	NA				1.50	8	0.15	0.12	90.10	10	4.58	3.28
83	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-5.1mM N	CC	15	5	A	14	7.20	30.30	10	1.66	1.19	NA				1.57	8	0.17	0.14	85.00	10	3.89	2.78
84	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-15.3mM N	CC	15	5	A	14	9.20	30.40	9	2.82	2.17	NA				1.53	9	0.15	0.11	90.10	10	4.47	3.20
85	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-0 mM N	CC	15	5	A	26	3.90	31.70	9	1.82	1.40	NA				1.47	9	0.18	0.14	96.50	10	3.32	2.38
86	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-1.7 mM N	CC	15	5	A	26	8.20	31.80	10	1.34	0.96	NA				1.47	10	0.20	0.14	92.00	10	2.50	1.79
87	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-5.1mM N	CC	15	5	A	26	7.30	31.60	7	1.79	1.66	NA				1.45	5	0.18	0.22	94.60	10	4.33	3.10
88	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-15.3mM N	CC	15	5	A	26	13.80	33.30	9	0.86	0.66	NA				1.49	7	0.20	0.18	94.60	10	2.69	1.92
89	slow	aspen	D'	Pc	BKM-F-1767	No control	No MCDM YE/L 5.1mM N	CC	15	5	A	14	3.05	32.10	6	2.57	2.70	NA				1.40	6	0.22	0.23	92.40	10	3.64	2.60
90	slow	aspen	D	Pc	BKM-F-1767	No control	No MCDM YE/L 15.3mM N	CC	15	5	A	14	4.94	33.14	9	1.43	1.10	NA				1.58	6	0.19	0.20	84.40	10	2.17	1.55
91	slow	aspen	D	Pc	BKM-F-1767	Z	lowN/lowC -Rep1	CC	15	5	A	14	6.56	27.30	5	0.98	1.22	0.30	5	0.03	0.03	1.16	5	0.16	0.20	NA			
92	slow	aspen	D	Pc	BKM-F-1767	Z	lowN/highC -Rep1	CC	15	5	A	14	10.56	28.30	5	2.36	2.93	0.34	5	0.02	0.03	1.36	5	0.09	0.11	NA			
93	slow	aspen	D	Pc	BKM-F-1767	Z	highN/lowC -Rep1	CC	15	5	A	14	11.82	28.70	5	2.41	3.00	0.34	5	0.05	0.06	1.31	5	0.14	0.17	NA			
94	slow	aspen	D	Pc	BKM-F-1767	Z	highN/highC -Rep1	CC	15	5	A	14	17.99	28.30	5	2.23	2.77	0.33	5	0.02	0.03	1.26	5	0.07	0.09	NA			
95	slow	aspen	D	Pc	BKM-F-1767	A'	lowN/lowC -Rep1	CC	16	5	A	28	11.24	26.40	5	3.96	4.92	0.29	5	0.04	0.05	1.44	5	0.26	0.32	NA			
96	slow	aspen	D	Pc	BKM-F-1767	A'	lowN/highC -Rep1	CC	16	5	A	28	11.27	28.90	5	1.22	1.52	0.30	5	0.02	0.02	1.37	5	0.07	0.09	NA			
97	slow	aspen	D	Pc	BKM-F-1767	A'	highN/lowC -Rep1	CC	16	5	A	28	19.44	30.10	5	2.06	2.55	0.32	5	0.04	0.05	1.38	5	0.15	0.19	NA			
98	slow	aspen	D	Pc	BKM-F-1767	A'	highN/highC -Rep1	CC	16	5	A	28	21.65	30.50	5	1.11	1.37	0.33	5	0.02	0.03	1.48	5	0.07	0.09	NA			
100	slow	loblolly	A	Hs	FP-106976-sp	K,L,R,V	wood type, fungal species	CC	29	10	RS	28	5.60	27.20	10	2.55	1.82	NA				1.38	10	0.16	0.11	NA			
101	slow	loblolly	A	Pb	HHB-7030-sp	K,L,R,V	wood type, fungal species	CC	29	10	RS	28	4.70	25.30	10	1.84	1.32	NA				1.31	10	0.21	0.15	NA			
102	slow	aspen	D	Pc	BKM-F-1767	C'	lowN/lowC - Rep 2	CC	14	5	A	14	3.68	26.50	5	0.98	1.22	0.24	5	0.05	0.07	1.90	5	0.32	0.39	NA			
103	slow	aspen	D	Pc	BKM-F-1767	C'	lowN/highC - Rep 2	CC	14	5	A	14	5.80	27.60	5	2.33	2.89	0.25	5	0.05	0.06	1.82	5	0.12	0.15	NA			
104	slow	aspen	D	Pc	BKM-F-1767	C'	highN/lowC - Rep 2	CC	14	5	A	14	8.01	28.30	5	1.96	2.43	0.25	5	0.04	0.05	1.86	5	0.30	0.37	NA			
105	slow	aspen	D	Pc	BKM-F-1767	C'	highN/highC - Rep 2	CC	14	5	A	14	4.33	25.10	5	2.69	3.34	0.19	5	0.05	0.06	1.65	5	0.24	0.30	NA			
106	slow	aspen	D	Pc	BKM-F-1767	D'	lowN/lowC - Rep 2	CC	15	5	A	28	12.58	25.60	5	1.71	2.12	0.24	5	0.04	0.05	1.85	5	0.15	0.18	NA			
107	slow	aspen	D	Pc	BKM-F-1767	D'	lowN/highC - Rep 2	CC	15	5	A	28	12.59	28.30	5	2.01	2.50	0.29	5	0.05	0.06	2.00	5	0.20	0.25	NA			
108	slow	aspen	D	Pc	BKM-F-1767	D'	highN/lowC - Rep 2	CC	15	5	A	28	20.30	24.20	5	1.50	1.86	0.22	5	0.04	0.04	1.91	5	0.24	0.29	NA			
109	slow	aspen	D	Pc	BKM-F-1767	D'	highN/highC - Rep 2	CC	15	5	A	28	19.29	21.30	5	1.95	2.42	0.20	5	0.05	0.06	1.97	5	0.21	0.26	NA			
110	slow	aspen	D	Cs	FP-90031-sp	E'	MCDM	CC	14	5	A	28	5.74	35.47	10	3.67	2.63	NA				1.45	10	0.18	0.13	NA			
111	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 5.1 mM N (YE)	CC	14	5	A	28	3.22	35.25	10	2.66	1.90	NA				1.60	10	0.42	0.30	NA			
112	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 15.3 mM N (YE)	CC	14	5	A	28	4.87	36.95	10	3.15	2.25	NA				1.59	10	0.23	0.16	NA			
113	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 45.9 mM N (YE)	CC	14	5	A	28	7.20	35.81	10	3.39	2.43	NA				1.53	10	0.31	0.22	NA			
115	slow	aspen	D	Pc	BKM-F-1767	F'	lowC - LowN inoculum	CC	15	5	A	14	4.18	30.73	5	1.50	1.87	0.30	5	0.03	0.04	1.69	5	0.28	0.35	NA			
116	slow	aspen	D	Pc	BKM-F-1767	F'	lowC - HighN inoculum	CC	15	5	A	14	6.42	32.10	5	2.13	2.64	0.31	5	0.04	0.05	1.72	5	0.15	0.18	NA			
117	slow	aspen	D	Pc	BKM-F-1767	F'	highC - LowN inoculum	CC	15	5	A	14	1.27	32.91	5	1.80	2.24	0.30	5	0.02	0.03	1.82	5	0.16	0.20	NA			
118	slow	aspen	D	Pc	BKM-F-1767	F'	highC - HighN inoculum	CC	15	5	A	14	8.69	31.97	5	1.51	1.88	0.31	5	0.05	0.06	1.70	5	0.22	0.27	NA			
119	slow	aspen	D	Pc	BKM-F-1767	G'	lowC - LowN inoculum	CC	15	5	A	28	4.78	32.05	5	0.80	0.99	0.31	5	0.02	0.02	1.80	5	0.11	0.13	NA			
120	slow	aspen	D	Pc	BKM-F-1767	G'	lowC - HighN inoculum	CC	15	5	A	28	14.35	33.29	5	3.55	4.41	0.32	5	0.06	0.07	1.82	5	0.27	0.34	NA			
121	slow	aspen	D	Pc	BKM-F-1767	G'	highC - LowN inoculum	CC	15	5	A	28	8.07	33.95	5	2.11	2.62	0.37	5	0.06	0.07	1.93	5	0.18	0.23	NA			
122	slow	aspen	D	Pc	BKM-F-1767	G'	highC - HighN inoculum	CC	15	5	A	28	16.09	30.95	5	1.73	2.15	0.29	5	0.06	0.07	1.79	5	0.25	0.30	NA			
123	slow	loblolly	A	Cs	L-14807	H'	strain comparison	CC	31	10	T	25	4.87	22.94	5	1.40	1.74	0.20	5	0.02	0.03	1.81	5	0.27	0.33	NA			
124	slow	loblolly	A	Cs	L-15225	H'	strain comparison	CC	31	10	T	25	6.12	22.61	5	0.99	1.23	0.20	5	0.02	0.02	1.69	5	0.27	0.33	NA			
125	slow	loblolly	A	Cs	FP-104027	H'	strain comparison	CC	31	10	T	25	3.42	24.68	5	1.53	1.90	0.23	5	0.03	0.03	1.98	5	0.23	0.29	NA			
126	slow	loblolly	A	Cs	FP-105752	H'	strain comparison	CC	31	10	T	25	7.26	22.47	5	1.56	1.94	0.20	5	0.04	0.04	1.95	5	0.28	0.35	NA			
127	slow	loblolly	A	Cs	FP-90031-sp	H'	strain comparison	CC	31	10	T	25	4.51	23.02	5	0.91	1.12	0.21	5	0.02	0.03	1.91	5	0.14	0.18	NA			
128	slow	aspen	E	Pc	BKM-F-1767	I'	frozen	CC	14	5	A	28	12.96	32.14	5	1.73	2.15	0.31	5	0.05	0.07	1.70	5	0.23	0.29	NA			
129	slow	aspen	E	Pc	BKM-F-1767	J'	fresh	CC	14	5	A	28	12.99	31.83	5	1.68	2.09	0.31	5	0.03	0.04	1.66	5	0.16	0.19	NA			

Table 1 B—Biopulping runs with control—on.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	bright-ness %	n	s.d.	.95 CI	opacity %	n	s.d.	.95 CI	scattering coefficient m^2/kg	n	s.d.	.95 CI	fiber length index mm	klason lignin %	Labra-tory
67	slow	loblolly	A	Pb	HHB-7030-sp	K,L,R	wood type, fungal species	CC	26	26	T	26	4.64	35.00	5	0.15	0.19	91.10	5			33.30	5			NA	26.27	FPL
68	slow	loblolly	A	Hs	FP-106976-sp	K,L,R	wood type, fungal species	CC	26	26	T	26	5.07	36.40	5	0.17	0.21	90.40	5			33.50	5			NA	27.87	FPL
73	slow	aspen	C	Pc	BKM-F-1767	S	aspen C vs D	CC	16	5	T	14	3.00	54.90	5	0.18	0.22	94.50	5			55.60	5			NA	NA	FPL
74	slow	aspen	D	Pc	BKM-F-1767	T	aspen C vs D	CC	16	5	T	14	3.40	54.40	5	0.22	0.27	94.40	5			55.00	5			NA	NA	FPL
75	slow	aspen	C	Pc	BKM-F-1767	S	aspen C vs D	CC	16	5	A	14	7.40	51.90	5	0.17	0.21	95.20	5			50.70	5			NA	NA	FPL
76	slow	aspen	D	Pc	BKM-F-1767	T	aspen C vs D	CC	16	5	A	14	4.40	53.50	5	0.15	0.19	94.20	5			53.70	5			NA	NA	FPL
78	slow	aspen	D	Cs	FP-90031-sp	U	fungal species	CC	30	10	T	28	3.50	50.20	5	0.28	0.35	92.10	5			43.80	5			NA	15.72	FPL
79	slow	loblolly	A	Cs	FP-90031-sp	V	wood type, fungal species	CC	30	10	RS	28	2.50	31.90	5	0.23	0.29	91.00	5			30.80	5			NA	25.63	FPL
80	slow	loblolly	A	Cs	FP-90031-sp	V	wood type, fungal species	CC	30	10	T	28	7.10	35.70	5	0.38	0.47	89.70	5			32.00	5			NA	25.31	FPL
81	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-0 mM N	CC	15	5	A	14	1.50	56.20	5	0.18	0.22	96.20	5			58.40	5			NA	NA	FPL
82	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-1.7 mM N	CC	15	5	A	14	2.50	55.60	5	0.28	0.35	94.40	5			56.70	5			NA	NA	FPL
83	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-5.1mM N	CC	15	5	A	14	7.20	53.90	5	0.17	0.21	94.40	5			54.10	5			NA	NA	FPL
84	slow	aspen	D	Pc	BKM-F-1767	W	Amm. Tart-15.3mM N	CC	15	5	A	14	9.20	53.20	5	0.20	0.25	94.50	5			53.50	5			NA	NA	FPL
85	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-0 mM N	CC	15	5	A	26	3.90	55.90	5	0.52	0.65	93.50	5			57.00	5			NA	NA	FPL
86	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-1.7 mM N	CC	15	5	A	26	8.20	54.60	5	0.16	0.20	93.60	5			52.10	5			NA	NA	FPL
87	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-5.1mM N	CC	15	5	A	26	7.30	53.70	5	0.32	0.40	94.80	5			54.10	5			NA	NA	FPL
88	slow	aspen	D	Pc	BKM-F-1767	X	Amm. Tart-15.3mM N	CC	15	5	A	26	13.80	51.30	5	0.43	0.53	93.10	5			50.10	5			NA	NA	FPL
89	slow	aspen	D	Pc	BKM-F-1767	No control	No MCDM YE/L 5.1mM N	CC	15	5	A	14	3.05	56.90	5	0.35	0.43	93.00	5			55.60	5			NA	NA	FPL
90	slow	aspen	D	Pc	BKM-F-1767	No control	No MCDM YE/L 15.3mM N	CC	15	5	A	14	4.94	53.90	5	0.32	0.40	93.50	5			50.70	5			NA	NA	FPL
91	slow	aspen	D	Pc	BKM-F-1767	Z	lowN/lowC -Rep1	CC	15	5	A	14	6.56	57.70	5	0.16	0.20	95.70	5	0.23	0.29	57.80	5	0.96	1.19	NA	18.78	WEY
92	slow	aspen	D	Pc	BKM-F-1767	Z	lowN/highC -Rep1	CC	15	5	A	14	10.56	57.60	5	0.27	0.34	96.20	5	0.53	0.66	56.90	5	2.75	3.41	NA	19.15	WEY
93	slow	aspen	D	Pc	BKM-F-1767	Z	highN/lowC -Rep1	CC	15	5	A	14	11.82	53.90	5	0.19	0.24	96.20	5	0.64	0.79	52.90	5	2.73	3.39	NA	17.36	WEY
94	slow	aspen	D	Pc	BKM-F-1767	Z	highN/highC -Rep1	CC	15	5	A	14	17.99	56.10	5	0.22	0.27	95.80	5	0.43	0.53	53.50	5	1.77	2.20	NA	18.02	WEY
95	slow	aspen	D	Pc	BKM-F-1767	A'	lowN/lowC -Rep1	CC	16	5	A	28	11.24	54.50	5	0.39	0.48	96.40	5	0.20	0.25	54.10	5	1.80	2.23	NA	18.83	WEY
96	slow	aspen	D	Pc	BKM-F-1767	A'	lowN/highC -Rep1	CC	16	5	A	28	11.27	54.00	5	0.24	0.30	96.00	5	0.49	0.61	51.70	5	1.94	2.41	NA	19.03	WEY
97	slow	aspen	D	Pc	BKM-F-1767	A'	highN/lowC -Rep1	CC	16	5	A	28	19.44	49.20	5	0.25	0.31	96.90	5	0.47	0.58	50.40	5	2.68	3.33	NA	18.40	WEY
98	slow	aspen	D	Pc	BKM-F-1767	A'	highN/highC -Rep1	CC	16	5	A	28	21.65	50.20	5	0.28	0.35	96.70	5	0.42	0.52	50.60	5	2.04	2.53	NA	18.85	WEY
100	slow	loblolly	A	Hs	FP-106976-sp	K,L,R,V	wood type, fungal species	CC	29	10	RS	28	5.60	NA				NA				NA				NA	26.70	FPL
101	slow	loblolly	A	Pb	HHB-7030-sp	K,L,R,V	wood type, fungal species	CC	29	10	RS	28	4.70	NA				NA				NA				NA	28.84	FPL
102	slow	aspen	D	Pc	BKM-F-1767	C'	lowN/lowC - Rep 2	CC	14	5	A	14	3.68	60.30	5	0.37	0.46	95.40	5	0.43	0.53	56.80	5	1.57	1.95	NA	18.24	WEY
103	slow	aspen	D	Pc	BKM-F-1767	C'	lowN/highC - Rep 2	CC	14	5	A	14	5.80	61.20	5	0.28	0.35	94.60	5	0.63	0.78	54.80	5	2.49	3.09	NA	20.12	WEY
104	slow	aspen	D	Pc	BKM-F-1767	C'	highN/lowC - Rep 2	CC	14	5	A	14	8.01	56.70	5	0.25	0.31	95.20	5	0.21	0.26	52.50	5	1.36	1.69	NA	17.34	WEY
105	slow	aspen	D	Pc	BKM-F-1767	C'	highN/highC - Rep 2	CC	14	5	A	14	4.33	57.50	5	0.18	0.22	95.70	5	0.37	0.46	55.10	5	1.54	1.91	NA	17.06	WEY
106	slow	aspen	D	Pc	BKM-F-1767	D'	lowN/lowC - Rep 2	CC	15	5	A	28	12.58	55.00	5	0.20	0.25	95.60	5	0.32	0.40	52.00	5	1.35	1.68	NA	17.01	WEY
107	slow	aspen	D	Pc	BKM-F-1767	D'	lowN/highC - Rep 2	CC	15	5	A	28	12.59	54.70	5	0.40	0.50	95.80	5	0.48	0.60	51.90	5	2.01	2.50	NA	18.84	WEY
108	slow	aspen	D	Pc	BKM-F-1767	D'	highN/lowC - Rep 2	CC	15	5	A	28	20.30	52.20	5	0.19	0.24	96.00	5	0.36	0.45	49.60	5	1.62	2.01	NA	19.12	WEY
109	slow	aspen	D	Pc	BKM-F-1767	D'	highN/highC - Rep 2	CC	15	5	A	28	19.29	52.90	5	0.16	0.20	96.60	5	0.51	0.63	52.00	5	2.42	3.00	NA	17.60	WEY
110	slow	aspen	D	Cs	FP-90031-sp	E'	MCDM	CC	14	5	A	28	5.74	53.90	5	0.30	0.37	NA				NA				NA	15.75	FPL
111	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 5.1 mM N (YE)	CC	14	5	A	28	3.22	54.81	5	0.33	0.41	NA				NA				NA	16.22	FPL
112	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 15.3 mM N (YE)	CC	14	5	A	28	4.87	51.60	5	0.36	0.45	NA				NA				NA	16.18	FPL
113	slow	aspen	D	Cs	FP-90031-sp	E'	No MCDM 45.9 mM N (YE)	CC	14	5	A	28	7.20	46.86	5	0.61	0.76	NA				NA				NA	16.25	FPL
115	slow	aspen	D	Pc	BKM-F-1767	F'	lowC - LowN inoculum	CC	15	5	A	14	4.18	58.16	5	0.27	0.34	96.18	5	0.22	0.27	60.12	5	1.54	1.91	NA	18.90	WEY
116	slow	aspen	D	Pc	BKM-F-1767	F'	lowC - HighN inoculum	CC	15	5	A	14	6.42	55.86	5	0.29	0.36	96.00	5	0.17	0.21	56.47	5	1.24	1.54	NA	18.11	WEY
117	slow	aspen	D	Pc	BKM-F-1767	F'	highC - LowN inoculum	CC	15	5	A	14	1.27	55.97	5	0.34	0.42	96.20	5	0.44	0.55	57.02	5	2.81	3.49	NA	18.78	WEY
118	slow	aspen	D	Pc	BKM-F-1767	F'	highC - HighN inoculum	CC	15	5	A	14	8.69	54.21	5	0.36	0.45	96.10	5	0.17	0.21	53.35	5	1.15	1.43	NA	19.59	WEY
119	slow	aspen	D	Pc	BKM-F-1767	G'	lowC - LowN inoculum	CC	15	5	A	28	4.78	54.05	5	0.40	0.50	96.72	5	0.25	0.31	55.57	5	1.61	2.00	NA	19.88	WEY
120	slow	aspen	D	Pc	BKM-F-1767	G'	lowC - HighN inoculum	CC	15	5	A	28	14.35	51.12	5	0.26	0.32	96.20	5	0.32	0.40	49.49	5	1.58	1.96	NA	16.98	WEY
121	slow	aspen	D	Pc	BKM-F-1767	G'	highC - LowN inoculum	CC	15	5	A	28	8.07	52.97	5	0.54	0.67	96.30	5	0.36	0.45	51.15	5	2.65	3.29	NA	18.09	WEY
122	slow	aspen	D	Pc	BKM-F-1767	G'	highC - HighN inoculum	CC	15	5	A	28	16.09	51.59	5	0.16	0.20	96.30	5	0.31	0.38	50.75	5	1.36	1.69	NA	16.74	WEY
123	slow	loblolly	A	Cs	L-14807	H'	strain comparison	CC	31	10	T	25	4.87	36.99	5	0.20	0.25	90.00	5	0.33	0.41	33.11	5	0.99	1.23	NA	26.10	WEY
124	slow	loblolly	A	Cs	L-15225	H'	strain comparison	CC	31	10	T	25	6.12	36.00	5	0.26	0.32	95.13	5	0.21	0.26	32.54	5	0.57	0.71	NA	26.44	WEY
125	slow	loblolly	A	Cs	FP-104027	H'	strain comparison	CC	31	10	T	25	3.42	36.16	5	0.30	0.37	95.69	5	0.16	0.20	33.91	5	0.36	0.45	NA	26.55	WEY
126	slow	loblolly	A	Cs	FP-105752	H'	strain comparison	CC	31	10	T	25	7.26	35.90	5	0.16	0.20	94.83	5	0.36	0.45	31.91	5	0.84	1.04	NA	26.53	WEY
127	slow	loblolly	A	Cs	FP-90031-sp	H'	strain comparison	CC	31	10	T	25	4.51	36.17	5	0.14	0.17	94.79	5	0.27	0.34	32.15	5	0.62	0.77	NA	26.27	WEY
128	slow	aspen	E	Pc	BKM-F-1767	I'	frozen	CC	14	5	A	28	12.96	50.57	5	0.14	0.17	96.39	5	0.61	0.76	50.37	5	2.97	3.69	NA	17.72	WEY
129	slow	aspen	E	Pc	BKM-F-1767	J'	fresh	CC	14	5	A	28	12.99	50.07	5	0.18	0.22	96.70	5	0.25	0.31	50.84	5	1.22	1.51	NA	18.06	WEY

Table 1 B—Biopulping runs with control—on.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	energy watt-hrs. per kg	density kg/m^3	n	s.d.	.95 CI	burst index kN/g	n	s.d.	.95 CI	tear index mN-m^2/g	n	s.d.	.95CI
				*1		*2	*3	*4			*5						*6	*7								
130	slow	aspen	E	Pc	BKM-F-1767	No control	room temp dried	CC	14	5	A	28	9.92	1655	437	8	6.67	5.58	1.28	10	0.16	0.11	2.20	10	0.18	0.13
131	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	20	5	A	13	NA	2037	489	8	15.73	13.15	1.35	10	0.16	0.11	2.17	10	0.18	0.13
132	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	35	5	A	13	NA	1984	472	8	11.69	9.77	1.28	10	0.10	0.07	2.25	10	0.25	0.18
133	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	60	5	A	13	NA	2044	467	8	8.75	7.32	1.28	10	0.10	0.07	2.14	10	0.26	0.19
134	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	20	5	A	27	NA	1700	NA				NA				NA			
135	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	35	5	A	27	NA	1772	NA				NA				NA			
136	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	60	5	A	27	NA	1780	NA				NA				NA			
137	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	47	5	RS	27	NA	2095	NA				NA				NA			
138	slow	aspen	E	Pc	BKM-F-1767	M'	aerat1.0 l/m for 1/2 hr/d	SPS	NA	NA	A	28	NA	1349	404	8	17.08	14.29	1.06	10	0.10	0.07	2.38	10	0.16	0.11
139	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.1 l/m	SPS	NA	NA	A	28	NA	1393	NA				NA				NA			
140	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.1 l/m	SPS	NA	NA	A	28	NA	1399	NA				NA				NA			
141	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 1.0 l/m	SPS	NA	NA	A	28	NA	1514	423	8	6.24	5.22	1.27	10	0.17	0.12	2.60	10	0.25	0.18
142	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.5 l/m	SPS	NA	NA	A	28	NA	1372	427	8	10.37	8.68	1.16	10	0.09	0.07	2.47	10	0.22	0.16
143	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	15	3.18	1870	445	8	9.01	7.54	1.00	10	0.15	0.11	1.86	10	0.18	0.13
144	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr	CC	15	5	A	15	3.46	1623	435	8	11.83	9.90	1.21	10	0.19	0.14	2.22	10	0.16	0.11
145	slow	aspen	E	Pc	BKM-F-1767	N'	aerat 4.4 cf/hr	CC	15	5	A	15	5.03	1676	449	8	9.06	7.58	1.16	10	0.26	0.18	2.22	10	0.23	0.16
146	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	15	3.20	1843	460	8	14.07	11.77	1.11	10	0.14	0.10	1.79	10	0.14	0.10
147	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr	CC	15	5	A	15	4.89	1735	448	8	3.22	2.69	1.20	10	0.11	0.08	2.08	10	0.34	0.24
148	slow	aspen	E	Pc	BKM-F-1767	N'	aerat 4.5 cf/hr	CC	15	5	A	15	1.70	1677	447	8	8.35	6.98	1.24	10	0.07	0.05	2.06	10	0.15	0.10
149	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	28	7.00	1910	442	8	4.18	3.50	1.24	10	0.17	0.12	2.00	10	0.12	0.09
150	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	28	5.40	1866	443	8	6.45	5.39	1.28	10	0.09	0.06	1.98	10	0.10	0.07
151	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr	CC	15	5	A	28	12.00	1778	430	8	4.89	4.09	1.26	10	0.09	0.07	2.04	10	0.12	0.09
152	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr	CC	15	5	A	28	11.40	1698	436	8	7.87	6.58	1.26	10	0.10	0.07	2.19	10	0.21	0.15
153	slow	aspen	E	Pc	BKM-F-1767	O'	aerat 4.3 cf/hr	CC	15	5	A	28	10.00	1792	444	8	13.17	11.01	1.36	10	0.12	0.09	2.24	10	0.23	0.17
154	slow	aspen	E	Pc	BKM-F-1767	O'	aerat 4.3 cf/hr	CC	15	5	A	28	10.00	1663	436	8	6.47	5.41	1.30	10	0.09	0.06	2.30	10	0.17	0.12
155	slow	aspen	E	Cs	FP-90031-sp	P'	fungal species	CC	28	10	A	28	6.09	1303	378	8	8.79	7.35	1.23	10	0.08	0.06	3.62	10	0.30	0.22
157	slow	aspen	E	Cs	FP-90031-sp	P'	reactor type	CC	28	10	T	28	NA	1693	398	8	5.99	5.01	1.18	10	0.08	0.06	2.77	10	0.19	0.13
158	slow	loblolly	A	Cs	FP-90031-sp	Q'	old loblolly	CC	74	10	A	28	NA	1198	341	8	4.23	3.54	0.91	10	0.11	0.08	2.70	10	0.33	0.23
165	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	14	5	A	28	11.25	1826	404	8	6.40	5.35	1.07	10	0.08	0.05	2.66	10	0.18	0.13
166	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	14	5	A	28	8.86	1762	398	8	6.92	5.79	1.03	10	0.08	0.06	2.65	10	0.19	0.13
167	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	28	5	A	28	9.14	1763	403	8	4.70	3.93	1.03	10	0.07	0.05	2.49	10	0.16	0.12
168	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	28	5	A	28	9.09	1809	409	8	7.78	6.50	1.05	10	0.07	0.05	2.44	10	0.14	0.10
169	fast	aspen	E	Cs	FP-90031-sp	T'(fast)	refining sequence	CC	28	10	T	28	2.80	1104	396	8	8.17	6.83	1.44	10	0.10	0.07	3.09	10	0.24	0.17
169	slow	aspen	E	Cs	FP-90031-sp	T'(slow)	refining sequence	CC	28	10	T	28	2.80	1207	380	8	10.84	9.07	1.23	10	0.15	0.11	3.62	10	0.49	0.35
170	fast	aspen	E	Pc	BKM-F-1767	U'(fast)	refining sequence	CC	30	5	A	31	NA	1669	415	8	6.34	5.30	1.16	10	0.07	0.05	2.18	10	0.13	0.09
170	slow	aspen	E	Pc	BKM-F-1767	U'(slow)	refining sequence	CC	30	5	A	31	NA	1768	385	8	4.60	3.85	0.98	10	0.09	0.07	2.53	10	0.14	0.10
171	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	42	5	A	28	6.12	1959	397	8	14.21	11.88	0.92	10	0.08	0.05	2.28	10	0.17	0.12
172	slow	aspen	E	Cs	FP-90031-sp	W'	fungal species	CC	29	10	A	29	6.00	1117	367	8	5.49	4.59	1.14	10	0.12	0.09	3.55	10	0.32	0.23
177	fast	aspen	E	Cs	FP-90031-sp	Y' fast	FP90031sp	CC	29	10	A	29	6.00	1243	377	8	7.18	6.00	1.18	10	0.11	0.08	3.42	10	0.31	0.22
177	slow	aspen	E	Cs	FP-90031-sp	Y' slow	FP90031sp	CC	32	10	A	30	4.64	1402	380	8	8.64	7.23	1.22	10	0.10	0.07	3.51	10	0.35	0.25
178	fast	aspen	E	Cs	FP-90031-sp	Y' fast	FP90031sp	CC	32	10	A	30	4.64	1202	371	8	9.00	7.53	1.17	10	0.10	0.07	3.50	10	0.27	0.20
178	slow	aspen	E	Cs	FP-90031-sp	Y' slow	FP90031sp	CC	32	10	A	30	3.50	1256	372	8	8.02	6.71	1.16	10	0.14	0.10	3.72	10	0.47	0.34
179	fast	aspen	E	Cs	L-6133	Y' fast	L6133	CC	32	10	A	30	3.50	1078	387	8	7.80	6.52	1.30	10	0.10	0.07	3.59	10	0.35	0.25
179	slow	aspen	E	Cs	L-6133	Y' slow	L6133	CC	32	10	A	30	6.56	1247	392	8	7.95	6.65	1.25	10	0.09	0.07	3.88	10	0.27	0.20
180	fast	aspen	E	Cs	L-6133	Y' fast	L6133	CC	32	10	A	30	6.56	1163	375	8	6.80	5.69	1.16	10	0.11	0.08	3.40	10	0.32	0.23
180	slow	aspen	E	Cs	L-6133	Y' slow	L6133	CC	32	10	A	30	8.05	1289	383	8	11.25	9.41	1.15	10	0.08	0.06	3.63	10	0.40	0.28
181	fast	aspen	E	Cs	CZ-3	Y ' fast	CZ-3	CC	32	10	A	30	8.05	1113	382	8	8.12	6.79	1.31	10	0.09	0.06	3.95	10	0.38	0.27
181	slow	aspen	E	Cs	CZ-3	Y' slow	CZ-3	CC	32	10	A	30	5.93	1183	375	8	7.29	6.10	1.30	10	0.10	0.07	4.09	10	0.50	0.36
182	fast	aspen	E	Cs	CZ-3	Y' fast	CZ-3	CC	32	10	A	30	5.93	1039	387	8	10.75	8.99	1.38	10	0.12	0.09	3.85	10	0.31	0.22
182	slow	aspen	E	Cs	CZ-3	Y' slow	CZ-3	CC	32	10	A	30	9.88	1082	389	8	10.81	9.04	1.36	10	0.15	0.10	4.14	10	0.43	0.31
183	fast	aspen	E	Pc	BKM-F-1767	Z'-1	No MCDM, No AC - high N inoc	CC	27	5	A	28	11.15	1615	366	8	6.93	5.79	0.85	10	0.06	0.05	2.37	10	0.28	0.20
184	fast	aspen	E	Pc	BKM-F-1767	Z'-3	MCDM, No AC - high N inoc	CC	27	5	A	28	12.41	1461	380	8	4.07	3.40	0.96	10	0.04	0.03	2.52	10	0.22	0.16
189	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc-shaken	CC	27	10	A	31	3.55	1016	382	8	5.03	4.20	1.37	10	0.09	0.07	4.07	10	0.44	0.31
190	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc-shaken	CC	27	10	A	31	4.22	1106	384	8	6.03	5.04	1.28	10	0.14	0.10	4.06	10	0.35	0.25
191	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc- not shaken	CC	27	10	A	31	6.09	1035	380	8	6.90	5.77	1.31	10	0.10	0.07	3.94	10	0.41	0.29

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	tensile index Nm/g	n	s.d.	.95CI	TEA index J/g	n	s.d.	.95 CI	elong-ation %	n	s.d.	.95 CI	zero span tensile Nm/g	n	s.d.	.95 CI
130	slow	aspen	E	Pc	BKM-F-1767	No control	room temp dried	CC	14	5	A	28	9.92	32.50	5	2.58	3.20	0.32	5	0.05	0.07	1.75	5	0.24	0.29	NA			
131	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	20	5	A	13	NA	33.46	5	3.81	4.73	0.33	5	0.10	0.12	1.68	5	0.26	0.32	NA			
132	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	35	5	A	13	NA	30.71	5	1.63	2.02	0.26	5	0.04	0.04	1.59	5	0.24	0.30	NA			
133	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	60	5	A	13	NA	32.46	5	1.59	1.98	0.32	5	0.04	0.05	1.72	5	0.22	0.27	NA			
134	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	20	5	A	27	NA	NA				NA				NA				NA			
135	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	35	5	A	27	NA	NA				NA				NA				NA			
136	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	60	5	A	27	NA	NA				NA				NA				NA			
137	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	47	5	RS	27	NA	NA				NA				NA				NA			
138	slow	aspen	E	Pc	BKM-F-1767	M'	aerat1.0 l/m for 1/2 hr/d	SPS	NA	NA	A	28	NA	27.71	5	2.86	3.55	0.24	5	0.04	0.05	1.32	5	0.18	0.23	NA			
139	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.1 l/m	SPS	NA	NA	A	28	NA	NA				NA				NA				NA			
140	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.1 l/m	SPS	NA	NA	A	28	NA	NA				NA				NA				NA			
141	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 1.0 l/m	SPS	NA	NA	A	28	NA	30.14	5	2.40	2.98	0.29	5	0.05	0.06	1.41	5	0.21	0.27	NA			
142	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.5 l/m	SPS	NA	NA	A	28	NA	28.42	5	1.99	2.47	0.24	5	0.05	0.06	1.27	5	0.17	0.21	NA			
143	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	15	3.18	27.23	5	1.94	2.40	0.27	5	0.03	0.04	2.05	5	0.24	0.30	NA			
144	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr	CC	15	5	A	15	3.46	29.57	5	2.34	2.91	0.29	5	0.06	0.07	2.08	5	0.28	0.35	NA			
145	slow	aspen	E	Pc	BKM-F-1767	N'	aerat 4.4 cf/hr	CC	15	5	A	15	5.03	30.17	5	3.95	4.90	0.29	5	0.07	0.08	2.05	5	0.29	0.36	NA			
146	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	15	3.20	28.09	5	4.69	5.83	0.26	5	0.09	0.11	2.01	5	0.40	0.49	NA			
147	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr	CC	15	5	A	15	4.89	30.28	5	2.94	3.65	0.30	5	0.06	0.07	2.05	5	0.18	0.22	NA			
148	slow	aspen	E	Pc	BKM-F-1767	N'	aerat 4.5 cf/hr	CC	15	5	A	15	1.70	30.54	5	1.45	1.80	0.30	5	0.07	0.08	2.08	5	0.51	0.63	NA			
149	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	28	7.00	32.25	5	1.71	2.13	0.32	5	0.04	0.05	1.45	5	0.12	0.15	NA			
150	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	28	5.40	31.71	5	2.96	3.68	0.30	5	0.05	0.06	1.43	5	0.14	0.17	NA			
151	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr	CC	15	5	A	28	12.00	32.13	5	2.50	3.10	0.31	5	0.04	0.05	1.42	5	0.09	0.11	NA			
152	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr	CC	15	5	A	28	11.40	31.77	5	1.68	2.09	0.31	5	0.03	0.03	1.45	5	0.08	0.09	NA			
153	slow	aspen	E	Pc	BKM-F-1767	O'	aerat 4.3 cf/hr	CC	15	5	A	28	10.00	33.03	5	2.24	2.78	0.33	5	0.03	0.04	1.48	5	0.10	0.12	NA			
154	slow	aspen	E	Pc	BKM-F-1767	O'	aerat 4.3 cf/hr	CC	15	5	A	28	10.00	31.47	5	2.86	3.55	0.29	5	0.05	0.06	1.38	5	0.14	0.17	NA			
155	slow	aspen	E	Cs	FP-90031-sp	P'	fungal species	CC	28	10	A	28	6.09	30.38	5	2.87	3.56	0.27	5	0.05	0.06	1.34	5	0.15	0.19	NA			
157	slow	aspen	E	Cs	FP-90031-sp	P'	reactor type	CC	28	10	T	28	NA	27.58	5	1.43	1.77	0.24	5	0.04	0.05	1.35	5	0.17	0.21	NA			
158	slow	loblolly	A	Cs	FP-90031-sp	Q'	old loblolly	CC	74	10	A	28	NA	23.99	5	1.91	2.37	0.23	5	0.02	0.03	1.49	5	0.42	0.52	NA			
165	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	14	5	A	28	11.25	27.49	5	2.20	2.73	0.24	5	0.06	0.07	1.31	5	0.22	0.28	NA			
166	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	14	5	A	28	8.86	27.76	5	1.42	1.77	0.26	5	0.05	0.06	1.36	5	0.14	0.18	NA			
167	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	28	5	A	28	9.14	28.09	5	1.41	1.75	0.25	5	0.03	0.03	1.35	5	0.09	0.11	NA			
168	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	28	5	A	28	9.09	28.09	5	1.40	1.74	0.25	5	0.02	0.02	1.35	5	0.06	0.08	NA			
169	fast	aspen	E	Cs	FP-90031-sp	T'(fast)	refining sequence	CC	28	10	T	28	2.80	33.03	5	3.00	3.73	0.31	5	0.08	0.09	1.42	5	0.21	0.26	NA			
169	slow	aspen	E	Cs	FP-90031-sp	T'(slow)	refining sequence	CC	28	10	T	28	2.80	30.98	5	1.84	2.28	0.30	5	0.03	0.04	1.45	5	0.11	0.14	NA			
170	fast	aspen	E	Pc	BKM-F-1767	U'(fast)	refining sequence	CC	30	5	A	31	NA	29.08	5	3.06	3.79	0.27	5	0.07	0.09	1.39	5	0.17	0.21	NA			
170	slow	aspen	E	Pc	BKM-F-1767	U'(slow)	refining sequence	CC	30	5	A	31	NA	27.04	5	2.07	2.57	0.25	5	0.04	0.05	1.35	5	0.13	0.16	NA			
171	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	42	5	A	28	6.12	25.07	5	1.24	1.54	0.22	5	0.04	0.04	1.30	5	0.14	0.18	NA			
172	slow	aspen	E	Cs	FP-90031-sp	W'	fungal species	CC	29	10	A	29	6.00	29.56	5	2.02	2.51	0.25	5	0.03	0.04	1.30	5	0.14	0.18	NA			
177	fast	aspen	E	Cs	FP-90031-sp	Y' fast	FP90031sp	CC	29	10	A	29	6.00	30.45	5	1.78	2.21	0.29	5	0.03	0.04	1.41	5	0.10	0.12	NA			
177	slow	aspen	E	Cs	FP-90031-sp	Y' slow	FP90031sp	CC	32	10	A	30	4.64	30.77	5	1.23	1.53	0.29	5	0.03	0.03	1.42	5	0.07	0.09	NA			
178	fast	aspen	E	Cs	FP-90031-sp	Y' fast	FP90031sp	CC	32	10	A	30	4.64	29.61	5	2.73	3.39	0.26	5	0.05	0.06	1.33	5	0.19	0.24	NA			
178	slow	aspen	E	Cs	FP-90031-sp	Y' slow	FP90031sp	CC	32	10	A	30	3.50	29.53	5	1.00	1.24	0.27	5	0.02	0.03	1.39	5	0.08	0.10	NA			
179	fast	aspen	E	Cs	L-6133	Y' fast	L6133	CC	32	10	A	30	3.50	31.66	5	2.28	2.83	0.29	5	0.04	0.05	1.39	5	0.13	0.16	NA			
179	slow	aspen	E	Cs	L-6133	Y' slow	L6133	CC	32	10	A	30	6.56	31.40	5	1.16	1.44	0.31	5	0.03	0.04	1.46	5	0.09	0.12	NA			
180	fast	aspen	E	Cs	L-6133	Y' fast	L6133	CC	32	10	A	30	6.56	30.74	5	1.26	1.56	0.30	5	0.03	0.04	1.46	5	0.10	0.12	NA			
180	slow	aspen	E	Cs	L-6133	Y' slow	L6133	CC	32	10	A	30	8.05	29.69	5	1.39	1.73	0.28	5	0.03	0.04	1.41	5	0.12	0.15	NA			
181	fast	aspen	E	Cs	CZ-3	Y ' fast	CZ-3	CC	32	10	A	30	8.05	33.46	5	1.51	1.87	0.32	5	0.02	0.02	1.45	5	0.08	0.10	NA			
181	slow	aspen	E	Cs	CZ-3	Y' slow	CZ-3	CC	32	10	A	30	5.93	30.57	5	1.86	2.31	0.26	5	0.05	0.07	1.29	5	0.17	0.21	NA			
182	fast	aspen	E	Cs	CZ-3	Y' fast	CZ-3	CC	32	10	A	30	5.93	34.71	5	2.81	3.49	0.34	5	0.04	0.05	1.50	5	0.10	0.13	NA			
182	slow	aspen	E	Cs	CZ-3	Y' slow	CZ-3	CC	32	10	A	30	9.88	31.89	5	1.42	1.76	0.29	5	0.04	0.05	1.35	5	0.12	0.14	NA			
183	fast	aspen	E	Pc	BKM-F-1767	Z'-1	No MCDM, No AC - high N inoc	CC	27	5	A	28	11.15	23.57	5	0.92	1.14	0.19	5	0.03	0.03	1.18	5	0.14	0.17	NA			
184	fast	aspen	E	Pc	BKM-F-1767	Z'-3	MCDM, No AC - high N inoc	CC	27	5	A	28	12.41	25.65	5	1.35	1.67	0.21	5	0.03	0.04	1.22	5	0.11	0.14	NA			
189	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc-shaken	CC	27	10	A	31	3.55	31.92	5	1.93	2.40	0.29	5	0.04	0.05	1.37	5	0.17	0.21	NA			
190	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc-shaken	CC	27	10	A	31	4.22	33.01	5	1.21	1.50	0.33	5	0.03	0.04	1.49	5	0.09	0.11	NA			
191	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc- not shaken	CC	27	10	A	31	6.09	32.18	5	2.44	3.03	0.31	5	0.06	0.08	1.47	5	0.15	0.18	NA			

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	bright-ness %	n	s.d.	.95 CI	opacity %	n	s.d.	.95 CI	scattering coefficient m^2/kg	n	s.d.	.95 CI	fiber length index mm	klason lignin %	Labra-tory
130	slow	aspen	E	Pc	BKM-F-1767	No control	room temp dried	CC	14	5	A	28	9.92	50.49	5	0.19	0.24	97.00	5	0.22	0.27	52.28	5	1.66	2.06	NA	17.60	WEY
131	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	20	5	A	13	NA	54.16	5	0.22	0.27	96.70	5	0.47	0.58	56.34	5	3.19	3.96	NA	NA	WEY
132	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	35	5	A	13	NA	55.22	5	0.13	0.16	96.60	5	0.35	0.43	56.88	5	2.08	2.58	NA	NA	WEY
133	slow	aspen	D	Pc	BKM-F-1767	K'	inoculum age	CC	60	5	A	13	NA	56.75	5	0.18	0.22	96.40	5	0.27	0.34	57.53	5	1.90	2.36	NA	NA	WEY
134	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	20	5	A	27	NA	NA				NA				NA				NA	NA	FPL
135	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	35	5	A	27	NA	NA				NA				NA				NA	NA	FPL
136	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	60	5	A	27	NA	NA				NA				NA				NA	NA	FPL
137	slow	aspen	D	Pc	BKM-F-1767	L'	inoculum age	CC	47	5	RS	27	NA	NA				NA				NA				NA	NA	FPL
138	slow	aspen	E	Pc	BKM-F-1767	M'	aerat1.0 l/m for 1/2 hr/d	SPS	NA	NA	A	28	NA	49.42	5	0.39	0.48	97.00	5	0.34	0.42	49.00	5	2.06	2.56	NA	16.49	WEY
139	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.1 l/m	SPS	NA	NA	A	28	NA	NA				NA				NA				NA	17.25	FPL
140	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.1 l/m	SPS	NA	NA	A	28	NA	NA				NA				NA				NA	21.90	FPL
141	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 1.0 l/m	SPS	NA	NA	A	28	NA	50.00	5	0.24	0.30	96.87	5	0.22	0.27	50.47	5	1.20	1.49	NA	17.07	WEY
142	slow	aspen	E	Pc	BKM-F-1767	M'	aerat 0.5 l/m	SPS	NA	NA	A	28	NA	49.76	5	0.47	0.58	97.13	5	0.34	0.42	50.19	5	1.94	2.41	NA	18.71	WEY
143	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	15	3.18	52.80	5	0.42	0.52	97.20	5	0.25	0.31	58.00	5	2.16	2.68	NA	NA	WEY
144	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr	CC	15	5	A	15	3.46	53.00	5	0.36	0.45	96.60	5	0.31	0.38	53.90	5	2.38	2.95	NA	NA	WEY
145	slow	aspen	E	Pc	BKM-F-1767	N'	aerat 4.4 cf/hr	CC	15	5	A	15	5.03	53.30	5	0.34	0.42	96.30	5	0.40	0.50	53.70	5	1.77	2.20	NA	NA	WEY
146	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	15	3.20	52.10	5	0.38	0.47	97.40	5	0.40	0.50	57.70	5	3.54	4.39	NA	NA	WEY
147	slow	aspen	E	Pc	BKM-F-1767	N'	aerat1 cf/hr	CC	15	5	A	15	4.89	51.30	5	0.24	0.30	97.40	5	0.17	0.21	56.50	5	0.88	1.09	NA	NA	WEY
148	slow	aspen	E	Pc	BKM-F-1767	N'	aerat 4.5 cf/hr	CC	15	5	A	15	1.70	52.40	5	0.26	0.32	97.10	5	0.22	0.27	55.00	5	1.45	1.80	NA	NA	WEY
149	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	28	7.00	52.15	5	0.42	0.52	96.86	5	0.32	0.40	55.37	5	2.48	3.08	NA	NA	WEY
150	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr for 1 hr/d	CC	15	5	A	28	5.40	52.83	5	0.21	0.26	96.64	5	0.14	0.17	55.24	5	0.70	0.87	NA	NA	WEY
151	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr	CC	15	5	A	28	12.00	52.29	5	0.21	0.26	96.60	5	0.33	0.41	53.69	5	1.85	2.30	NA	NA	WEY
152	slow	aspen	E	Pc	BKM-F-1767	O'	aerat1 cf/hr	CC	15	5	A	28	11.40	52.14	5	0.21	0.26	96.46	5	0.35	0.43	52.87	5	2.19	2.72	NA	NA	WEY
153	slow	aspen	E	Pc	BKM-F-1767	O'	aerat 4.3 cf/hr	CC	15	5	A	28	10.00	50.74	5	0.24	0.30	96.28	5	0.46	0.57	50.92	5	2.60	3.23	NA	NA	WEY
154	slow	aspen	E	Pc	BKM-F-1767	O'	aerat 4.3 cf/hr	CC	15	5	A	28	10.00	51.91	5	0.34	0.42	96.17	5	0.27	0.34	51.02	5	1.82	2.26	NA	NA	WEY
155	slow	aspen	E	Cs	FP-90031-sp	P'	fungal species	CC	28	10	A	28	6.09	49.91	5	0.14	0.17	94.60	5	0.33	0.41	42.65	5	1.03	1.28	NA	NA	WEY
157	slow	aspen	E	Cs	FP-90031-sp	P'	reactor type	CC	28	10	T	28	NA	51.86	5	0.14	0.17	95.76	5	0.35	0.43	49.04	5	1.31	1.63	NA	NA	WEY
158	slow	loblolly	A	Cs	FP-90031-sp	Q'	old loblolly	CC	74	10	A	28	NA	32.49	5	0.53	0.66	96.67	5	0.54	0.67	32.53	5	1.11	1.38	NA	NA	WEY
165	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	14	5	A	28	11.25	54.32	5	0.09	0.11	95.72	5	0.21	0.26	51.10	5	1.02	1.27	NA	NA	WEY
166	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	14	5	A	28	8.86	53.31	5	0.25	0.31	96.09	5	0.22	0.27	51.99	5	1.11	1.38	NA	NA	WEY
167	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	28	5	A	28	9.14	54.32	5	0.22	0.27	96.03	5	0.23	0.29	53.52	5	0.89	1.10	NA	NA	WEY
168	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	28	5	A	28	9.09	53.30	5	0.47	0.58	96.18	5	0.29	0.36	52.45	5	1.43	1.78	NA	NA	WEY
169	fast	aspen	E	Cs	FP-90031-sp	T'(fast)	refining sequence	CC	28	10	T	28	2.80	49.26	5	0.25	0.31	95.00	5	0.44	0.55	42.72	5	1.23	1.53	NA	NA	WEY
169	slow	aspen	E	Cs	FP-90031-sp	T'(slow)	refining sequence	CC	28	10	T	28	2.80	48.93	5	0.21	0.26	95.45	5	0.43	0.53	42.36	5	1.20	1.49	NA	NA	WEY
170	fast	aspen	E	Pc	BKM-F-1767	U'(fast)	refining sequence	CC	30	5	A	31	NA	53.58	5	0.21	0.26	96.52	5	0.23	0.29	54.37	5	0.91	1.13	NA	NA	WEY
170	slow	aspen	E	Pc	BKM-F-1767	U'(slow)	refining sequence	CC	30	5	A	31	NA	53.41	5	0.18	0.22	95.81	5	0.16	0.20	50.76	5	0.64	0.79	NA	NA	WEY
171	slow	aspen	E	Pc	BKM-F-1767	S'	inoculum age	CC	42	5	A	28	6.12	54.02	5	0.20	0.25	96.50	5	0.14	0.17	54.69	5	0.75	0.93	NA	NA	WEY
172	slow	aspen	E	Cs	FP-90031-sp	W'	fungal species	CC	29	10	A	29	6.00	50.42	5	0.12	0.15	95.02	5	0.59	0.73	43.15	5	1.40	1.74	NA	15.04	WEY
177	fast	aspen	E	Cs	FP-90031-sp	Y' fast	FP90031sp	CC	29	10	A	29	6.00	52.21	5	0.16	0.20	94.44	5	0.45	0.56	44.24	5	1.31	1.63	NA	NA	WEY
177	slow	aspen	E	Cs	FP-90031-sp	Y' slow	FP90031sp	CC	32	10	A	30	4.64	50.99	5	0.20	0.25	94.59	5	0.41	0.51	42.98	5	0.99	1.23	NA	15.98	WEY
178	fast	aspen	E	Cs	FP-90031-sp	Y' fast	FP90031sp	CC	32	10	A	30	4.64	51.53	5	0.14	0.17	94.39	5	0.40	0.50	43.54	5	1.51	1.87	NA	NA	WEY
178	slow	aspen	E	Cs	FP-90031-sp	Y' slow	FP90031sp	CC	32	10	A	30	3.50	50.37	5	0.25	0.31	94.37	5	0.31	0.38	41.96	5	0.86	1.07	NA	16.01	WEY
179	fast	aspen	E	Cs	L-6133	Y' fast	L6133	CC	32	10	A	30	3.50	49.57	5	0.32	0.40	94.80	5	0.53	0.66	43.11	5	1.61	2.00	NA	NA	WEY
179	slow	aspen	E	Cs	L-6133	Y' slow	L6133	CC	32	10	A	30	6.56	48.88	5	0.20	0.24	95.31	5	0.31	0.38	42.28	5	1.08	1.34	NA	15.94	WEY
180	fast	aspen	E	Cs	L-6133	Y' fast	L6133	CC	32	10	A	30	6.56	50.41	5	0.22	0.27	95.07	5	0.29	0.35	44.22	5	1.13	1.40	NA	NA	WEY
180	slow	aspen	E	Cs	L-6133	Y' slow	L6133	CC	32	10	A	30	8.05	49.51	5	0.14	0.18	94.91	5	0.40	0.50	42.72	5	1.25	1.55	NA	16.00	WEY
181	fast	aspen	E	Cs	CZ-3	Y ' fast	CZ-3	CC	32	10	A	30	8.05	50.05	5	0.34	0.42	94.37	5	0.49	0.61	42.19	5	1.31	1.63	NA	NA	WEY
181	slow	aspen	E	Cs	CZ-3	Y' slow	CZ-3	CC	32	10	A	30	5.93	48.84	5	0.06	0.08	94.46	5	0.65	0.81	40.16	5	1.58	1.96	NA	17.00	WEY
182	fast	aspen	E	Cs	CZ-3	Y' fast	CZ-3	CC	32	10	A	30	5.93	49.05	5	0.56	0.70	94.50	5	0.40	0.50	41.68	5	1.13	1.40	NA	NA	WEY
182	slow	aspen	E	Cs	CZ-3	Y' slow	CZ-3	CC	32	10	A	30	9.88	48.66	5	0.42	0.52	94.61	5	0.71	0.88	40.40	5	1.72	2.14	NA	14.66	WEY
183	fast	aspen	E	Pc	BKM-F-1767	Z'-1	No MCDM, No AC - high N inoc	CC	27	5	A	28	11.15	56.73	5	0.25	0.31	94.83	5	0.17	0.21	51.50	5	0.71	0.88	NA	18.11	WEY
184	fast	aspen	E	Pc	BKM-F-1767	Z'-3	MCDM, No AC - high N inoc	CC	27	5	A	28	12.41	54.40	5	0.18	0.22	94.96	5	0.13	0.16	49.65	5	0.58	0.72	NA	18.48	WEY
189	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc-shaken	CC	27	10	A	31	3.55	48.43	5	0.33	0.41	94.46	5	0.41	0.51	40.31	5	1.31	1.63	NA	NA	WEY
190	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc-shaken	CC	27	10	A	31	4.22	49.75	5	0.08	0.10	93.84	5	0.34	0.42	40.17	5	0.82	1.02	NA	NA	WEY
191	fast	aspen	E	Cs	FP90031-sp	AA	precolonized inoc- not shaken	CC	27	10	A	31	6.09	49.43	5	0.14	0.17	94.22	5	0.32	0.40	40.80	5	0.77	0.96	NA	NA	WEY

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	energy watt-hrs. per kg	density kg/m^3	n	s.d.	.95 CI	burst index kN/g	n	s.d.	.95 CI	tear index mN-m^2/g	n	s.d.	.95CI
				*1		*2	*3	*4			*5						*6	*7								
192	fast	aspen	E	Cs	FP90031-sp	AA	mycelial suspension	MS	6	0.1	A	31	4.43	1293	392	8	3.91	3.27	1.21	10	0.09	0.06	3.26	10	0.30	0.21
193	fast	aspen	E	Cs	FP90031-sp	AA	mycelial suspension	MS	6	0.1	A	31	6.40	1203	379	8	6.43	5.38	1.21	10	0.12	0.09	3.58	10	0.34	0.24
194	fast	aspen	E	Cs	FP90031-sp	BB	MCDM AC'd on chips	CC	39	10	A	28	6.97	1215	366	8	6.27	5.24	1.03	10	0.10	0.07	3.23	10	0.24	0.17
195	fast	aspen	E	Cs	FP90031-sp	BB	MCDM AC'd on chips	CC	39	10	A	28	3.38	1127	366	8	10.30	8.61	1.13	10	0.12	0.08	3.54	10	0.31	0.22
196	fast	aspen	E	Cs	FP90031-sp	CC	Filtered MCDM	CC	39	10	A	28	4.04	1178	368	8	5.06	4.23	1.12	10	0.09	0.07	3.39	10	0.24	0.17
197	fast	aspen	E	Cs	FP90031-sp	CC	Filtered MCDM	CC	39	10	A	28	5.38	1184	374	8	9.61	8.04	1.13	10	0.09	0.06	3.38	10	0.24	0.17
198	fast	aspen	E	Cs	FP90031-sp	DD	No MCDM, AC'd	CC	39	10	A	28	2.06	1686	383	8	4.27	3.57	0.98	10	0.06	0.04	2.43	10	0.16	0.11
199	fast	aspen	E	Pc	BKM-F-1767	EE	MCDM, No AC	SPS	NA	*8	A	31	4.50	1739	387	8	4.66	3.90	0.92	10	0.07	0.05	2.53	10	0.19	0.13
200	fast	aspen	E	Pc	BKM-F-1767	FF	No MCDM, No AC	SPS	NA	*8	A	31	11.00	1483	365	8	5.50	4.60	0.83	10	0.06	0.05	2.36	10	0.15	0.11
201	fast	aspen	E	Pc	BKM-F-1767	GG	MCDM, AC	SPS	NA	*8	A	31	2.50	1716	400	8	4.21	3.52	1.03	10	0.05	0.04	2.45	10	0.19	0.13
202	fast	aspen	E	Pc	BKM-F-1767	GG	No MCDM, AC	SPS	NA	*8	A	31	2.00	1682	391	8	5.95	4.98	1.04	10	0.05	0.04	2.71	10	0.17	0.12
219	fast	aspen	F	Cs	CZ-3	OO	Chip source & size	MS	17	0.14	A	29	NA	1074	400	8	6.62	5.54	1.54	10	0.13	0.09	3.93	10	0.41	0.29
220	fast	aspen	E	Cs	CZ-3	QQ	Chip source & size	MS	17	0.14	A	29	NA	1008	390	8	8.29	6.94	1.41	10	0.14	0.10	3.78	10	0.43	0.31
A	slow	white birch	A			1	No chip treatment				NR			NA	402	10	11.01	7.88	0.25	3	0.05	0.04	0.84	5	0.04	0.05
B	slow	aspen	A			2,3-7					NR			NA	395	10	8.10	5.79	0.44	10	0.05	0.04	1.94	5	0.14	0.17
C	slow	aspen	A			2,3-7	No chip treatment				NR			NA	395	10	13.80	9.87	0.36	10	0.07	0.05	1.69	5	0.13	0.16
D	slow	aspen	B			9-27,28	AC				NR			NA	400	10	20.79	14.87	0.80	9	0.09	0.07	2.81	5	0.21	0.27
E	slow	aspen	B			9-27,28	No chip treatment				NR			NA	427	10	10.53	7.53	1.00	9	0.08	0.06	2.68	5	0.16	0.20
F	slow	aspen	B			9-27,28	No chip treatment				NR			NA	426	10	18.96	13.56	1.09	10	0.11	0.08	2.77	5	0.15	0.19
H	slow	white spruce	A			27	CDM, AC				NR			NA	408	10	18.33	13.11	1.37	10	0.15	0.11	3.29	5	0.22	0.28
I	slow	aspen	C			30-35,41,54-56	MCDM, AC				NR			NA	425	10	17.90	12.81	0.88	10	0.08	0.06	2.35	5	0.16	0.19
J	slow	Aspen	C			30-35,41,54-56	MCDM, AC				NR			2746	420	10	20.60	14.74	0.92	10	0.10	0.07	2.03	5	0.14	0.18
						58,67,68,100,101																				
K	slow	loblolly	A			36-40,42,53,57,58	MCDM, AC				NR			2052	369	10	11.96	8.56	0.71	10	0.08	0.06	2.66	5	0.15	0.19
						58,67,68,100,101																				
L	slow	loblolly	A			36-40,42,53,57,58	MCDM, AC				NR			2404	356	10	12.77	9.14	0.58	9	0.07	0.06	2.74	5	0.14	0.18
						58,67,68,100,101																				
M	slow	aspen	C			30-35,41,54-56					NR			NA	389	10	29.48	21.09	0.65	10	0.07	0.05	2.14	5	0.15	0.18
N	slow	aspen	C			30-35,41,54-56	MCDM				RS			2666	382	10	15.07	10.78	0.60	10	0.09	0.07	2.15	5	0.11	0.13
O	slow	aspen	C			30-35,41,54-56	No chip treatment				NR			2149	361	10	13.00	9.30	0.63	10	0.08	0.06	2.20	5	0.22	0.27
P	slow	aspen	C			59-62	MCDM				T			2120	381	10	23.53	16.83	0.80	10	0.07	0.05	2.77	5	0.22	0.27
Q	slow	aspen	C			63-66	MCDM				T			2095	415	10	22.08	15.80	1.07	10	0.09	0.07	2.61	5	0.29	0.37
R	slow	loblolly	A			67-68, 100, 101	MCDM				T			1846	336	10	19.28	13.79	0.53	10	0.06	0.04	2.77	5	0.16	0.19
S	slow	aspen	C			73 & 75	MCDM				T			1801	418	10	24.42	17.47	1.02	10	0.08	0.06	2.61	5	0.15	0.18
T	slow	aspen	D			74 & 76	MCDM				T			1728	427	10	24.98	17.87	0.95	10	0.08	0.06	2.47	5	0.15	0.18
U	slow	aspen	D			78	MCDM				T			1861	421	10	20.81	14.89	1.03	10	0.08	0.06	2.54	5	0.12	0.14
V	slow	loblolly	A			79-80, 100, 101	MCDM				T			1700	348	10	17.88	12.79	0.67	10	0.05	0.04	3.19	5	0.24	0.30
W	slow	aspen	D			81-84	MCDM				A			2116	405	10	17.54	12.55	0.98	10	0.08	0.05	2.40	5	0.13	0.16
X	slow	aspen	D			85-88	MCDM				A			2152	411	10	30.73	21.98	0.97	10	0.08	0.06	2.31	5	0.18	0.22
Z	slow	aspen	D			91-94	MCDM				A			2043	432	8	5.57	4.66	1.02	10	0.09	0.06	1.87	10	0.16	0.12
A'	slow	aspen	D			95-98	MCDM				A			2187	462	8	12.28	10.27	1.13	10	0.07	0.05	1.61	10	0.11	0.08
C'	slow	aspen	D			102-105	MCDM				A			2048	450	8	21.53	18.01	0.89	10	0.11	0.08	1.45	10	0.10	0.07
D'	slow	aspen	D			106-109	MCDM				A			2079	451	8	15.38	12.86	1.04	10	0.08	0.06	1.84	10	0.14	0.10
E'	slow	aspen	D			110-113	MCDM				A			2389	430	10	32.72	23.41	1.16	10	0.16	0.11	2.29	4	0.11	0.18
F'	slow	aspen	D			115-118	MCDM				A			2285	454	8	12.64	10.57	1.08	10	0.15	0.10	1.40	10	0.10	0.07
G'	slow	aspen	D			119-122	MCDM				A			2068	521	8	9.50	7.95	1.28	10	0.08	0.06	1.42	10	0.13	0.09
H'	slow	loblolly	A			123-127	MCDM				T			1916	405	8	9.39	7.86	0.81	10	0.04	0.03	2.18	10	0.19	0.13
I'	slow	aspen	E			128	MCDM				A			2017	491	8	8.54	7.14	1.18	10	0.10	0.07	1.47	10	0.14	0.10
J'	slow	aspen	E			129	MCDM				A			2063	472	8	7.61	6.37	1.17	10	0.10	0.07	1.40	10	0.14	0.10
K'	slow	aspen	D			131-133	MCDM				A			2181	484	8	6.40	5.35	1.22	10	0.12	0.09	1.80	10	0.15	0.11
L'	slow	aspen	D			134-137	MCDM				A			2039	460	10	35.70	25.54	0.90	10	0.11	0.08	1.96	5	0.12	0.14
M'	slow	aspen	D			138-142	MCDM				A			2048	471	8	12.05	10.07	1.07	10	0.08	0.06	1.54	10	0.08	0.06

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	tensile index Nm/g	n	s.d.	.95CI	TEA index J/g	n	s.d.	.95 CI	elong-ation %	n	s.d.	.95 CI	zero span tensile Nm/g	n	s.d.	.95 CI
192	fast	aspen	E	Cs	FP90031-sp	AA	mycelial suspension	MS	6	0.1	A	31	4.43	30.24	5	2.08	2.58	0.27	5	0.05	0.07	1.34	5	0.14	0.17	NA			
193	fast	aspen	E	Cs	FP90031-sp	AA	mycelial suspension	MS	6	0.1	A	31	6.40	30.09	5	1.79	2.22	0.29	5	0.04	0.05	1.42	5	0.17	0.21	NA			
194	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	MCDM AC'd on chips	CC	39	10	A	28	6.97	27.39	5	1.53	1.90	0.22	5	0.03	0.04	1.25	5	0.10	0.13	NA			
195	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	MCDM AC'd on chips	CC	39	10	A	28	3.38	27.63	5	1.86	2.31	0.21	5	0.04	0.05	1.17	5	0.17	0.21	NA			
196	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	Filtered MCDM	CC	39	10	A	28	4.04	28.36	5	3.04	3.78	0.24	5	0.06	0.07	1.28	5	0.23	0.28	NA			
197	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	Filtered MCDM	CC	39	10	A	28	5.38	28.79	5	1.78	2.21	0.24	5	0.04	0.05	1.27	5	0.15	0.18	NA			
198	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	No MCDM, AC'd	CC	39	10	A	28	2.06	25.79	5	1.47	1.83	0.20	5	0.03	0.04	1.21	5	0.12	0.15	NA			
199	fast	aspen	E	Pc	BKM-F-1767	EE,FF,GG	MCDM, No AC	SPS	NA	*8	A	31	4.50	24.86	5	1.60	1.99	0.18	5	0.04	0.04	1.14	5	0.13	0.16	NA			
200	fast	aspen	E	Pc	BKM-F-1767	EE,FF,GG	No MCDM, No AC	SPS	NA	*8	A	31	11.00	23.56	5	0.88	1.09	0.19	5	0.03	0.03	1.22	5	0.09	0.12	NA			
201	fast	aspen	E	Pc	BKM-F-1767	EE,FF,GG	MCDM, AC	SPS	NA	*8	A	31	2.50	27.09	5	1.56	1.94	0.23	5	0.03	0.04	1.29	5	0.13	0.16	NA			
202	fast	aspen	E	Pc	BKM-F-1767	EE,FF,GG	No MCDM, AC	SPS	NA	*8	A	31	2.00	27.73	5	1.48	1.84	0.23	5	0.02	0.03	1.25	5	0.09	0.11	NA			
219	fast	aspen	F	Cs	CZ-3	OO, QQ	Chip source & size	MS	17	0.14	A	29	NA	37.77	5	2.10	2.61	0.40	5	0.06	0.07	1.57	5	0.16	0.20	NA			
220	fast	aspen	E	Cs	CZ-3	OO#QQ	Chip source & size	MS	17	0.14	A	29	NA	33.78	5	2.64	3.28	0.31	5	0.08	0.09	1.37	5	0.18	0.22	NA			
A	slow	white birch	A			1	No chip treatment				NR			13.20	10	0.98	0.70	NA				NA				68.80	10	3.74	2.68
B	slow	aspen	A			2,3-7					NR			22.42	10	1.44	1.03	NA				NA				92.30	10	3.25	2.33
C	slow	aspen	A			2,3-7	No chip treatment				NR			21.05	10	1.37	0.98	NA				NA				81.84	10	4.40	3.15
D	slow	aspen	B			9-27,28	AC				NR			30.50	10	2.87	2.05	NA				NA				93.40	10	6.07	4.34
E	slow	aspen	B			9-27,28	No chip treatment				NR			35.30	10	2.64	1.89	NA				NA				95.02	10	6.33	4.53
F	slow	aspen	B			9-27,28	No chip treatment				NR			34.77	10	4.30	3.08	NA				NA				95.31	10	4.53	3.24
H	slow	white spruce	A			27	CDM, AC				NR			37.20	10	2.69	1.92	NA				NA				90.30	10	5.20	3.72
I	slow	aspen	C			30-35,41,54-56	MCDM, AC				NR			28.46	10	1.79	1.28	NA				NA				86.43	10	3.93	2.81
J	slow	Aspen	C			30-35,41,54-56	MCDM, AC				NR			29.53	10	1.99	1.42	NA				NA				93.17	10	2.84	2.03
						58,67,68,100,101																							
K	slow	loblolly	A			36-40,42,53,57,58	MCDM, AC				NR			23.90	10	1.89	1.35	NA				NA				81.80	10	4.79	3.43
						58,67,68,100,101																							
L	slow	loblolly	A			36-40,42,53,57,58	MCDM, AC				NR			22.30	10	1.06	0.76	NA				NA				79.40	10	4.76	3.41
						58,67,68,100,101																							
M	slow	aspen	C			30-35,41,54-56								25.00	10	1.21	0.87	NA				NA				89.10	10	4.61	3.30
N	slow	aspen	C			30-35,41,54-56	MCDM				RS			21.20	10	3.46	2.48	NA				NA				100.30	10	4.03	2.88
O	slow	aspen	C			30-35,41,54-56	No chip treatment				NR			18.00	8	1.55	1.30	NA				1.10	8	0.15	0.12	86.60	10	4.89	3.50
P	slow	aspen	C			59-62	MCDM				T			26.00	10	2.25	1.61	NA				1.34	10	0.12	0.09	94.10	10	6.64	4.75
Q	slow	aspen	C			63-66	MCDM				T			30.00	9	1.27	0.98	NA				1.59	9	0.22	0.17	101.30	10	4.96	3.55
R	slow	loblolly	A			67-68, 100, 101	MCDM				T			19.20	6	1.83	1.92	NA				1.40	6	0.16	0.17	85.30	10	7.78	5.57
S	slow	aspen	C			73 & 75	MCDM				T			29.50	10	1.85	1.32	NA				1.59	7	0.20	0.18	98.90	10	3.30	2.36
T	slow	aspen	D			74 & 76	MCDM				T			28.39	7	1.32	1.22	NA				1.48	7	0.21	0.19	101.90	10	2.79	2.00
U	slow	aspen	D			78	MCDM				T			30.80	9	1.12	0.86	NA				1.43	9	0.20	0.15	103.70	10	4.62	3.31
V	slow	loblolly	A			79-80, 100, 101	MCDM				T			22.70	8	1.86	1.56	NA				1.34	8	0.21	0.18	83.10	10	4.74	3.39
W	slow	aspen	D			81-84	MCDM				A			28.40	8	2.68	2.24	NA				1.34	7	0.12	0.11	93.40	10	4.43	3.17
X	slow	aspen	D			85-88	MCDM				A			30.44	8	1.53	1.28	NA				1.37	5	0.16	0.19	95.30	10	2.13	1.52
Z	slow	aspen	D			91-94	MCDM				A			26.00	5	2.50	3.10	0.29	5	0.04	0.05	1.19	5	0.14	0.18	NA			
A'	slow	aspen	D			95-99	MCDM				A			27.75	5	1.79	2.23	0.29	5	0.04	0.04	1.37	5	0.11	0.14	NA			
C'	slow	aspen	D			102-105	MCDM				A			25.80	5	2.67	3.31	0.24	5	0.04	0.04	1.70	5	0.19	0.24	NA			
D'	slow	aspen	D			106-109	MCDM				A			25.00	5	1.76	2.18	0.20	5	0.02	0.02	1.72	5	0.20	0.24	NA			
E'	slow	aspen	D			110-113	MCDM				A			33.08	10	3.95	2.83	NA				1.50	10	0.27	0.19	NA			
F'	slow	aspen	D			115-118	MCDM				A			29.24	5	0.86	1.06	0.28	5	0.03	0.04	1.69	5	0.31	0.39	NA			
G'	slow	aspen	D			119-122	MCDM				A			32.09	5	2.05	2.54	0.30	5	0.07	0.09	1.82	5	0.30	0.37	NA			
H'	slow	loblolly	A			123-127	MCDM				T			22.23	5	1.20	1.49	0.22	5	0.03	0.04	1.90	5	0.22	0.27	NA			
I'	slow	aspen	E			128	MCDM				A			30.41	5	1.41	1.75	0.29	5	0.04	0.05	1.65	5	0.27	0.34	NA			
J'	slow	aspen	E			129	MCDM				A			28.85	5	2.15	2.67	0.24	5	0.04	0.05	1.49	5	0.16	0.20	NA			
K'	slow	aspen	D			131-133	MCDM				A			30.66	5	1.27	1.58	0.28	5	0.02	0.03	1.70	5	0.19	0.24	NA			
L'	slow	aspen	D			134-137	MCDM				A			27.28	10	1.90	1.36	NA				1.39	10	0.18	0.13	NA			
M'	slow	aspen	D			138-142	MCDM				A			28.31	5	1.91	2.37	0.28	5	0.03	0.04	1.45	5	0.15	0.18	NA			

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	bright-ness %	n	s.d.	.95 CI	opacity %	n	s.d.	.95 CI	scattering coefficient m^2/kg	n	s.d.	.95 CI	fiber length index mm	klason lignin %	Labra-tory
192	fast	aspen	E	Cs	FP90031-sp	AA	mycelial suspension	MS	6	0.1	A	31	4.43	51.26	5	0.15	0.19	94.70	5	0.63	0.78	44.32	5	1.87	2.32	NA	NA	WEY
193	fast	aspen	E	Cs	FP90031-sp	AA	mycelial suspension	MS	6	0.1	A	31	6.40	51.31	5	0.11	0.14	94.85	5	0.31	0.38	44.20	5	1.01	1.25	NA	NA	WEY
194	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	MCDM AC'd on chips	CC	39	10	A	28	6.97	51.62	5	0.31	0.38	94.63	5	0.46	0.57	45.07	5	1.65	2.05	NA	NA	WEY
195	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	MCDM AC'd on chips	CC	39	10	A	28	3.38	50.73	5	0.10	0.12	94.16	5	0.76	0.94	42.51	5	1.88	2.33	NA	NA	WEY
196	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	Filtered MCDM	CC	39	10	A	28	4.04	52.71	5	0.28	0.35	94.27	5	0.44	0.55	44.25	5	1.43	1.78	NA	NA	WEY
197	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	Filtered MCDM	CC	39	10	A	28	5.38	52.22	5	0.11	0.14	94.30	5	0.41	0.51	44.18	5	1.34	1.66	NA	NA	WEY
198	fast	aspen	E	Cs	FP90031-sp	BB,CC,DD	No MCDM, AC'd	CC	39	10	A	28	2.06	57.18	5	0.32	0.40	94.79	5	0.27	0.34	51.40	5	1.08	1.34	NA	NA	WEY
199	fast	aspen	E	Pc	BKM-F-1767	EE,FF,GG	MCDM, No AC	SPS	NA	*8	A	31	4.50	54.92	5	0.31	0.38	95.15	5	0.13	0.16	49.45	5	0.59	0.73	NA	NA	WEY
200	fast	aspen	E	Pc	BKM-F-1767	EE,FF,GG	No MCDM, No AC	SPS	NA	*8	A	31	11.00	53.78	5	0.11	0.14	95.00	5	0.33	0.41	47.85	5	1.00	1.24	NA	NA	WEY
201	fast	aspen	E	Pc	BKM-F-1767	EE,FF,GG	MCDM, AC	SPS	NA	*8	A	31	2.50	53.66	5	0.40	0.50	95.78	5	0.17	0.21	51.48	5	0.63	0.78	NA	NA	WEY
202	fast	aspen	E	Pc	BKM-F-1767	EE,FF,GG	No MCDM, AC	SPS	NA	*8	A	31	2.00	54.16	5	0.38	0.47	95.12	5	0.38	0.47	48.84	5	1.43	1.78	NA	NA	WEY
219	fast	aspen	F	Cs	CZ-3	OO, QQ	Chip source & size	MS	17	0.14	A	29	NA	49.07	5	0.44	0.55	94.24	5	0.42	0.52	41.16	5	1.30	1.61	NA	NA	WEY
220	fast	aspen	E	Cs	CZ-3	OO, QQ	Chip source & size	MS	17	0.14	A	29	NA	49.62	5	0.32	0.40	94.20	5	0.26	0.32	41.81	5	0.68	0.84	NA	NA	WEY
A	slow	white birch	A			1	No chip treatment				NR			58.60	5	0.54	0.67	98.40	5			81.50	5			0.06	NA	FPL
B	slow	aspen	A			2,3-7					NR			63.03	5	0.18	0.22	93.65	5			64.45	5			0.08	NA	FPL
C	slow	aspen	A			2,3-7	No chip treatment				NR			50.87	5	0.23	0.29	97.15	5			59.15	5			0.08	NA	FPL
D	slow	aspen	B			9-27,28	AC				NR			64.70	5	0.23	0.29	93.57	5			63.49	5			0.10	NA	FPL
E	slow	aspen	B			9-27,28	No chip treatment				NR			65.57	5	0.25	0.31	92.64	5			61.37	5			0.09	20.51	FPL
F	slow	aspen	B			9-27,28	No chip treatment				NR			61.85	5	0.30	0.37	94.21	5			62.15	5			0.10	NA	FPL
H	slow	white spruce	A			27	CDM, AC				NR			55.40	5	0.30	0.37	94.60	5			57.50	5			0.12	NA	FPL
I	slow	aspen	C			30-35,41,54-56	MCDM, AC				NR			54.48	5	0.30	0.37	95.96	5			58.56	5			0.08	NA	FPL
J	slow	Aspen	C			30-35,41,54-56	MCDM, AC				NR			61.66	5	0.30	0.37	93.67	5			62.00	5			0.05	NA	FPL
						58,67,68,100,101																						
K	slow	loblolly	A			36-40,42,53,57,58	MCDM, AC				NR			46.80	5	0.44	0.55	94.90	5			47.90	5			0.11	NA	FPL
						58,67,68,100,101																						
L	slow	loblolly	A			36-40,42,53,57,58	MCDM, AC				NR			46.80	5	0.51	0.63	94.70	5			49.20	5			0.11	NA	FPL
						58,67,68,100,101																						
M	slow	aspen	C			30-35,41,54-56								61.70	5	0.22	0.27	92.10	5			57.10	5			0.06	NA	FPL
N	slow	aspen	C			30-35,41,54-56	MCDM				RS			57.40	5	0.35	0.43	93.50	5			56.40	5			0.08	18.22	FPL
O	slow	aspen	C			30-35,41,54-56	No chip treatment				NR			66.80	5	0.19	0.24	93.60	5			64.50	5			0.08	18.95	FPL
P	slow	aspen	C			59-62	MCDM				T			62.30	5	0.13	0.16	93.90	5			64.30	5			0.06	19.35	FPL
Q	slow	aspen	C			63-66	MCDM				T			63.80	5	0.24	0.30	93.60	5			62.70	5			0.09	NA	FPL
R	slow	loblolly	A			67-68, 100, 101	MCDM				T			44.50	5	0.22	0.27	93.10	5			43.70	5			NA	NA	FPL
S	slow	aspen	C			73 & 75	MCDM				T			62.20	5	0.12	0.15	94.00	5			62.30	5			NA	NA	FPL
T	slow	aspen	D			74 & 76	MCDM				T			60.50	5	0.21	0.26	94.70	5			63.80	5			NA	NA	FPL
U	slow	aspen	D			78	MCDM				T			60.60	5	0.09	0.11	95.40	5			66.10	5			NA	NA	FPL
V	slow	loblolly	A			79-80, 100, 101	MCDM				T			45.00	5	0.31	0.38	92.70	5			44.50	5			NA	27.03	FPL
W	slow	aspen	D			81-84	MCDM				A			62.30	5	0.22	0.27	94.20	5			64.40	5			NA	NA	FPL
X	slow	aspen	D			85-88	MCDM				A			61.60	5	0.28	0.35	94.90	5			65.50	5			NA	NA	FPL
Z	slow	aspen	D			91-94	MCDM				A			61.26	5	0.22	0.27	95.60	5	0.35	0.43	61.27	5	1.61	2.00	NA	19.44	WEY
A'	slow	aspen	D			95-98	MCDM				A			62.64	5	0.10	0.12	96.27	5	0.23	0.29	62.64	5	1.48	1.84	NA	19.62	WEY
C'	slow	aspen	D			102-105	MCDM				A			63.80	5	0.18	0.22	95.60	5	0.36	0.45	64.90	5	1.81	2.25	NA	17.49	WEY
D'	slow	aspen	D			106-109	MCDM				A			61.10	5	0.13	0.16	96.60	5	0.29	0.36	64.00	5	1.98	2.46	NA	17.19	WEY
E'	slow	aspen	D			110-113	MCDM				A			60.90	5	0.19	0.24	NA				NA				NA	18.85	FPL
F'	slow	aspen	D			115-118	MCDM				A			61.68	5	0.19	0.24	96.23	5	0.15	0.19	65.81	5	1.20	1.49	NA	19.62	WEY
G'	slow	aspen	D			119-122	MCDM				A			58.96	5	0.31	0.38	96.69	5	0.25	0.31	63.01	5	2.04	2.53	NA	20.21	WEY
H'	slow	loblolly	A			123-127	MCDM				T			45.50	5	0.28	0.35	95.64	5	0.19	0.24	44.11	5	0.97	1.20	NA	27.96	WEY
I'	slow	aspen	E			128	MCDM				A			59.18	5	0.10	0.12	96.92	5	0.24	0.30	64.90	5	1.72	2.14	NA	19.40	WEY
J'	slow	aspen	E			129	MCDM				A			59.87	5	0.10	0.12	96.70	5	0.29	0.36	65.14	5	1.73	2.15	NA	20.19	WEY
K'	slow	aspen	D			131-133	MCDM				A			56.82	5	0.32	0.40	97.49	5	0.36	0.45	63.77	5	2.01	2.50	NA	NA	WEY
L'	slow	aspen	D			134-137	MCDM				A			NA				NA				NA				NA	NA	FPL
M'	slow	aspen	D			138-142	MCDM				A			58.49	5	0.23	0.29	97.09	5	0.21	0.26	65.02	5	1.39	1.73	NA	NA	WEY

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec. *1	strain #	control *2	treatments *3	inoc. type *4	inoc. age days	inoc. level %	reactor type *5	reactor incubat. days	weight loss %	energy watt-hrs. per kg	density kg/m^3	n	s.d. *6	.95 CI *7	burst index kN/g	n	s.d.	.95 CI	tear index mN-m^2/g	n	s.d.	.95CI
N'	slow	aspen	E			143-148	MCDM				A			1986	467	8	11.19	9.35	1.01	10	0.10	0.07	1.50	10	0.10	0.07
O'	slow	aspen	E			149-154	MCDM				A			2267	503	8	6.01	5.02	1.22	10	0.11	0.08	1.26	10	0.08	0.06
P'	slow	aspen	E			155, 157	MCDM				A			2479	440	8	2.52	2.11	1.01	10	0.06	0.04	1.65	10	0.14	0.10
Q'	slow	loblolly	A			158	MCDM				A			2113	391	8	5.30	4.43	0.96	10	0.06	0.04	1.60	10	0.12	0.09
S'	slow	aspen	E			165-168,171	MCDM				A			2321	445	8	6.02	5.03	0.98	10	0.04	0.03	1.78	10	0.13	0.09
T'(fast)	fast	aspen	E			169 (fast)	MCDM				A			2023	437	8	6.07	5.08	0.93	10	0.07	0.05	1.03	10	0.09	0.07
T'(slow)	slow	aspen	E			169 (slow)	MCDM				A			2463	444	8	4.88	4.08	1.12	10	0.06	0.04	1.26	10	0.12	0.09
U'(fast)	fast	aspen	E			170 (fast)	MCDM				A			2395	447	8	6.31	5.28	0.97	10	0.04	0.03	1.30	10	0.09	0.07
U'(slow)	slow	aspen	E			170 (slow)	MCDM				A			2483	433	8	4.88	4.08	0.88	10	0.08	0.05	1.54	10	0.07	0.05
W'	slow	aspen	E			172	MCDM				A			1947	425	8	9.99	8.35	0.84	10	0.04	0.03	1.40	10	0.10	0.07
Y'(fast)	fast	aspen	E			177-182 (fast)	MCDM				A			2077	438	8	5.85	4.89	0.92	10	0.04	0.03	1.44	10	0.13	0.09
Y'(slow)	slow	aspen	E			177-182 (slow)	MCDM				A			2193	439	8	9.61	8.04	0.99	10	0.07	0.05	1.61	10	0.10	0.07
Z'-1	fast	aspen	E			183	No MCDM, No AC				A			2169	420	8	3.88	3.24	0.92	10	0.04	0.03	1.54	10	0.08	0.06
Z'-3	fast	aspen	E			184	MCDM, No AC				A			1959	409	8	6.19	5.17	0.93	10	0.06	0.05	1.88	10	0.24	0.17
AA	fast	aspen	E			189-193	MCDM				A			2168	432	8	4.64	3.88	0.96	10	0.05	0.03	1.50	10	0.12	0.09
BB	fast	aspen	E			194-195	MCDM				A			2092	416	8	5.33	4.45	0.85	10	0.05	0.03	1.59	10	0.08	0.05
CC	fast	aspen	E			196-197	Filtered MCDM				A			2131	422	8	3.88	3.24	0.88	10	0.04	0.03	1.49	10	0.09	0.07
DD	fast	aspen	E			198	No MCDM				A			2077	420	8	4.09	3.42	0.86	10	0.06	0.04	1.60	10	0.08	0.06
EE	fast	aspen	E			199	MCDM, No AC				A			1780	390	8	3.24	2.71	0.86	10	0.07	0.05	2.13	10	0.23	0.17
FF	fast	aspen	E			200	No MCDM, No AC				A			1933	385	8	5.64	4.72	0.87	10	0.05	0.04	2.25	10	0.12	0.08
GG	fast	aspen	E			201-202	No MCDM				A			2207	434	8	5.22	4.36	0.90	10	0.08	0.06	1.70	10	0.14	0.10
OO	fast	aspen	F			219	MCDM				A			2123	417	8	4.48	3.74	0.87	10	0.03	0.02	1.37	10	0.21	0.15
QQ	fast	aspen	E			220	MCDM				A			1990	426	8	3.45	2.89	0.91	10	0.04	0.03	1.21	10	0.16	0.11

*1=Fungal species
Cs=Ceriporiopsis subvermispora
Cv=Coriolus versicolor
Ds=Dichomitus squalens
Hs=Hypodontia setulosa
Pb=Phlebia brevispora
Pc=Phanerochaete chrysosporium
Pfa=Phanerochaete flavido-alba
Pm=Pholiota mutablis
Pmp=Perenniporia medulla-panis
Ps=Phlebia subserialis
Pt=Phlebia tremellosa
Wc=Wolfiporia cocos

*2=When more than one control is listed the average value of the group was used.
AC=Autoclaving
*3= MCDM is in all runs unless indicated
CDM=Chemically defined medium
MCDM=Modified chemically defined medium
*4=Inoculum type
CC=colonized chips
MS=mycelial suspension
SPS=spore suspension

*5=reactor type
A=aerated static bed
NR=no reactor
RP= perforated drum
RS=solid drum
SS=stationary solid drum
T=tray

*6=standard deviation

*7=Confidence Interval

*8=3x10^5 spores/g od chips

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	tensile index Nm/g	n	s.d.	.95CI	TEA index J/g	n	s.d.	.95 CI	elong-ation %	n	s.d.	.95 CI	zero span tensile Nm/g	n	s.d.	.95 CI
N'	slow	aspen	E			143-148	MCDM				A			27.49	5	1.14	1.42	0.24	5	0.04	0.05	1.89	5	0.23	0.29	NA			
O'	slow	aspen	E			149-154	MCDM				A			30.80	5	2.73	3.39	0.30	5	0.07	0.08	1.38	5	0.15	0.19	NA			
P'	slow	aspen	E			155, 157	MCDM				A			27.26	5	2.13	2.64	0.25	5	0.07	0.08	1.33	5	0.24	0.30	NA			
Q'	slow	loblolly	A			158	MCDM				A			25.48	5	1.61	2.00	0.26	5	0.04	0.05	1.49	5	0.16	0.19	NA			
S'	slow	aspen	E			165-168,171	MCDM				A			26.43	5	0.91	1.13	0.26	5	0.04	0.04	1.42	5	0.14	0.18	NA			
T'(fast)	fast	aspen	E			169 (fast)	MCDM				A			24.83	5	2.78	3.45	0.22	5	0.07	0.09	1.30	5	0.21	0.26	NA			
T'(slow)	slow	aspen	E			169 (slow)	MCDM				A			28.20	5	1.72	2.14	0.28	5	0.03	0.04	1.44	5	0.09	0.11	NA			
U'(fast)	fast	aspen	E			170 (fast)	MCDM				A			27.83	5	2.21	2.74	0.29	5	0.05	0.07	1.50	5	0.12	0.15	NA			
U'(slow)	slow	aspen	E			170 (slow)	MCDM				A			25.18	5	1.18	1.47	0.25	5	0.04	0.05	1.39	5	0.13	0.17	NA			
W'	slow	aspen	E			172	MCDM				A			23.50	5	1.71	2.12	0.20	5	0.03	0.04	1.28	5	0.10	0.12	NA			
Y'(fast)	fast	aspen	E			177-182 (fast)	MCDM				A			25.13	5	1.24	1.54	0.23	5	0.03	0.04	1.35	5	0.1	0.13	NA			
Y'(slow)	slow	aspen	E			177-182 (slow)	MCDM				A			26.25	5	0.85	1.06	0.24	5	0.03	0.03	1.40	5	0.23	0.29	NA			
Z'-1	fast	aspen	E			183-186	No MCDM, No AC				A			25.24	5	0.93	1.16	0.25	5	0.02	0.02	1.42	5	0.09	0.11	NA			
Z'-3	fast	aspen	E			183-186	MCDM, No AC				A			24.91	5	1.12	1.39	0.21	5	0.03	0.04	1.26	5	0.13	0.16	NA			
AA	fast	aspen	E			189-193	MCDM				A			25.11	5	1.30	1.61	0.23	5	0.04	0.05	1.41	5	0.22	0.27	NA			
BB	fast	aspen	E			194-195	MCDM				A			23.91	5	0.94	1.17	0.23	5	0.04	0.05	1.34	5	0.16	0.19	NA			
CC	fast	aspen	E			196-197	Filtered MCDM				A			24.01	5	0.91	1.12	0.20	5	0.03	0.03	1.22	5	0.13	0.16	NA			
DD	fast	aspen	E			198	No MCDM				A			24.22	5	0.91	1.13	0.22	5	0.02	0.03	1.32	5	0.08	0.10	NA			
EE	fast	aspen	E			199	MCDM, No AC				A			24.83	5	1.15	1.43	0.21	5	0.02	0.03	1.28	5	0.10	0.12	NA			
FF	fast	aspen	E			200	No MCDM, No AC				A			24.15	5	0.62	0.76	0.19	5	0.01	0.01	1.23	5	0.06	0.07	NA			
GG	fast	aspen	E			201-202	No MCDM				A			26.06	5	1.40	1.73	0.26	5	0.03	0.04	1.42	5	0.16	0.19	NA			
OO	fast	aspen	F			219	MCDM				A			24.82	5	1.09	1.36	0.22	5	0.04	0.04	1.29	5	0.12	0.15	NA			
QQ	fast	aspen	E			220	MCDM				A			24.99	5	0.66	0.82	0.22	5	0.03	0.03	1.30	5	0.10	0.13	NA			

Table 1 B—Biopulping runs with controls—con.

run #	refining sequence	wood type	chip batch	fungal spec.	strain #	control	treatments	inoc. type	inoc. age days	inoc. level %	reactor type	reactor incubat. days	weight loss %	bright-ness %	n	s.d.	.95 CI	opacity %	n	s.d.	.95 CI	scattering coefficient m^2/kg	n	s.d.	.95 CI	fiber length index mm	klason lignin %	Labra-tory
N'	slow	aspen	E			143-148	MCDM				A			60.00	5	0.22	0.27	96.50	5	0.18	0.22	63.80	5	1.39	1.73	NA	NA	WEY
O'	slow	aspen	E			149-154	MCDM				A			58.18	5	0.16	0.20	97.42	5	0.25	0.31	64.95	5	1.78	2.21	NA	NA	WEY
P'	slow	aspen	E			155, 157	MCDM				A			61.39	5	0.32	0.40	96.27	5	0.27	0.34	65.33	5	1.31	1.63	NA	NA	WEY
Q'	slow	loblolly	A			158	MCDM				A			41.74	5	0.15	0.19	98.71	5	0.22	0.27	51.58	5	1.55	1.92	NA	NA	WEY
S'	slow	aspen	E			165-168,171	MCDM				A			61.98	5	0.14	0.17	96.23	5	0.25	0.31	64.93	5	1.33	1.65	NA	NA	WEY
T'(fast)	fast	aspen	E			169 (fast)	MCDM				A			62.48	5	0.20	0.25	96.90	5	0.30	0.37	66.77	5	2.02	2.51	NA	NA	WEY
T'(slow)	slow	aspen	E			169 (slow)	MCDM				A			62.35	5	0.23	0.29	96.85	5	0.37	0.46	66.30	5	2.47	3.07	NA	NA	WEY
U'(fast)	fast	aspen	E			170 (fast)	MCDM				A			65.77	5	0.21	0.26	96.43	5	0.31	0.38	71.92	5	2.14	2.66	NA	NA	WEY
U'(slow)	slow	aspen	E			170 (slow)	MCDM				A			66.78	5	0.12	0.15	95.14	5	0.52	0.65	65.99	5	3.06	3.80	NA	NA	WEY
W'	slow	aspen	E			172	MCDM				A			62.10	5	0.21	0.26	96.81	5	0.13	0.16	67.77	5	0.56	0.70	NA	19.09	WEY
Y'(fast)	fast	aspen	E			177-182 (fast)	MCDM				A			63.24	5	0.18	0.22	96.05	5	0.13	0.16	65.72	5	0.65	0.81	NA	NA	WEY
Y'(slow)	slow	aspen	E			177-182 (slow)	MCDM				A			61.52	5	0.21	0.26	96.58	5	0.1	0.12	64.96	5	0.58	0.72	NA	NA	WEY
Z'-1	fast	aspen	E			183-186	No MCDM. No AC				A			64.15	5	0.23	0.29	95.92	5	0.16	0.20	66.23	5	0.82	1.02	NA	NA	WEY
Z'-3	fast	aspen	E			183-186	MCDM, No AC				A			57.87	5	0.21	0.26	96.31	5	0.22	0.27	59.13	5	1.15	1.43	NA	NA	WEY
AA	fast	aspen	E			189-193	MCDM				A			63.24	5	0.07	0.09	96.34	5	0.07	0.09	67.01	5	0.47	0.58	NA	NA	WEY
BB	fast	aspen	E			194-195	MCDM				A			63.01	5	0.34	0.42	96.00	5	0.15	0.19	65.13	5	0.91	1.13	NA	NA	WEY
CC	fast	aspen	E			196-197	Filtered MCDM				A			64.63	5	0.19	0.24	95.65	5	0.12	0.15	66.47	5	0.74	0.92	NA	NA	WEY
DD	fast	aspen	E			198	No MCDM				A			64.30	5	0.21	0.26	95.66	5	0.32	0.40	64.48	5	1.88	2.33	NA	NA	WEY
EE	fast	aspen	E			199	MCDM, No AC				A			55.99	5	0.43	0.53	95.39	5	0.38	0.47	53.53	5	1.36	1.69	NA	NA	WEY
FF	fast	aspen	E			200	No MCDM, No AC				A			58.34	5	0.27	0.34	95.34	5	0.34	0.42	55.31	5	1.84	2.28	NA	NA	WEY
GG	fast	aspen	E			201-202	No MCDM				A			63.84	5	0.31	0.38	95.79	5	0.15	0.19	66.20	5	1.18	1.46	NA	NA	WEY
OO	fast	aspen	F			219	MCDM				A			58.82	5	0.34	0.42	97.32	5	0.16	0.20	65.55	5	1.05	1.30	NA	NA	WEY
QQ	fast	aspen	E			220	MCDM				A			64.03	5	0.25	0.31	96.29	5	0.12	0.15	68.76	5	0.75	0.93	NA	NA	WEY

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