

11 Engineering, Scale-Up, and Economic Aspects of Fungal Pretreatment of Wood Chips

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INTRODUCTION

Biopulping is the treatment of wood chips with lignin-degrading fungi prior to pulping. Two sequential biopulping consortia at the USDA Forest Service, Forest Products Laboratory (FPL), Madison, Wisconsin, established the technical feasibility of biomechanical pulping on a laboratory-scale basis. Through the use of a proper lignin-degrading fungus, at least 30% electrical energy is saved in mechanical pulping and paper strength properties are improved. Past work and an overview of fungal and pulp and paper research conducted during the consortia are summarized in Chapter 10 of this book and elsewhere in the literature (Akhtar et al., 1997; Blanchette et al., 1991; Kirk et al., 1994; Lawson and Still, 1957; Scott et al., 1995a,b; Sykes, 1994).

Current research is aimed at determining the engineering and commercial feasibility of biopulping, which is the subject of this chapter. Our recent work has focused on *Ceriporiopsis subvermispota* (the best biopulping fungus to date) and loblolly pine (the most commonly used wood species for papermaking in the United States), with greater attention to those factors most likely to affect the engineering and economics of this technology. These factors are attainment of the necessary degree of asepsis, reducing the cost of fungal inoculum, maintaining a hospitable environment in the chip pile, and optimizing overall process economics. Chip piles, silo-based systems, and indoor or covered piles are all being considered for operation of the solid-state fermentation. A new biopulping fungus, *Phlebia subserialis*, is also being investigated (Akhtar et al., 1996b). As discussed in this chapter, this fungus has several advantages over the *C. subvermispota*, especially when the aforementioned factors are considered.

An overview of the proposed process and the steps involved in using the fungus pretreatment are discussed. Various reactor configurations were used to explore the behavior of the fungus under controlled conditions, and an economic analysis of the process was performed to demonstrate the feasibility of biopulping technology. The chapter closes with some thoughts on the incorporation of biopulping into mill-scale operations and a discussion of the future research in this area.

OVERVIEW OF OPERATIONS

Based on the results of previous work and discussions with mill operations personnel, we envision a fungal treatment system that fits into existing mill operations with minimal disturbance. Figure 11.1 gives a conceptual overview of the biotreatment process in relation to existing wood yard operations. Wood is harvested and transported to the mill site for debarking, chipping, and screening. At this point the first change in the normal operation occurs, as the chips must be decontaminated by steaming. The steaming maintains a high temperature for a sufficient time to decontaminate the wood chip surfaces and allows the desired fungus to grow effectively. After decontamination, the chips are cooled sufficiently so that the fungus can be applied to the chips. The chips are then placed in piles that can be ventilated in order to maintain the proper temperature, humidity, and moisture content for the fungal growth. The retention time in the pile is envisioned to be about 1 to 4 weeks.

Although Figure 11.1 shows a basic concept for the process, several variations can be easily envisioned. In those mills that purchase chips rather than logs, the chips can be fed directly into the decontamination step from the trucks or other storage. The process of decontamination, cooling, and inoculation can be done in screw conveyors (described later) or on conveyor belts. If sufficient silo or other indoor capacity is available, the entire incubation could be enclosed, thus minimizing environmental factors.

ENGINEERING CHALLENGES

Several engineering challenges have to be answered in order to bring biopulping to commercialization. Most challenges involve taking a successful laboratory procedure and redesigning it to be practical on a larger scale. These challenges occur in two main areas: (1) preparing and inoculating the chips and (2) maintaining the proper growth conditions for the fungus during incubation. These issues are discussed briefly, followed by a description of the experiments performed to answer the questions posed.

On a laboratory scale, each step in the process (Figure 11.1) is done in a batchwise fashion. That is, for a given amount of chips, each step in the process is completed before the next step is started. In early work, wood chips were sterilized by autoclaving, which is not practical on a larger scale. However, *C. subvermispora* is not aggressive enough to compete with indigenous microorganisms in unsterilized

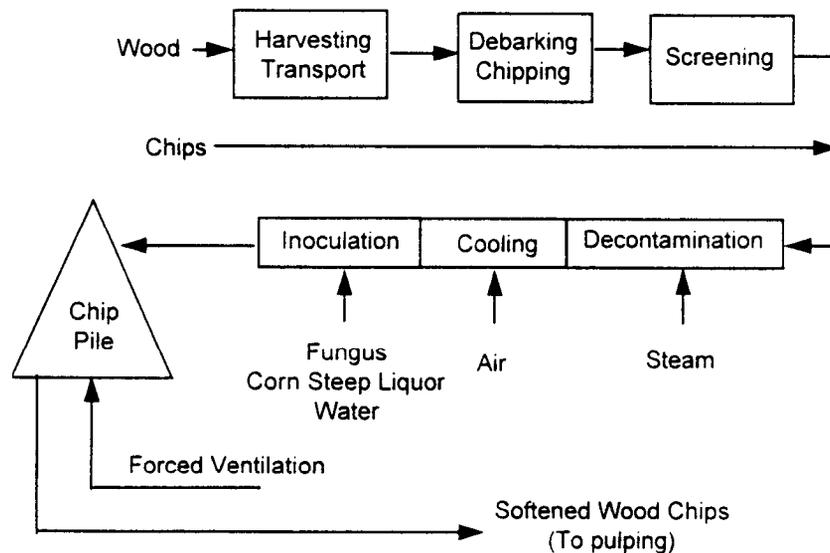


Figure 11.1 Overview of proposed biopulping process showing how the biotreatment process fits into an existing mill's wood handling system.

wood chips (Akhtar, unpublished results). Recent work showed that a brief steaming of the chips allows *C. subvermispora* to colonize and be effective. Although this steaming is not a complete sterilization of the wood chips, it is sufficient to allow the growth of the biopulping fungus. Steaming is currently being investigated as the decontamination method to be used in the scaled-up process.

After steaming, the chips are usually near 100°C, at least at the surface. Thus, the chips must be cooled sufficiently to allow the inoculum to be added. Complete cooling is not needed before the inoculum is added; however, the chips must be within the temperature growth range of the fungus within a relatively short period of time after addition of the inoculum. Hence, cooling can take place in two stages; before inoculation and after the chips are placed into storage that has a ventilation system for further cooling.

The next step in the process is the inoculation of the wood chips with a suspension containing the fungus, nutrients, and additional water. The addition of an inexpensive and commercially available nutrient, corn steep liquor, was found to reduce the amount of inoculum required from 3 kg to 5 g or less per ton of wood chips (dry basis) (Akhtar, et al., 1996a, 1997). The challenges involved in this step include metering the inoculum, nutrients, and water to give the proper amount of fungus and obtain the correct moisture content for the chips themselves. An additional challenge is the distribution of the inoculum evenly over the wood chips to promote uniform growth.

The second engineering challenge is to maintain the proper condition, in the chip pile to promote fungus growth. The key variables here are the temperature and

humidity of the air and the moisture content of the chips. The fungus has an optimum growth range for each of these variables. Furthermore, the fungus is not self-regulating in respect to any of these variables. For example, when biopulping was performed in a 1 ton chip pile without forced ventilation, the pile center reached about 42°C within 48 h after inoculation as a result of metabolic heat generated by the fungus. Similar heat buildup is seen in commercial chip piles simply because of the natural microorganisms present in the wood. Proper moisture conditions are critical for the establishment of the fungus. The use of forced air was explored for controlling temperature and moisture throughout the pile. This requires an understanding of the air flow through the chip bed, the heat generation of the fungus, the changes in the chip structure because of the fungus, and the nutrient and oxygen requirements of the fungus.

An early preliminary investigation into some of the engineering aspects of biopulping was carried out by biopulping consortia researchers (Wall et al., 1993). The early work concentrated on the white-rot fungus *Phanerochaete chrysosporium* on aspen wood. In that work, carbon dioxide production was measured as a function of time to predict the weight loss in the reactor via a carbon balance. The results indicated that carbon dioxide production was linear with time during the biopulping of chips unsupplemented with nutrients. However, the carbon dioxide production was found to be exponential when a nutrient supplement was added, at least in the initial stages. In the current work described in this chapter, carbon dioxide production was not used as an indicator of fungal growth because the variations in the measurements were quite high. Temperature measurements in well-insulated reactors seemed to be a better indicator of fungus metabolism.

A large number of process variables have to be considered in a process such as this, and many of these variables are summarized in Table 11.1. Depending on the configuration of the treatment equipment and the storage systems, the relative importance of the various variables will change.

PILOT-SCALE EQUIPMENT AND METHODS

Current efforts are focused on bringing the successful laboratory-scale procedures up to the industrial level. In the laboratory approximately 1.5 kg of chips are processed at one time, whereas commercial levels process about 200 to 2,000 tons or more per day, representing a 10^5 increase in scale. This gap is currently being bridged through a series of experiments to bring the process scale to this level (see Table 11.2). The goals of these scale-up studies are twofold: (1) to demonstrate that chips can be decontaminated and inoculated on a continuous basis, rather than as a batch process as is done on the laboratory scale, and (2) to demonstrate the process scales as expected from an engineering standpoint.

Laboratory Procedures

Two fungi, *C. subvermispora* and *P. subserialis*, were obtained from the Center for Forest Mycology Research at the USDA Forest Service, Forest Products Laboratory,

TABLE 11.1 System Variables for the Biopulping Process.

	Variables
Chips	Size (distribution) Moisture content Species Age (since harvest/chipping) Temperature
Inoculation	Fungus species Nutrient composition Water Amount of fungus Amount of nutrients
Decontamination	Steam pressure Steam quality Steam flow rate Final chip temperature Time at temperature Geometry
Cooling	Air flow Air temperature Air humidity Geometry
Fungus Metabolism	Growth rate Optimum temperature Optimum humidity Optimum chip moisture Heat generation Water generation Carbon dioxide production
Pile/Reactor Ventilation	Air flow Temperature Humidity Sterility Chip size (distribution) Geometry Fungal growth (aerial hyphae)
Environmental Factors	Ambient temperature Ambient humidity Amount of sunlight Wind (and direction) Precipitation
Economic Factors	Electricity cost Steam cost Capital cost Inoculum cost Nutrient cost Labor Overhead

TABLE 11.2 Scales of Reactor Systems used During the Biopulping Scale-up.

Description	Scale (kg dry chips)
Flask	0.05
Small Bioreactor	0.10
Large Bioreactor	1.50
Tubular Reactor	6.00
Small Indoor Chip Pile	40
Silo Reactor	160
Large Indoor Chip Pile	220
Large Indoor Chip Pile	380
Enclosed Pile	5,000
Outdoor Chip Pile	50,000
Industrial Scale	200,000 kg/day and up

Madison, Wisconsin. Cultures were continuously maintained in cereal culture and potato dextrose agar slants. Working cultures were prepared from the stock cultures as needed and refrigerated until used. Potato dextrose agar plate cultures were inoculated from a working culture and incubated at 27°C and 65% relative humidity for ten days.

In preparing the liquid inoculum, potato dextrose broth (4.8 g) and yeast extract (1.46 g) were added to 200 ml of distilled water and mixed well; 100 ml of this medium was poured into two 1 L flasks. Each flask was autoclaved for 20 min at 121°C. After cooling to room temperature, each flask was inoculated with 10 plugs cut with a number 9 cork bore from a 10-day-old potato dextrose agar plate of the fungal culture. The flasks were then incubated at 27°C at 65% relative humidity for 10 days. Prior to use, the flasks containing the fungal biomass were decanted and washed with sterile distilled water to remove excess medium from the fungal biomass. The fungal biomass was then placed in distilled water and blended in a Waring blender twice for 15 s, each time at high speed; distilled water was then added to the suspension to make the total volume 100 ml (stock). Enough stock to produce an inoculation rate of 5 g per ton on a dry weight basis was diluted to 100 ml of suspension with 15 g of unsterilized corn steep liquor (0.5% on a dry weight basis) and an appropriate amount of sterilized water.

The chips to be treated were thawed (if frozen) and thoroughly mixed to obtain uniform samples. Laboratory-scale bioreactors, each containing 1,500 g of chips (dry weight), were decontaminated by using atmospheric steam for 10 min and then cooled to room temperature prior to inoculation (Akhtar et al., 1996a; Fischer et al., 1994). Uninoculated bioreactors served as the controls. About 55% moisture (wet weight basis) in wood chips was maintained during fermentation. After receiving inocula, the bioreactors were shaken vigorously for uniform mixing. Each bioreactor was sealed and placed in an incubator at 27°C for 2 weeks and ventilated at a rate of

0.0227 volume/volume/min (v/v/m) (0.0283 m³/h). Three types of laboratory-scale bioreactors were designed and used: a rotating drum bioreactor, a stationary tray bioreactor, and a static bed bioreactor. Details on the configuration of each bioreactor have been published (Kirk et al., 1993).

Reactor Design

Two types of reactor systems were investigated in the reactor scale-up studies: tubular reactors and chip piles. The tubular reactors are advantageous in that the engineering and kinetic data necessary for scaling up the process can be collected. The one-dimensional nature of the system is easy to analyze and model. The reactor also allows for well-controlled airflow in the system with airflow patterns that are well known. Heat loss from the system is easily controlled with exterior insulation, producing conditions similar to those found in the center of large chips piles. Two sizes of tubular reactors were used in our scale-up studies.

Chip piles, both ventilated and unventilated, are analogous to one of the industrial implementations that we envision. However, more complicated, two- (or three-) dimensional airflow patterns must be considered. Chip piles, being less contained than the tubular reactors, are more exposed to the competition from undesirable fungal species that may be present in the environment. Chip piles also experience “edge” effects, that is, changes in the airflow, growth, and effectiveness of biopulping as a result of the free chip-air interface. The surfaces of chip piles are also exposed to the changes in the weather, including precipitation, freezing temperatures, and wind. However, even though the piles studied are quite small as compared with large industrial piles, they can provide insights into the flow of air in larger chip piles.

Tubular Reactors The small tubular reactor used in our investigation was a cylindrical PVC tube, 0.20 m in diameter and 1.0 m high (see Figure 11.2). The bottom has a polyethylene grid perforated with 6 mm holes. Forced air is supplied to the bottom of the reactor beneath the grid. The reactor has a cover with an air outlet hole in it. Six thermocouples are aligned vertically along the center of the reactor, spaced at 0.15 m intervals, with the bottom thermocouple being 0.075 m above the perforated grid. Prior to use, the inside of the reactor is cleaned and decontaminated with atmospheric steam.

Four bioreactors, each containing 1.5 kg dry weight of chips, were steamed, cooled, and inoculated as described previously. The bioreactors were vigorously shaken for uniform mixing, and the inoculated chips were poured from the bioreactors into the tubular reactor, which was then capped and sealed. The reactor was insulated and placed in an incubator at 27°C for 2 weeks. Humidified air was supplied to the bottom of the reactor at a rate ranging from 0.055 v/v/m to 0.220 v/v/m. At harvest, the fungus-treated and control chips were refined in a 300 mm diameter mechanical atmospheric disk refiner to measure energy consumption during refining. In some cases, the resulting pulp was made into paper and tested for strength properties.

We also constructed a cylindrical bioreactor that could be placed in a press and



Figure 11.2 Photograph of a tubular reactor, which is approximately 1.0 m high and 0.20 m in diameter. The reactor holds 6.0 kg of dry chips. Humidified air is supplied at the bottom of the reactor, and the temperature is monitored at six locations throughout the reactor. The reactor is covered with vented cover.

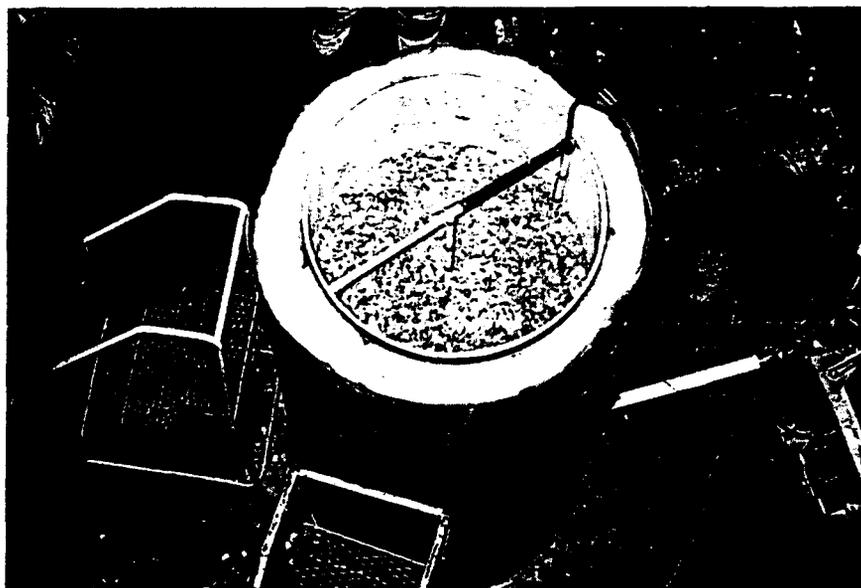


Figure 11.3 Photograph of a silo reactor, which is approximately 2.0 m high and 0.76 m in diameter. The reactor held a total of 140 kg of dry chips. Humidified air was supplied at the bottom of the reactor, and the temperature monitored at 12 locations throughout the reactor.

loaded to simulate the weight that would be placed on chips at the bottom of a large chip pile or silo. A piston with a perforated plate was used to compress the chips while allowing free flow of the air through the column. In this way, ventilation flow studies could be done while the chips were under a load. Chips were placed into the reactor to a height of slightly less than 1 m. In the case of the treated chips. The incubation was done directly in this reactor to prevent the disturbance of the aerial hyphae of the fungus. The piston was placed on the top of the chips, and the reactor was placed in a press that had a constant rate of displacement. The chips were compressed at a rate of 0.25 cm/min, and the load and compression readings taken at 222 N intervals. During compression, air was blown upward through the column of chips at a superficial velocity of 0.88 cm/sec. A maximum load of 4450 N was used.

Silo Reactor Figure 11.3 is a photograph of the larger tubular reactor (silo reactor) used in our studies. This silo reactor has a capacity of approximately 160 kg of chips on a dry basis. This reactor is 0.76 m in diameter with an overall height of 2.0 m. A perforated plate at the bottom of the reactor supports the chips approximately 5 cm above the bottom of the reactor. Air is supplied to this void space at the bottom center of the reactor. A baffle plate immediately above the air inlet distributes the air more evenly across the bottom of the reactor. Temperature is monitored at 12 locations in the reactor. Six thermocouples are aligned vertically along the center

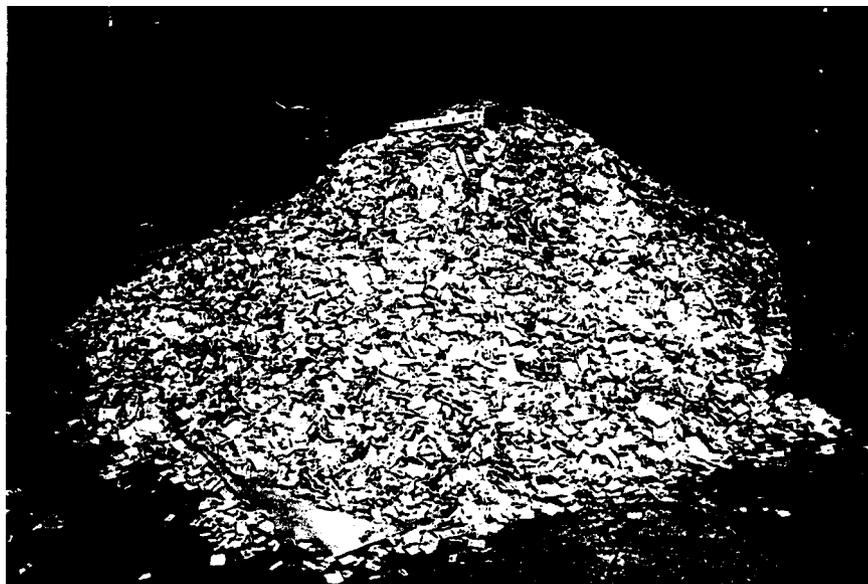


Figure 11.4 Photograph of a small chip pile. The pile consisted of 30 kg (dry) of inoculated chips and 10 kg of cover chips and was 0.65 m high. The pile was not ventilated. The temperature was monitored near the center-top of the pile.

axis of the reactor spaced at 30 cm intervals, and six are aligned vertically 5 cm from the outer edge of the reactor. The bottom thermocouple is 15 cm above the perforated plate. The velocity of the air in the supply pipe is monitored to determine the overall airflow rate in the reactor.

Approximately 160 kg of chips (dry basis) were decontaminated by either autoclaving or steaming. After cooling (typically overnight), the chips were inoculated using the standard inoculation protocol. Mixing of the inoculum was done in a large rotating “V” mixer with a capacity of five barrels of chips. The mixer was then rotated for another 20 min to mix the inoculum with the chips. The inoculated chips were then transferred to the silo reactor using a barrel as a transfer vessel. The chips were then ventilated with nearly saturated moist air, with the velocity adjusted to maintain the proper temperature range throughout the reactor. The specific ventilation rate ranged from 0 to 0.7 v/v/m. At harvest, the chips were removed from the bioreactor, and chips from three zones (top, middle, and bottom) were refined as described previously.

Chip Piles Both small and large chip piles were used to investigate the efficacy of biopulping under less controlled conditions. Small chip piles (Figure 11.4) typically consisted of approximately 30 kg (dry) of inoculated chips covered with 10 kg of uninoculated chips, resulting in a pile approximately 0.65 m high. Inoculated chips were placed on an insulated pad, and the internal temperature of the pile was moni-



Figure 11.5 Photograph of a large chip pile. The pile consisted of 160 to 320 kg (dry) of inoculated chips and 60 kg of cover chips and was 1.1 to 1.4 m high. The piles were built with the provision of ventilation from the center-bottom of the pile. Temperature was monitored at various locations throughout the pile.

tored near the top of the pile. The chips were left in the piles for 2 to 3 weeks and, at harvest, refined and the energy savings determined.

The large chip piles contained from 160 to 320 kg of inoculated chips and, like the small chip piles, were covered with about 60 kg of noninoculated chips (Figure 11.5). Each pile was about 1.1 to 1.4 m high and about 2.5 m in diameter. Each was built with provision for ventilation from the center bottom of the pile, and the temperature was monitored at various locations throughout the pile. To analyze the temperature profiles, thermocouple readings were divided into various pile regions (Figure 11.6). It was expected that the center region would be the most influenced by the forced ventilation and the outer shell influenced by the ambient conditions, because of the natural draft of air into the pile. At least two temperature measurements in each zone were averaged. At harvest, after 2 to 3 weeks, samples from each pile were refined and the energy savings determined.

KEY ENGINEERING FINDINGS

Decontamination provided several challenges as we moved from the laboratory scale to larger reactors. Decontamination is important, because fungal effectiveness increases with the degree of decontamination in all situations that we have studied.

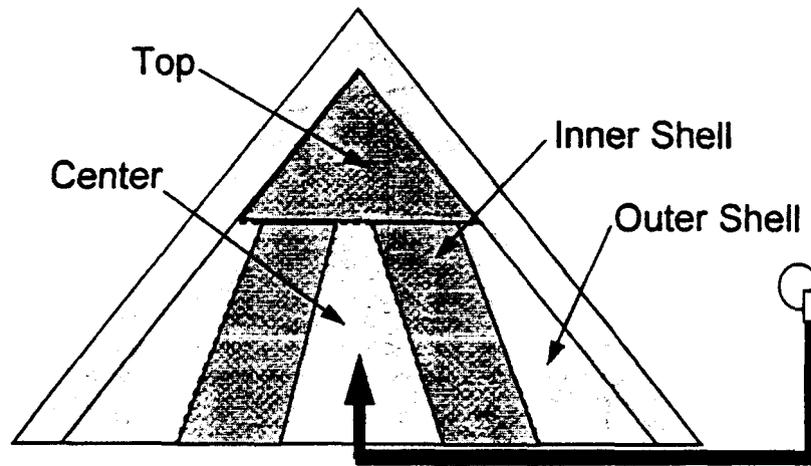


Figure 11.6 Zones in which the chip pile temperature readings are divided for analysis. In subsequent graphs, each zone contains at least two temperature measurements that are averaged.

Maintaining decontaminated conditions through cooling, inoculation, and building of the pile has been significantly challenging. For the tubular reactor, silo reactor, and chip pile studies, the chip preparation and inoculation were done batchwise in a similar manner to those steps performed at the laboratory scale. As described in detail in this section, the chips were initially steamed in batches and allowed to cool with time. After cooling sufficiently, the inoculum was added and well mixed with the chips. Subsequently, the inoculated chips were transferred to the incubation vessel or placed in a chip pile. Several different decontamination protocols have been used, including autoclaving, chemical treatment, and steaming. Initially, we thought that complete sterilization of wood chips was necessary prior to fungal inoculation. Therefore, chips in bioreactors were decontaminated either by autoclaving or with a solution of sodium bisulfite. The energy and time requirements for autoclaving do not make it a practical method of sterilization on a larger scale. Curve 1 of Figure 11.7 represents a typical temperature-time curve for autoclaving. Although chemical treatment with a sodium bisulfite solution was found to be effective (Akhtar et al., 1995), concern over the use of chemical agents may limit its application.

Recently, we discovered that complete sterilization is not necessary; only the surfaces of wood chips need to be decontaminated. This was accomplished by steaming wood chips for a very short time. The steaming was done for 10 min using laboratory steam at atmospheric pressure. In almost all cases, steam was found to be effective. Shorter times proved to have varying degrees of effectiveness, but even 2.5 min of steaming was sufficient to allow fungal growth. This steaming was relatively gentle, and the force of the steam injection did not displace the chips. Curve 2 in Figure 11.7 represents the temperature-time curve used in this protocol.

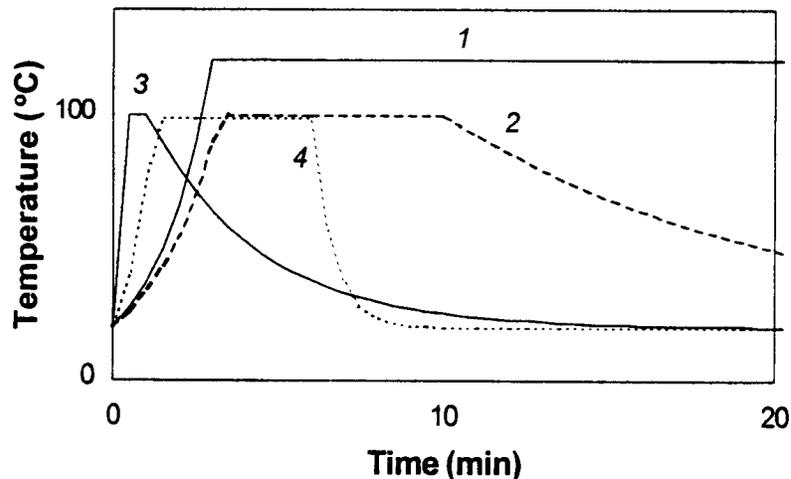


Figure 11.7 Temperature-time curves used for decontamination in the biopulping experiments. Curve 1 is autoclaving (total time of 90 minutes); curve 2 is the normal steaming used for 21 L bioreactors; curve 3 is the protocol used in 1 L bioreactors; and curve 4 is the proposed curve needed for pilot-scale equipment.

A series of decontamination experiments were also performed in 1-L bioreactors containing 50 to 100 g of wood chips. In these experiments, steam was injected vigorously in the reactors so that the chips agitated vigorously. The temperature-time curve in this case is shown as curve 3 in Figure 11.7. Under these conditions, very short steaming times were effective in sufficiently decontaminating the wood chips. All reactors steamed for 30 sec to 5 min were successfully decontaminated.

Curve 4 in Figure 11.7 shows the temperature-time curve for the pilot-scale decontamination equipment used in our research. The major differences in this curve as compared with the laboratory curves are the shorter time at temperature and the relatively rapid cooling of the chips. In addition, the chips tumbled in a screw conveyor for the initial portion of the steaming time, but then were relatively still as they were held in a surge bin. This method was fairly effective in decontaminating the chips and was used in a 4-ton trial performed at FPL.

The amount of time and the temperature needed for decontamination is a complicated function of the steaming method, the amount of contamination present on the wood, the size of the wood chips, and the aggressiveness of the biopulping fungus. As previously mentioned, only a surface decontamination is necessary, because when the fungus is established on the chip, it is able to compete effectively against other organisms. Figure 11.8 shows a hypothetical “killing curve” for decontamination of the chips. The line represents a certain efficiency in removing contaminants from the chips. The curve demonstrates two key points. First, a certain minimum temperature is needed to effectively decontaminate the chips. Second, as the temperature of decontamination increases, the time required decreases.

In designing steam decontamination equipment, several factors must be consid-

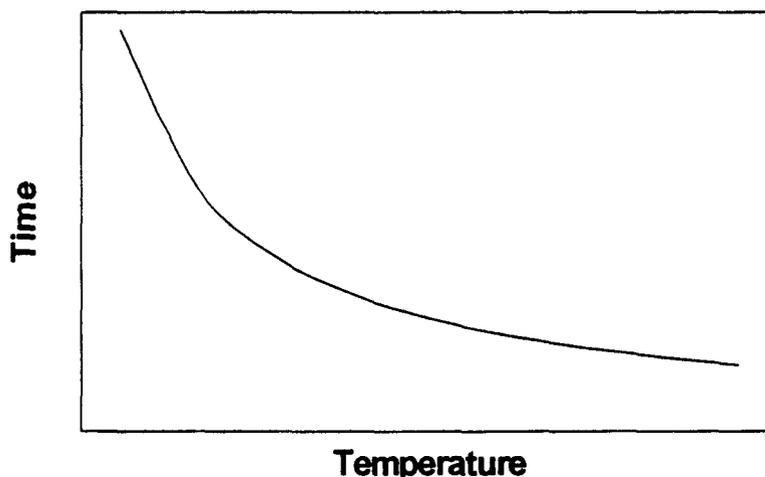


Figure 11.8 Hypothetical “killing curve” for decontamination of wood chips. The line represents the time needed at a certain temperature to remove most contaminants on the chips.

ered. First, to reach temperatures greater than 100°C, a pressurized vessel is needed. Although pressurized vessels require a greater capital investment and complex chip handling, the decontamination would be much more effective. Second, because it is thought that only surface decontamination is needed, only the surface must be held at the high temperatures necessary for inactivation of the unwanted microorganisms. Raising the temperature of the entire chip only increases the cooling load in the next operation. To minimize heat penetration into the chip, the chips should be heated for the shortest possible time and cooled quickly. It can also be concluded that exposure of the entire surface of the chip to the steam is important for effective decontamination. In the 21-L bioreactors, the chips were not positionally disturbed during steaming, and at least 2.5 min of steaming was needed to be effective. However, in the 1-L bioreactors, where the chips were actively tumbled, exposing all the surfaces to the steam, much less time was needed, as little as 15 s. The screw conveyor used for steaming provides some tumbling to expose all surfaces of the chips to the steam.

Cooling and Inoculation

Prior to inoculation with the biopulping fungus, the chips must be cooled so that the fungus is not inactivated or killed upon application. In the laboratory-scale experiments, cooling was achieved with time, that is, allowing the chip bed to naturally dissipate the heat to the surroundings. However, this is too time-consuming in a continuous process, so more active cooling is necessary. The most practical cooling mechanism is achieved through ventilation of the chips and evaporation of water from the chips. The question that needs to be answered here is, to what temperature

do the chips have to be cooled so that the viability of the fungus is not compromised?

Although the most viable biopulping fungus, *C. subvermispora*, has an optimum growth temperature of 27 to 32°C, it can be applied to chips as hot as 50°C, provided further cooling after the application brings the temperature down to 30°C fairly promptly. This means that even though the chips will be near 100°C from the previous steaming step, the entire cooling process does not have to be accomplished before the inoculum is applied to the chips. Further cooling can take place after inoculation and after the treated chips have been placed in the chip pile or silo.

Heat Generation

Further experiments were focused on maintaining an appropriate environment for growth, using the reactor systems previously described. Several engineering concerns had to be addressed for scaling-up, including heat generation by the fungus, compression of the chips in large piles, and the pressure drop through the pile during ventilation. The key results of a series of experiments are described as follows.

The fungus essentially metabolizes wood and nutrients; therefore, a significant amount of heat is produced that must be removed to promote the growth of the fungus. In the small bioreactors, the heat buildup was not a problem because the reactors were uninsulated and the relative surface-area-to-volume ratio was high. It has been found that the fungus is not self-regulating in respect to heat production. Thus, in larger reactors and in larger piles, the temperature can quickly exceed the optimum growth temperature of the fungus.

Figure 11.9 shows the temperature profiles for a large (1 ton) indoor pile that did not have artificial cooling. For analysis, the pile was divided into regions, as shown in Figure 11.6. Note that the center of the pile, which was well insulated from the outside by the bulk of the chips, reached nearly 42°C by the sixth day of the trial as a result of the generation of heat. This was too hot for survival of *C. subvermispora*. The outer shell of the pile, those chips immediately under the surface of the pile, at first cooled to below the initial temperature, probably because of evaporative cooling. The pile then heated up as a result of metabolic heat produced by the fungus, reaching an ultimate temperature of approximately 32°C. This section of the pile was probably cooled somewhat by the natural draft of the pile and the infiltration of the cooler ambient air. However, the draft also carried the heat of the center and the outer shell to the top of the pile, heating it also to nearly 42°C. The center temperature reached a maximum and then began to decline as the fungus began to inactivate, and the heat production in the pile decreased sufficiently to allow some of the heat in the center of the pile to dissipate.

These results illustrate several points regarding the growth of the fungus in larger reactors. First, the fungus is not self-regulating and can quickly generate sufficient heat to raise the temperature above the optimum for fungal growth. In the case of *C. subvermispora*, the range is generally considered to be 27 to 32°C, which was greatly exceeded even in this relatively small pile. Also shown is that the natural

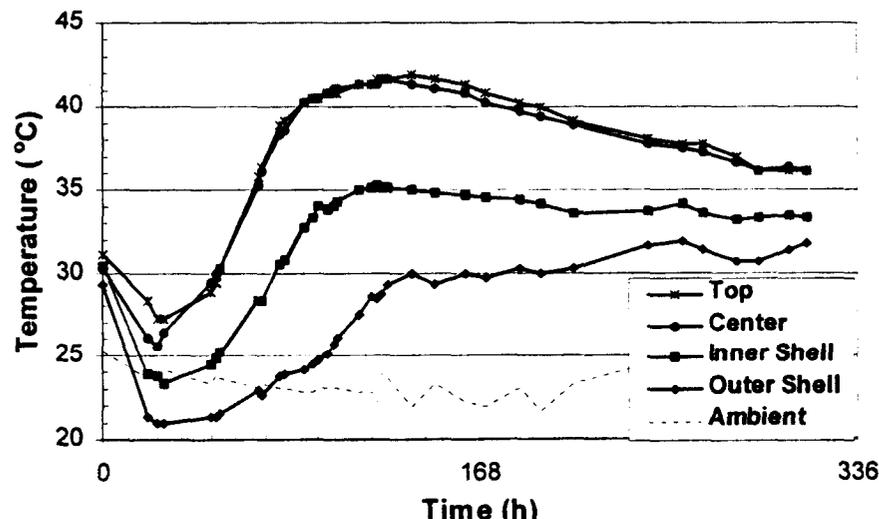


Figure 11.9 Temperature profiles for a 2-week incubation in an unventilated chip pile. Note that the temperature near the center of the pile reached 42°C, much higher than the maximum effective temperature of the fungus, 32°C.

draft generated by the heat production is not sufficient to cool the pile so as to keep the fungus within its optimum range. In larger piles, the heat buildup will probably be even greater. In fact, large temperature increases are often seen even in untreated chip piles, simply because of the indigenous organisms that are present (Hatton, 1979). In those cases in which the chips are inoculated with the biopulping fungus, the generation of heat is expected to be much greater because of the reduced competition and the greater focus of the fungus metabolism on the oxidation of lignin that generates heat. All this demonstrates the need for active cooling of the pile. Ventilation and evaporative cooling constitute one such cooling mechanism.

Figure 11.10 shows that with ventilation it is possible to bring the temperature of the pile to within the optimum growth range of the fungus. In this pile, the ventilation rate was adjusted to maintain the upper temperature of the pile at approximately 32°C or below. Initially, the ventilation was maintained at a very low level, sufficient to maintain positive pressure in the pile. As Figure 11.10 shows, the initial temperature increase, as a result of the growth of the fungus, occurred between the third and fourth day of the trial, at which time the airflow rate was increased. Although the top and the center were initially the hottest regions of the pile, after the ventilation rate was increased, the center was cooled to the optimum temperature for fungal growth. Moreover, as in the unventilated pile, the outer shell of the pile was strongly affected by the outside air (edge effect). The hot areas of the pile were the top, which was affected by the heat being generated below, and the inner shell, which was also affected by the heat being generated in the center of the pile and removed by the forced ventilation. However, the inner shell received little benefit

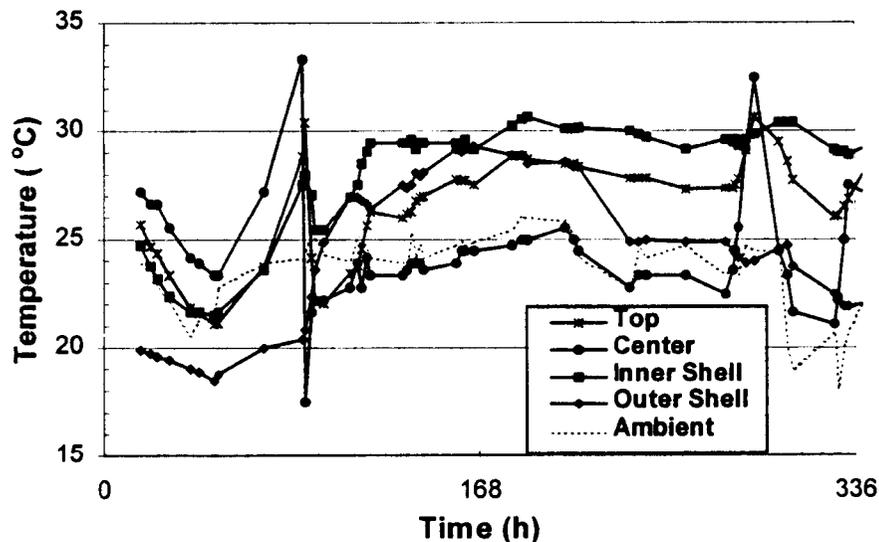


Figure 11.10 Temperature profiles for a 2-week incubation in a ventilated chip pile. A comparison with Figure 11.9 shows that ventilation is able to maintain the proper temperature in the pile.

Several smaller piles were also constructed consisting of approximately 40 kg of chips. The only source of ventilation for these piles was the natural draft created by the heat generation within the pile and air infiltration at the surface. With piles of this size, overheating of the pile was not a problem, as the natural air exchange was sufficient to keep the pile within the levels necessary for fungal growth. Energy savings upon refining chips from these smaller piles were comparable to those achieved with the bioreactors.

These results indicate that the air flow in a chip pile, even one of small size, can be very complicated. However, the chip pile experiments resulted in several important observations. Ventilation is needed for cooling even in modest-sized piles. The amount of air needed for cooling is generally much more than that needed for fungus metabolism. An understanding of the airflow in chip piles will be necessary when the process is scaled-up to industrial levels. Chip piles also test the robustness of the system, because of their greater exposure to an uncontrolled environment. In fact, the small chip piles were essentially fully exposed to the ambient conditions but still produced results comparable to those achieved in a bioreactor.

Tubular reactors have several advantages, including the production of the necessary engineering data for scale-up. They allow for controlled airflow in one dimension through the reactor, with controlled heat loss through the sides of the reactor. In general, a well-insulated tubular reactor can represent conditions that will be found in the center of large chip piles: good insulation with essentially linear airflow.

Several experiments in the small tubular reactor helped correlate airflow with temperature increase and energy savings. Figure 11.11 shows the temperature profile

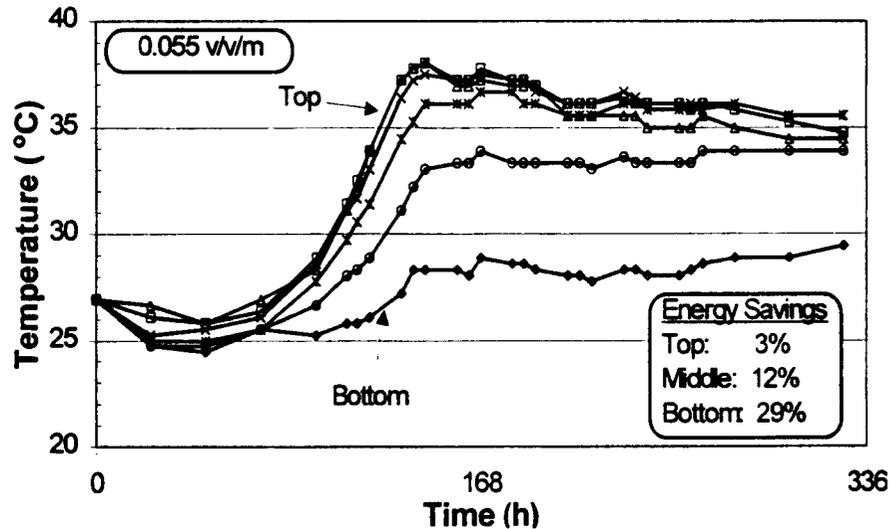


Figure 11.11 Temperature profiles in a small tubular reactor, along with the energy savings by position in the reactor. In areas in which little additional heat was generated (indicated by adjacent profiles being close together), energy savings were minimal.

for a 2-week incubation of treated chips in such a reactor. In this experiment, the chips were treated with *C. subvermispora* using the standard inoculation protocol. Ventilation was constant during the entire period at a rate of 0.055 v/v/m (0.113 m³/hr). The air supplied was relatively sterile and conditioned to be nearly moisture saturated at 27°C. The initial drop in temperature during the first 2 days was due to evaporative cooling, as the air was not quite saturated. After 4 days, there was a rapid increase in temperature from 25–27°C to 38°C at the top of the reactor. This temperature rise was due to the rapid growth of the fungus and the metabolism of the wood and the nutrients. However, as in the piles, the heat generation rate rapidly increased between the third and fifth days of incubation. The reactor system is a simple one-dimensional system; therefore, heat generation is exhibited by an increase in temperature between two adjacent thermocouples. As shown in Figure 11.11, between the bottom measurement and the next measurement there is a significant increase in the temperature difference, of 4 or 5°C, during the second week of the experiment. However, the differences between the remaining measurements are much smaller, indicating that less heat is being generated; thus, the fungus metabolism is less. It is interesting to note that the temperature difference between the second and third probe (from the bottom) was initially 3°C at the sixth day but decreased to less than 1°C after 14 days, indicating the reduction in the fungus metabolism during this time at high temperature. The energy savings during refining correlates well with the heat generation. Only 3% energy was saved in the high-temperature region where fungal metabolism was curtailed and little additional heat generated. However, at lower temperatures near the bottom of the reactor, energy savings were comparable to those obtained in static-bed bioreactors.

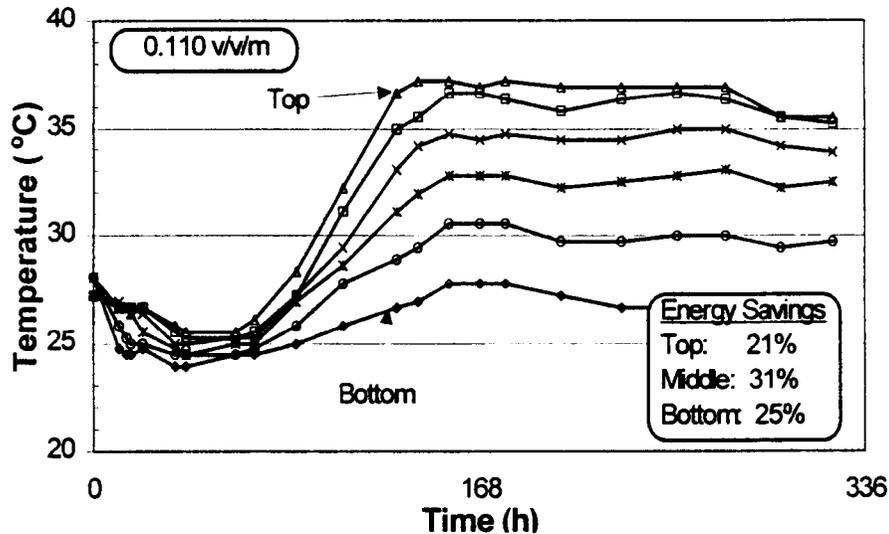


Figure 11.12 Temperature profiles in a small tubular reactor, along with the energy savings by position. This reactor had twice the airflow as that shown in Figure 11.11. Note that the energy savings were more relatively uniform through the reactor.

Results of the previous experiment indicate that more air is needed to maintain the entire reactor within the range of 27 to 32°C. Figure 11.12 shows the temperature profiles for a tubular reactor ventilated at 0.110 v/v/m (0.227 m³/hr) with essentially twice as much air. The profiles are similar to those for the previous reactor however, there is less “crowding” at the top, indicating that heat was generated, for the most part, throughout the column except at the very top. The energy savings again reflected observations. Only at the very top were the energy savings slightly reduced. Figure 11.13 shows the temperature profiles at an airflow rate of 0.220 v/v/m (0.453 m³/hr), four times that of the first reactor run. The final temperatures ranged from 25 to 32°C and are fairly evenly spaced, indicating uniform heat generation throughout the column. The energy savings increased at the top as the temperature in this location of the reactor was lowered as the result of the higher airflow. Energy savings were lower at the bottom, perhaps because of the chips’ drying out at the higher airflow rate.

The temperature profiles in a silo reactor run are shown in Figure 11.14. The control strategy in this trial was to maintain the temperature of the chips at 30°C during the initial 2 days of the incubation, and then maintain the temperature from 27 to 32°C for the remaining 2 weeks. The airflow rate and the inlet air temperature were the two variables used to control the temperature in the silo. During the first day, the temperature at all locations in the silo increased to 30°C, the inlet air temperature. After 2 days, a rapid increase in the heat production rate required an increase in the airflow rate and a decrease in the inlet temperature. Two additional changes in the inlet temperature brought the reactor temperature to the optimum range for growth of *C. subvermispota*.

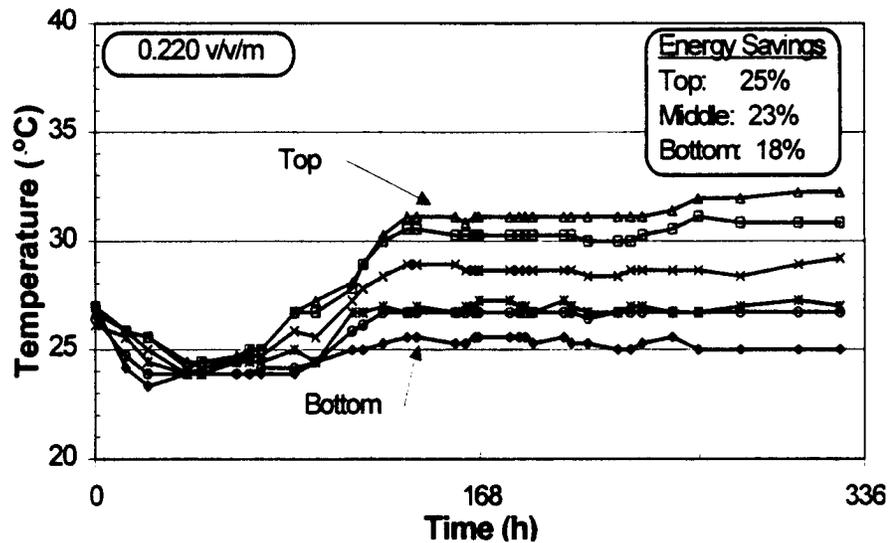


Figure 11.13 Temperature profiles in a small tubular reactor, along with the energy savings by position. This reactor had four times the airflow as that shown in Figure 11.11. Note that the energy savings at the top of the reactor increased, and at the bottom decreased.

Temperature profiles, such as those in Figure 11.14 and the preceding figures, can be used to estimate the heat generation rate as a function of temperature by performing an energy balance on a cross section of the reactor. Consider a cross section of the tubular reactor shown in Figure 11.15 (the nomenclature is summarized in Table 11.3). Air is introduced at temperature T_{in} at the bottom of the section and leaves the section at temperature T_{out} , as measured by the thermocouples. The airflow rate is given by q_a . The heat loss through the walls can be estimated as h_{loss} , based on the temperature difference between the chips and the outside temperature and the amount of insulation in the walls of the reactor. Under steady-state conditions, all heat being generated that is not lost to the surroundings is removed by the air. Furthermore, the chip moisture content and chip packing density are assumed not to change appreciably. If the air is assumed to be saturated (a reasonable assumption given the moisture content of the chips and the low superficial velocity of the air) and there is negligible conduction through the chip bed, the average volumetric heat generation rate can be calculated for that section by

$$h_s = \frac{q_a[H(T_{out}) - H(T_{in})] - h_{loss}}{V} \quad [11.1]$$

where $H(T)$ is the enthalpy of the saturated air at temperature T . In this simplified case, the changes in wood moisture content through evaporation and the production of metabolic water are ignored. Figure 11.16 shows the calculated heat generation rate in the silo as a function of time. As can be seen, the heat generation rapidly

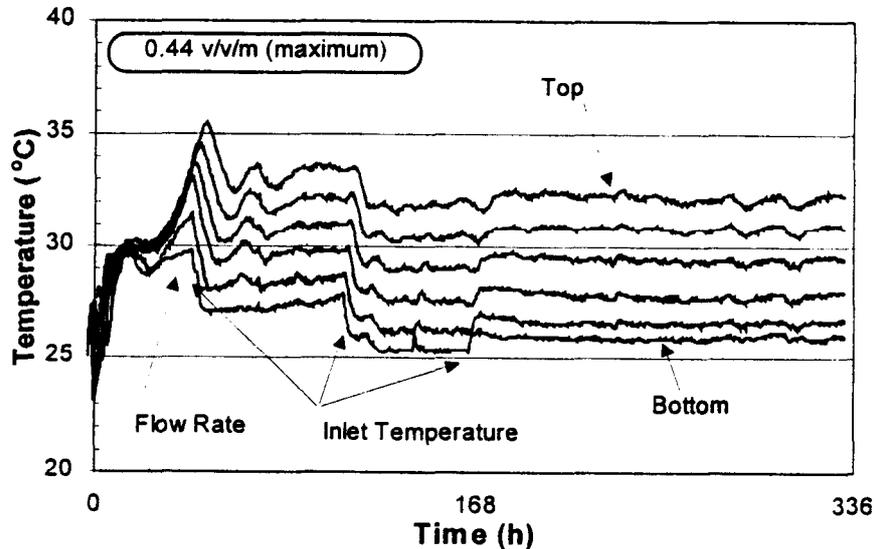


Figure 11.14 Temperature profiles in a large silo reactor. The lines indicate the temperature in the reactor from the bottom of the reactor to the top. Note the changes in the temperature profiles with changes in the airflow rate and the inlet temperature of the air.

increased from near 0 to a range of 240 to 400 W/m³ during the second to fourth day of incubation. Moreover, the heat generation rate was greater at the top of the reactor than at the bottom. This corresponds to the higher temperatures at the top of the reactor as compared with the bottom. Because the heat generation rate is a function of the temperature, the mean temperature of a section can be calculated as the average of the inlet and outlet temperatures:

$$T_{\text{mean}} = \frac{T_{\text{in}} + T_{\text{out}}}{2} \quad [11.2]$$

From the silo reactor run and several small tubular reactor runs, the heat generation as a function of temperature can be estimated for two strains of *C. subvermispora* that were used in the experiments. Figure 11.17 shows the heat generation as a function of temperature. Note that the heat generation by SS-3 (a newer, more effective strain) is much greater than that by CZ-3. This seems to indicate some relationship between the amount of heat released and the efficacy of biopulping (as measured by energy savings). Data such as presented in Figure 11.17 are useful in modeling large-scale systems in order to design the air handling equipment.

Note that in all these cases, the heating of the reactor followed a very characteristic pattern. The reactors start with an initial temperature near the inlet temperature of the air. After several days the metabolism of the fungus increases dramatically, producing heat and increasing the temperature of the column of chips. The last 9 days of the trial are typically at a fairly steady-state temperature and, hence, heat

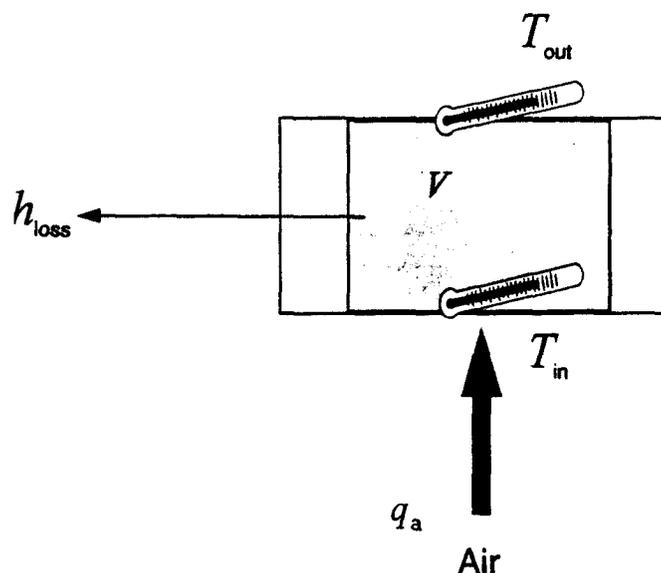


Figure 11.15 Estimation of the rate of heat generation by the fungus *C. subvermispora*. The heat generation rate is estimated by calculating the temperature rise between adjacent temperature measurements.

production. Knowledge regarding the amount of heat generated is useful for designing and sizing the air handling and cooling systems necessary for the successful operation of the reactors. Of course, other species of fungi will have different heat production rates as a function of temperature. Non-lignin-degrading fungi will generate much less heat, thus requiring lower airflow rates (probably in the range of 0 to 0.4 v/v/m) to maintain temperature within the optimum growth range for the particular fungus.

Chip Compression As the process is scaled-up, another issue to be addressed is the compression of chips by the chips above them in the pile. Greater compression is expected in fungally treated chips because of the softening action of the fungus. A certain amount of settling is observed in the bioreactors during the 2-week incubation (approximately 5%); this is expected to be of greater concern in the larger chip piles. It is also a factor in ventilation. Air is being blown through the chip pile for ventilation; therefore, compression of the chip piles will increase the pressure drop through the pile.

It was noted that the amount of fungal biomass produced by *C. subvermispora* created a significant increase in the pressure drop; therefore, *C. subvermispora* and *P. subserialis* were studied for their compression and airflow characteristics. Figure 11.18 shows the compression of fungally treated wood chips and untreated chips as a function of applied load. A load of 100 kPa is equivalent to the weight of a column of wet wood chips (50% moisture) approximately 30 m high. The chips treated with

TABLE 11.3 Nomenclature Used in Engineering Analysis.

Symbol	Definition
a, b	Constants for Suggs and Lanier correlation
D_p	Diameter of particles in a packed bed
h_{loss}	Heat loss through walls
h_s	Heat generation rate
$H(T)$	Enthalpy of saturated air at temperature T
$\frac{\Delta P}{L}$	Pressure drop per unit length
ΔP	Total pressure drop
q_a	Mass flow rate of air
T_{in}	Air temperature entering reactor section
T_{mean}	Mean temperature of reactor section
T_{out}	Air temperature leaving reactor section
u_b	Superficial velocity
V	Volume of reaction section
V_a	Volumetric flow rate of air
ϵ	Void fraction in a packed bed
μ	Viscosity of air
ρ	Density of air
ρ_b	Bulk dry density of the wood chips
ρ_w	Density of solid wood

C. subvermispora are highly compressible, reaching compressions of more than 15% under a load of 80 kPa. At the same load, control chips compressed only about 7%. *P. subserialis*, on the other hand, did not soften the chips to such a large extent as *C. subvermispora*. The chips treated with this fungus compressed only approximately 1 to 2% more than the untreated control chips. The lower compression has the advantage of not restricting airflow to as large a degree, thus reducing the cost of ventilation.

Pressure Drop Through Chip Bed Forced ventilation is one method to remove the metabolic heat of the fungus from a pile or reactor. The primary mechanism for heat removal is through the evaporation of water that is present in the chips or metabolically produced by the fungus. This air must be blown through the pile against the resistance of the chips. As this resistance increases, so does the cost of ventilation; thus, it is important that resistance be minimized. The energy cost of ventilation is proportional to the volume of air required and the pressure drop through the chips. Furthermore, the pressure drop is a strong function of the velocity (volume) of the air. Several factors are important in determining the amount of pressure drop that is experienced, including the size and size distribution of the chips, the amount of compression the chips are under, the amount of fungal growth, and the velocity of the air through the chips.

Suggs and Lanier (1985) studied the pressure drop through wood chips and other materials as a function of the superficial velocity through a column of chips. In their

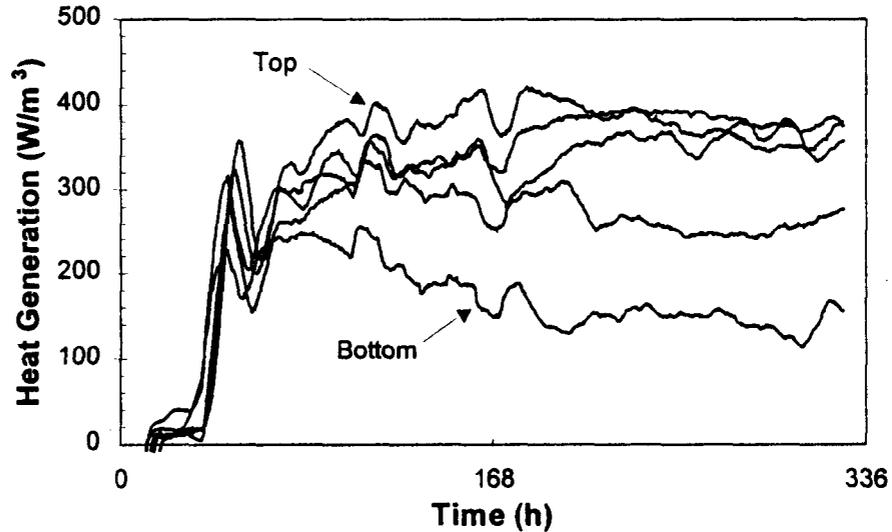


Figure 11.16 Heat generation rate by the fungus with time at different heights in the reactor. Note that there is generally an increase in the heat generation rate from the bottom to the top of the reactor corresponding to the increase in the local temperature.

study, the objective was to use air to dry the materials. They empirically found that the superficial velocity, v_o (in m/s), and the pressure drop per unit length, $\frac{\Delta P}{L}$ (in Pa/m), were related by

$$\log v_o = \log a + b \log \frac{\Delta P}{L} \quad [11.3]$$

where a and b are constants that were experimentally determined. Their values obtained for different size wood chips are given in Table 11.4.

The Ergun Equation is a common design equation used to predict the pressure drop through packed beds of material (Bird et al., 1960). The Ergun Equation is

$$\frac{\Delta P}{L} = \frac{150\mu v_o (1-\epsilon)^2}{D_p^2 \epsilon^3} + \frac{1.75\rho v_o^2 (1-\epsilon)}{D_p \epsilon^3} \quad [11.4]$$

In Equation 11.4, $\frac{\Delta P}{L}$ is the pressure drop per unit length; μ is the viscosity; v_o is the superficial velocity; and ρ is the density of the gas. The two parameters defining the characteristics of the chip bed are the effective diameter of the particles, D_p , and the void fraction of the packed bed, ϵ . The two terms on the right-hand side of the equation represent the limiting cases for laminar (viscous) and turbulent (iner-

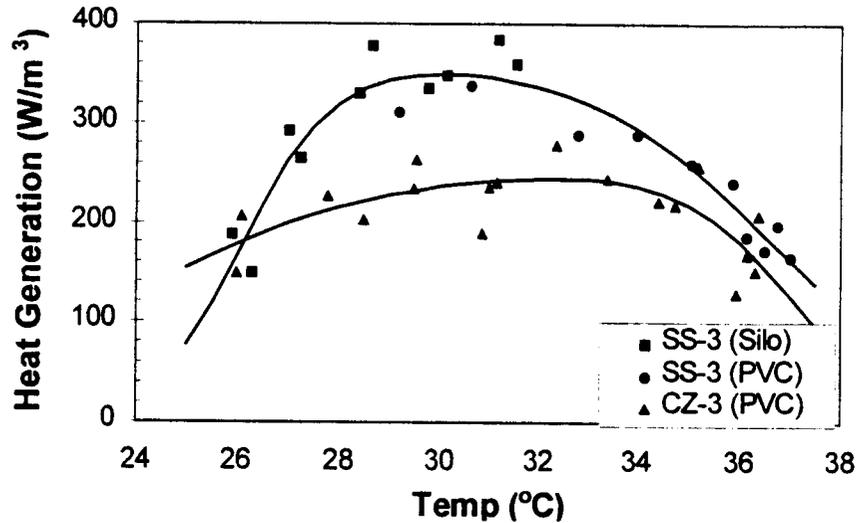


Figure 11.17 Heat generation rate as a function of temperature for two strains of *C. subvermispora*. These data are obtained from both tubular reactor and silo reactor runs after the reactor has reached steady state (generally after day 7 of the incubation).

tial) flow. For laminar flow, the first term dominates, and the pressure drop is essentially linear with increasing velocity. At higher flow rates, the flow is turbulent and the second term dominates. Hence, at higher flow rates, the pressure drop increases with the square of the velocity. The void fraction, ϵ , is related to the bulk dry density, ρ_b (the “packing” density), and the density of the wood, ρ_w , according to

$$\epsilon = 1 - \frac{\rho_b}{\rho_w} \quad [11.5]$$

The empirical equation of Suggs and Lanier is consistent with the Ergun Equation (Equation 11.4) in the turbulent regime, with the following values for the constants. The first term of the Ergun Equation is considered to be negligible.

$$a = -\log\left(\frac{1.75\rho(1-\epsilon)^{0.5}}{D_p\epsilon^3}\right) \quad [11.6]$$

$$b = \frac{1}{2} \quad [11.7]$$

Note that the values for b , as determined by Suggs and Lanier (1985) (Table 11.4), are close to the theoretical value of 0.5, especially for the larger chips. The increasing deviation as the chip size decreases is probably due to the increasing importance of the laminar term in the Ergun Equation (Equation 11.4). The determination of the

TABLE 11.4 Regression Constants for Equation 11.3.

Chip Size		b	a
Large	(> 1.9- by 1.9-cm sieve)	0.5204	0.0295
Medium	(> 1.3- by 1.3-cm sieve)	0.5352	0.0220
Small	(< 1.3- by 1.3-cm sieve)	0.6169	0.0124

values D_p and ϵ from these values is difficult because air temperature (and hence density and viscosity) and packing density were not reported.

However, these literature data can be compared with our pressure drop measurements made with control chips as a function of velocity. Figure 11.19 shows the pressure drop with velocity for the three sizes of chips studied by Suggs and Lanier (1985). Data from loblolly pine control chips in our laboratory are also shown in Figure 11.19. There is excellent correspondence between our data and the data from the literature. Although the chips in the literature were classified into three different size ranges, our chips were screened only to remove grossly oversized chips, pin chips, and sawdust. Thus, our chips contained a wider size distribution, which would lead to greater pressure drops as the smaller chips fill in the interstitial spaces between the larger chips. Differences in wood species and surface characteristics may also account for the slightly higher pressure drops we experienced at greater velocities.

The amount of compression has implications for the ventilation of the pile.

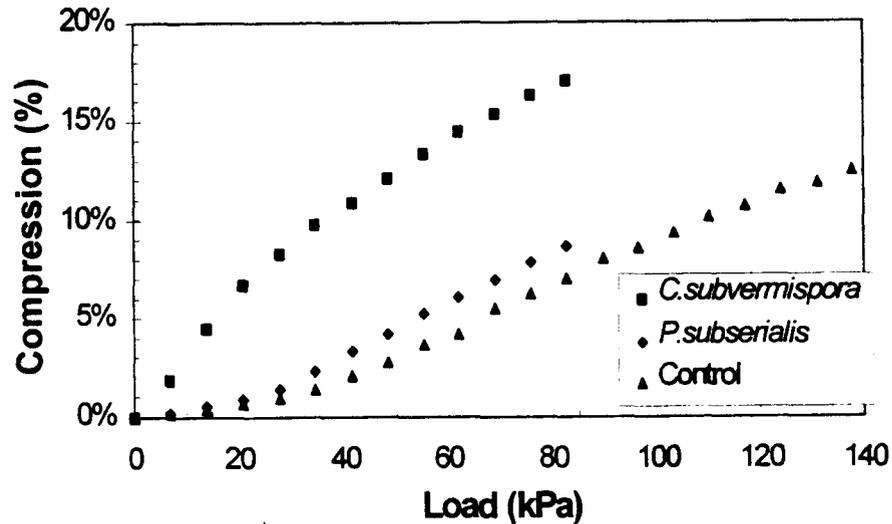


Figure 11.18 Compression of 2-week treated chips with two fungi and control (untreated) chips. A load of 100 kPa is equivalent to a column of wet wood chips approximately 30 m high.

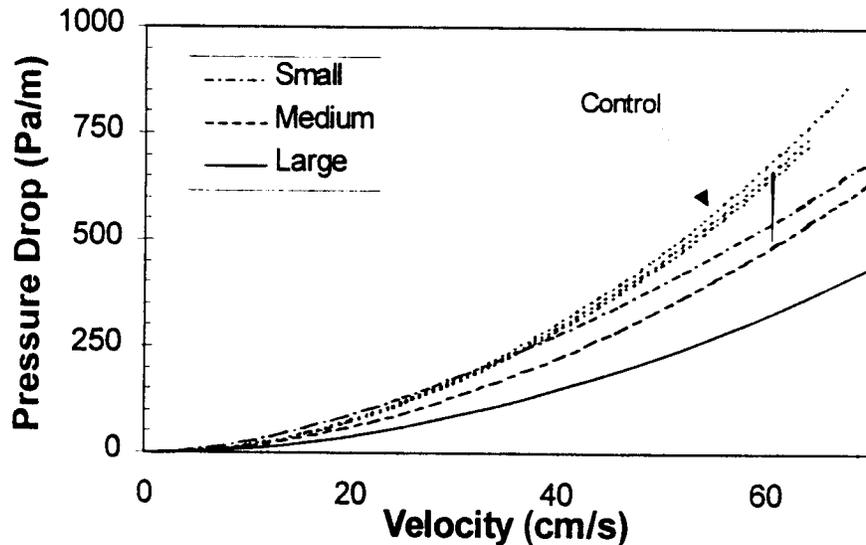


Figure 11.19 Pressure drop through a column of wood chips as a function of the velocity of the air. The small, medium, and large chip curves are based on the correlations developed by Suggs and Lanier (1985). The control (untreated) chip data correspond well with the literature data.

Greater compression reduces the void spaces between the chips, thus restricting the airflow, increasing the pressure drop, and increasing the ventilation costs. With increasing load, the bulk density of the wood chips also increases. Figure 11.20 shows the pressure drop through the column versus the dry packing density of the chips. Note that these measurements were taken after 2 weeks of fungus growth. The superficial air velocity was 0.88 cm/sec. When plotted against bulk density, there is little difference in the pressure drop between the control chips and the *P. subserialis* - treated chips. *P. subserialis* is only slightly higher in pressure drop at this velocity. However, chips treated with *C. subvermispora* exhibited significantly higher pressure drops than did the control and the *P. subserialis* - treated chips.

Analysis of the literature data and the Ergun Equation shows that the pressure drop is a strong function of the velocity of air through the chips. Air at varying velocities was blown through chips in the small tubular reactor, and the pressure drop was measured as a function of the velocity. Note that these much higher velocities put the airflow in the turbulent flow regime. Figure 11.21 shows the results for several trials including controls and 2-week treatment with *C. subvermispora* and *P. subserialis*. In Figure 11.21, the data have been fit to the Ergun Equation (Equation 11.4) by a least squares fit. The degree of fit to this equation is very good.

The three controls are quite consistent, whereas the four trials of *P. subserialis* and the two trials of *C. subvermispora* show some variation. This variation is probably due to variations in the growth patterns of the fungus near to where the pressure

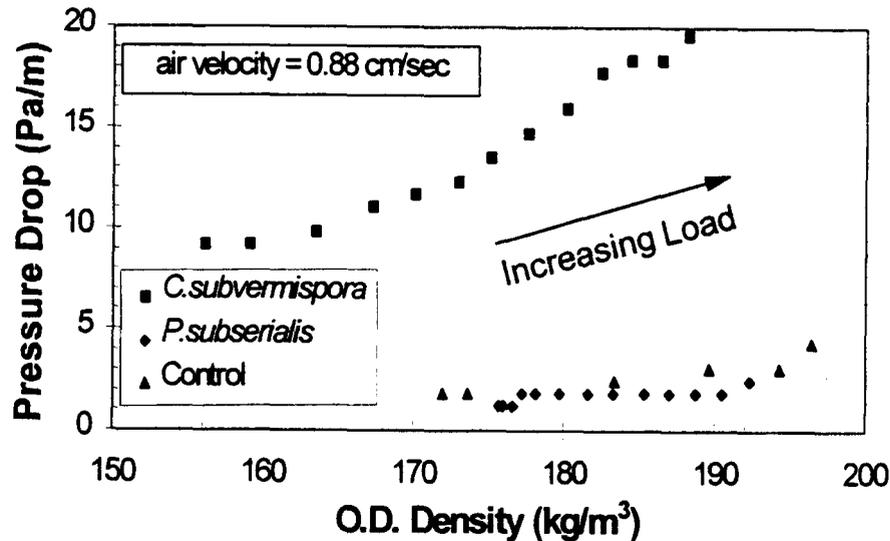


Figure 11.20 Pressure drop of air blown through a column of chips as a function of dry density in the column. The density of the packed column of chips was increased by compressing the chips at a constant rate of strain. The superficial air velocity was 0.88 cm/sec; the air temperature was 22°C at the inlet the pressure was atmospheric.

drop readings were taken. Despite the variation, *C. subvermispora* - treated chips caused significantly greater pressure drop than did either the control or the *P. subserialis* - treated chips. *C. subvermispora* produces a great deal of aerial hyphae when grown on chips, which tends to restrict the airflow through and around the chips. These hyphae become visible during the second week of the incubation; and near the end, the chips have a distinctly fuzzy appearance. *P. subserialis*, on the other hand, does not produce such a large amount of hyphae external to the chip and does not restrict the airflow as much. It appears that *P. subserialis* directs the majority of its growth into the center of the wood chips, as reflected in the ergosterol analysis. Ergosterol is the measurement of fungal biomass.

The experiments discussed so far in regard to the pressure drop through the wood chips dealt with completely developed growth. However, at the beginning of a 2-week incubation, one essentially has control chips. Thus, the effect of the time since inoculation is also a factor affecting the pressure drop. Figure 11.22 shows the pressure drop through a column of chips treated with *C. subvermispora* as a function of velocity at different times during the incubation. Note that the low velocities are primarily in the laminar flow regime. During the first 4 days, the pressure drop increased only slightly. However, during the last week of incubation (days 7 to 14), the pressure drop increased daily. This is consistent with observations made of the fungal growth on the surface. It is only after 5 days or so that the fungus was visible on the surface of the chips. At the end of the 2 weeks, the aerial hyphae often bridged between adjacent chips, causing airflow restriction.

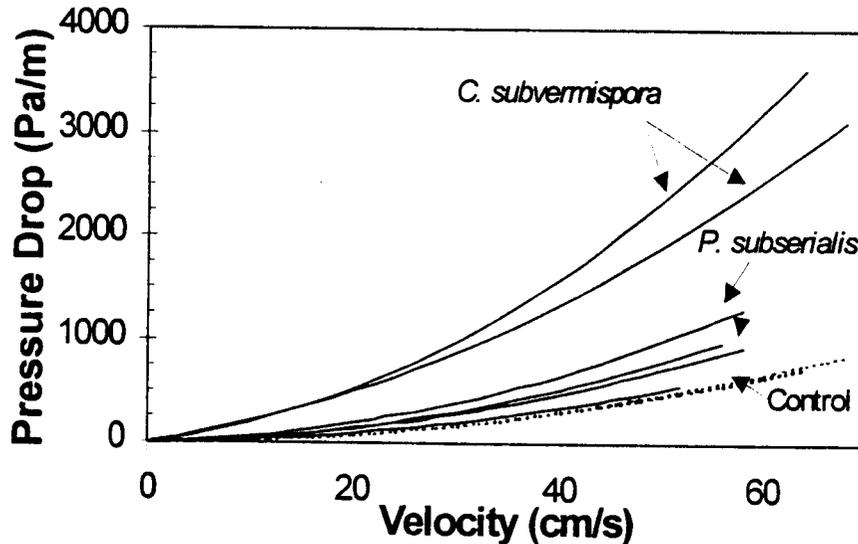


Figure 11.21 Pressure drop of air blown through a column of chips as a function of velocity for two different fungal treatments. Shown are two trials with *C. subvermispora*, four trials with *P. subserialis*, and three control trials. The air temperature was 22°C and the pressure was atmospheric.

The velocity of the air required to cool a chip pile depends on the height and the geometry of the pile. For silo or tubular reactors, the velocity is relatively constant throughout the reactors because there is essentially a one-dimensional flow of air. However, the flow in chip piles is two-dimensional and, hence, more complicated. The velocity will vary throughout the chip pile, being much greater near the air inlet and much lower near the free surface of the chip pile. The velocities shown in Figure 11.21 and the corresponding pressure drops are representative of the air velocities near the inlets to the chip piles. Figure 11.23 shows the same data extrapolated to lower velocities, which would be representative of the velocities in the bulk portion of the chip pile after the air had dispersed as a result of the larger cross-sectional area available for the flow. Even at these low velocities, the chips treated with *C. subvermispora* produced a much higher pressure drop.

The relative cost in terms of blower energy can be estimated from the product of the pressure drop through the pile and the volume of air being blown through the pile. That is,

$$\text{Ventilation cost} \propto V_a \Delta P \quad [11.8]$$

where V_a is the volumetric flow rate of the air and ΔP is the pressure drop. *P. subserialis* has two distinct advantages from an engineering point of view. First of all, it is viable over a larger temperature range (22-39°C), thus requiring less air for cooling. In addition, the lower intrinsic pressure drop also reduces the overall

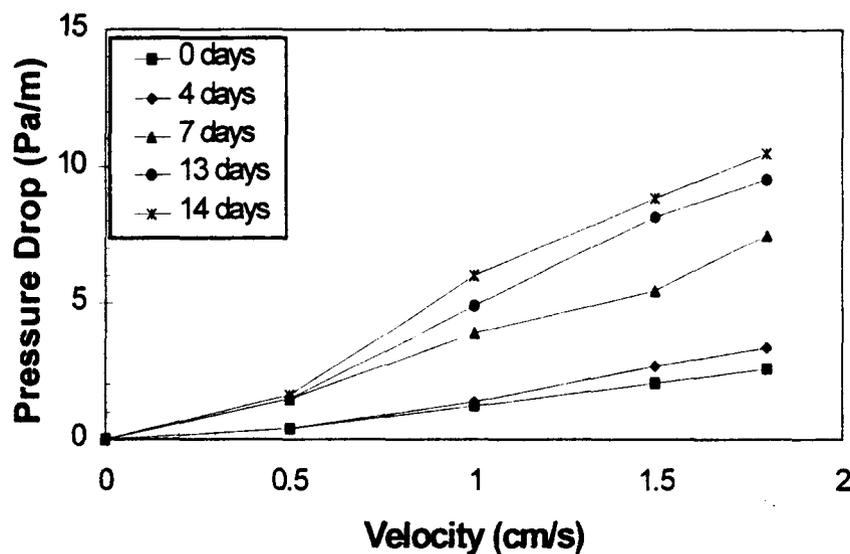


Figure 11.22 Pressure drop of air blown through a silo reactor as a function of time and velocity of the air for *C. subvermisporea*. Most of the increase in the pressure drop occurs after the fifth day of the incubation, at which time aerial hyphae are visible on the surface of the chip.

ventilation costs. Figure 11.24 shows the relative blower operation costs for chips treated with the two fungi. Note that this comparison does not take into account the additional blower costs involved in filtering and conditioning the air; only the pressure drop through the pile is considered. This comparison is based on a chip pile with a triangular cross section 20 m high and 43 m wide. The inlet air is at 27°C.

Figure 11.24 shows the relative ventilation costs as a function of the temperature increase that is allowed through the pile. All data are shown relative to *C. subvermisporea* with a 5° temperature increase, from 27 to 32°C. The graph shows control chips (or day 0 treated chips) and chips treated with the two fungi for 2 weeks. The relative costs are compared over a 2-week incubation of the wood chips. Near the beginning of the incubation, the chips are essentially control chips in their air flow restrictions. After 2 days, the heat production increases from essentially 0 to the maximum for the fungus. After 5 days, the growth of aerial hyphae increases the pressure drop almost linearly until the end of the 2 weeks. First to be noted is that when more than a 5°C temperature increase is allowed, even with *C. subvermisporea*, there is a significant reduction in the ventilation cost during the last week of a treatment. Allowing a temperature range of 27 to 33°C (a 6° temperature increase) reduces the ventilation cost to 58% of the standard. An 8° increase reduces it to 25%.

With *P. subserialis*, over the same temperature range of 27 to 32°C, the ventilation cost is about 45% of the cost for *C. subvermisporea*, simply because of the

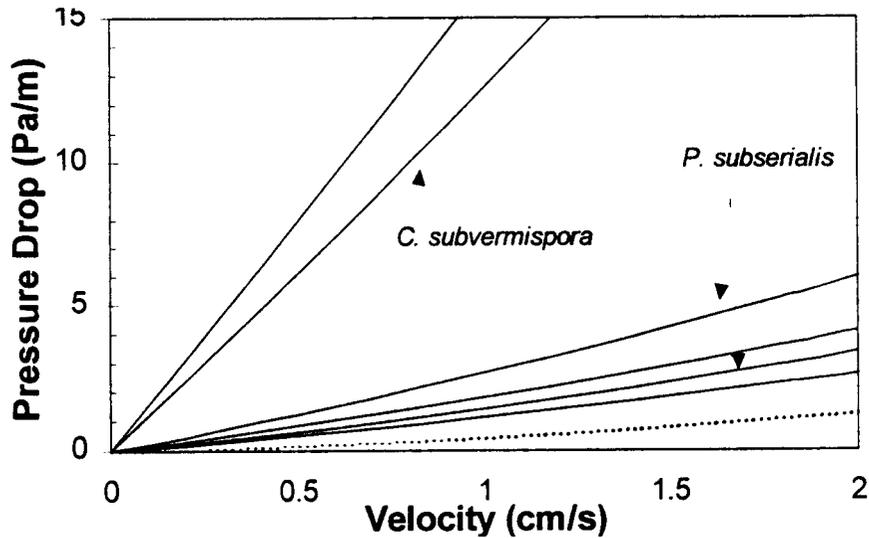


Figure 11.23 Pressure drop of air blown through a column of chips as a function of velocity for two different fungal treatments. Data from Figure 11.21 were extrapolated to the low velocity.

lessened aerial hyphae that this fungus produces. Furthermore, *P. subserialis* can grow at much higher temperatures (up to 39°C); therefore, additional energy reductions result when the larger temperature increase in the pile is allowed. A 10°C temperature increase further reduces the blower costs to 15%. The combination of the lower air volume required, because of the lower production of aerial hyphae, and, more important, the larger temperature range allowed, significantly reduces the ventilation cost for *P. subserialis*. Of course, there are additional blower resistances present regardless of the fungus, and the levels of resistance to airflow for the two fungi are significantly lower during the first week of incubation. However, there will still be benefits from the use of *P. subserialis*.

Energy Savings in Mechanical Pulping Table 11.5 shows the energy savings achieved at the various process scales for *C. subvermispora* with loblolly pine. Also shown are the improvements in tear strength of the resulting paper. The energy savings achieved for this and other fungi are discussed in detail in Chapter 10. Nearly the same energy savings were achieved from the larger-scale trials as have been regularly achieved with the laboratory-scale bioreactors. This indicates that the process can be scaled-up and the same benefits realized. Table 11.5 also indicates that greater energy savings can be achieved with longer incubation times, up to 67% with a 6-week treatment. Note that even with a 4-week treatment, the energy savings were 50% with an 80% improvement in the tear strength of the paper. The length of the treatment versus the energy savings is an economic question that will depend on the particular situation of each mill.

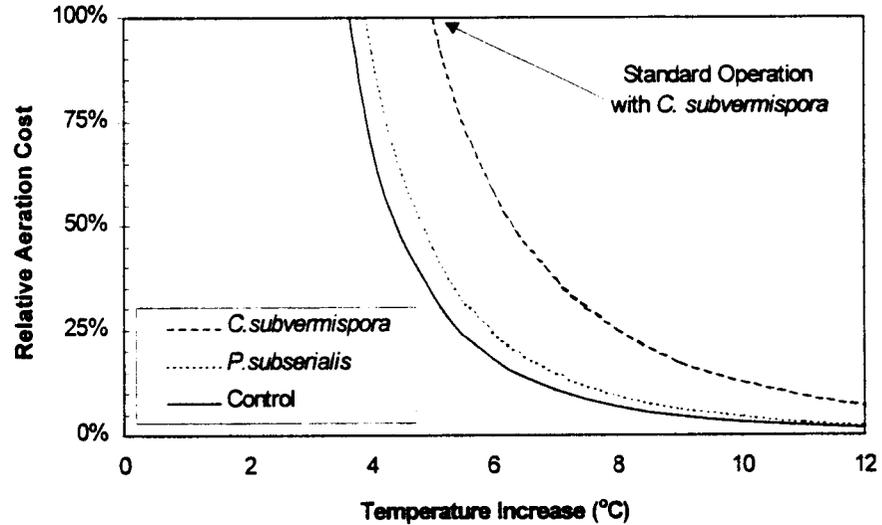


Figure 11.24 Relative blower costs for ventilation of treated wood chips in a triangular cross section woodpile. The cost is calculated over a 2-week incubation time.

Chip Inoculation on a Large Scale Chips have to be decontaminated and inoculated on a larger scale than those described here. Furthermore, the decontamination and inoculation must be done on a continuous basis and not batchwise, as has been done in the laboratory trials. To demonstrate the operation on a continuous basis, a treatment system was built that was based on two screw conveyers, which transport the chips and act as treatment chambers. Figure 11.25 is an overview of the continuous process equipment. Steam is injected into the first screw conveyor, which heats and begins to decontaminate the chips. A surge bin is located between the two conveyors to act as a buffer as well as to hold the chips for a sufficient time for

TABLE 11.5 Experimental Results from Larger-scale Reactors for *C. subvermispora* on Loblolly Pine.

Process Scale	Incubation Time (Weeks)	Energy Savings ^a (%)	Tear Improvement ^a (%)
Large Bioreactor	2	32	45
Tubular Reactor	2	29	N/A
Silo Reactor	2	28	77
Silo Reactor	3	37	N/A
Bioreactor	4	50	80
Bioreactor	6	67	N/A

^aPercent energy savings or tear improvement calculated on basis of untreated control values.
N/A = Not Available

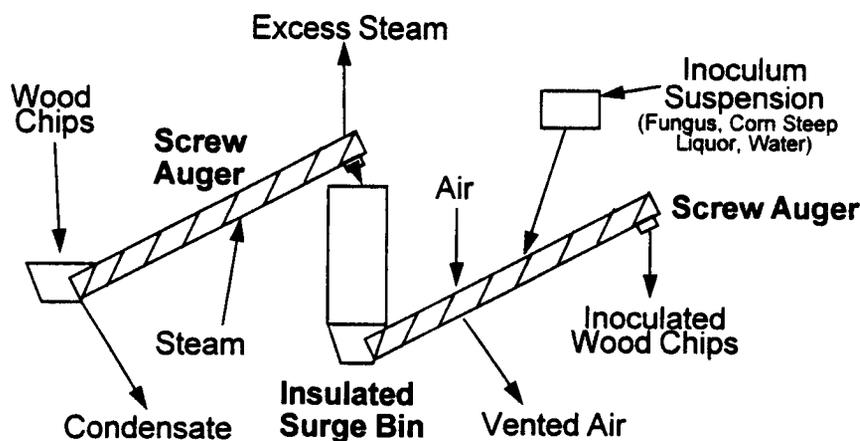


Figure 11.25 Overview of a continuous treatment process for decontaminating, cooling, and inoculating wood chips. The system is based on two screw conveyers with a surge bin between them.

decontamination. Additional steam can be injected into the surge bin to maintain the temperature of the chips. This surge bin may or may not be required on an industrial scale. From the bottom of the surge bin, a second screw conveyor removes the chips, which are subsequently cooled with blown air in half the length of the screw conveyor. The air is filtered prior to use to maintain the cleanliness of the chips. In the remaining half of the second screw conveyor, the inoculum suspension containing fungus, corn steep liquor, and water is applied and mixed thoroughly with the chips through the tumbling action in the screw conveyor. Because cooling air is still moving up the conveyor, further cooling takes place throughout the entire conveyor. From the screw conveyor, the chips fall into the pile or reactor for the 2-week incubation.

Two trials at the Forest Products Laboratory in Madison, Wisconsin, have successfully implemented this design at larger scales. In the first scale-up trial, 4 tons of spruce wood chips were inoculated and incubated at a throughput of approximately 0.5 tons per h. At the end of 2 weeks, the chips were refined and the same results were obtained as those at the laboratory scale. The design of the first successful outdoor trial with the biopulping fungus *C. subvermispora* is shown in Figure 11.26. In this trial, 40 tons of spruce were treated at a throughput of approximately 2 tons per h continuously for newly 24 hs. The equipment for decontamination and inoculation is shown in Figures 11.27 and 11.28 and is based on the process diagram shown in Figure 11.25. During the 2 weeks, the chip pile was maintained within the temperature growth range for the fungus despite exposure to much colder ambient conditions. At the end of 2 weeks, more than 30% energy savings were realized in thermomechanical pulping. These two demonstrations have verified the technology at a scale that is within an order of magnitude of the industrial level.



Figure 11.26 Overview of the large, 40-ton trial held at the Forest Products Laboratory in Madison, Wisconsin, in October 1996. To the left of the pile are the aeration units, and to the right is the treatment apparatus.

SCALE-UP TO INDUSTRIAL LEVELS

In a related development, large-scale treatment of wood chips with a fungus was performed commercially in an operation known as the Cartapip™ process, developed by Sandoz Chemicals Co. (now Clariant Corporation) (Farrell et al., 1992). The Cartapip process removes pitch and controls unwanted colored microorganisms that consume bleach chemicals. It differs from the biopulping process in that the Cartapip fungus does not attack lignin and does not save any energy during mechanical pulping. Nor are decontamination of the chips and ventilation of the piles practiced with Cartapip™, although these steps would probably lead to better control of the process. Based on the simplicity of the biopulping process and the substantial benefits it confers, we anticipate that the economic analysis following large-scale evaluation will be compelling. The fact that the Cartapip™ process is successful shows that mills are able and willing to insert a biotechnological step into their existing operations. A full description of the Cartapip process is given in Chapter 18.

Several issues must be considered for the final scale-up to industrial levels, which can range from 200 to 2,000 tons (dry) or more of chips to be processed on a daily basis. The larger scale with a 2-week treatment time would require the routine storage of 28,000 tons of wood for a 2,000-ton-per-day plant, which is a pile 160,000 m³ in volume. To put this amount of chips in perspective, it would be a pile of chips 100 m long, 40 m wide, and 40 m high. Although some mills do store and manage

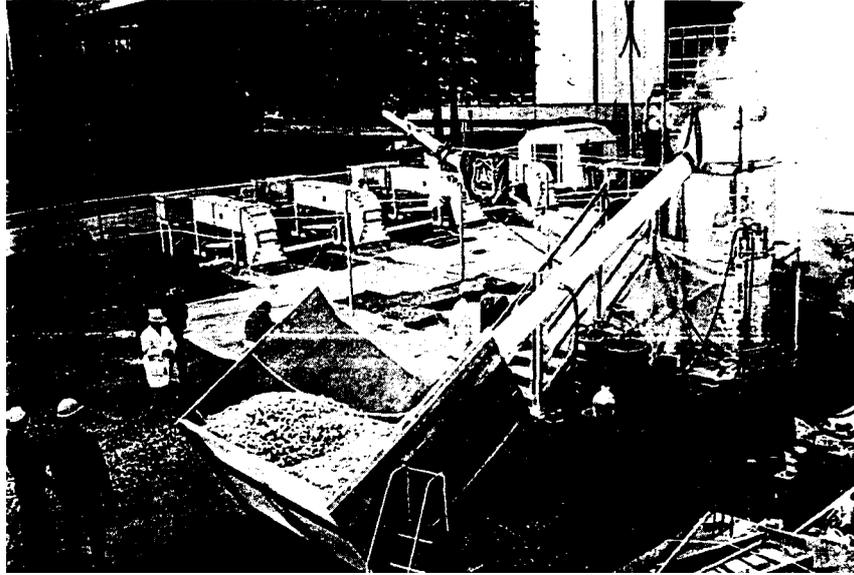


Figure 11.27 Closeup view of the screw conveyor used for steaming in the trial shown in Figure 11.26. The screw conveyor picked up the chips from the hopper and transported them to the top of the surge bin while steam was injected.

inventories in these ranges, others may have to make significant changes in their wood yard operations to take advantage of this technology. As is the case with most new technology, incorporating into new construction would be much easier than retrofitting into an existing system. However, the first large-scale operation would probably be a retrofit. Chip rotation has to be controlled with a first-in, first-out policy to maintain a consistent furnish to the pulp mill. However, this strategy is not seen as a great difficulty for most mills, because it is currently used in inventory maintenance.

One concern about the use of fungal treatment is the variation in different parts of the piles. As temperatures in the pile vary, so does the efficacy of the biopulping process. Moreover, near the edges of the piles, contamination with other microorganisms may increase competition and reduce the biopulping efficacy. The results of our 4-ton experiment, however, showed that the surface penetration of the contaminants was only 10 to 30 cm into the pile. In the 4-ton experiment, this represents about 5% of the volume of the pile. In larger piles, where the surface-to-volume ratio is even lower, the percentage would be even less, as was observed with a 40-ton trial. Furthermore, untreated chips in large industrial piles often heat to more than 50°C because of respiration and oxidation of the wood and extractives as well as bacterial and fungal metabolism. This natural growth in piles leads to variation of the quality of the chips through the pile, with the hotter center of the pile more affected by this growth. In addition, some of the indigenous organisms also degrade

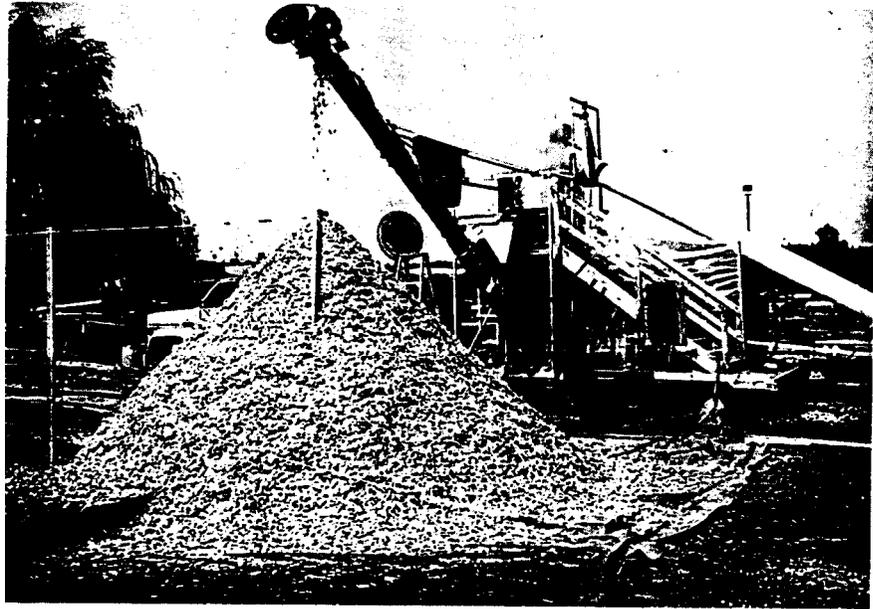


Figure 11.28 Closeup view of the screw conveyor used for cooling and inoculation for the trial shown in Figure 11.26. As the chips travel through the screw conveyor, they are cooled with air, mixed with the inoculum, and dumped onto the chip pile.

the cellulose in the wood, leading to pulp quality reductions and variation (Parham, 1983). With biopulping, this suite of naturally occurring organisms is being replaced with a single lignin-specific fungus that is grown under controlled conditions. The single organism, together with the better control of chip pile conditions, should lead to quality improvements.

Decontamination

As the scale of the project increases, construction of the equipment will probably become much easier. On the industrial scale, equipment is available in the required capacity ranges that will suit the purpose of this technology. For example, chip steaming and decontamination could be easily accomplished in a presteaming vessel similar to that used for Kamyr digesters (Smook, 1982). In this device a star valve feeds the chips to the vessel, where a slowly turning screw conveyor carries the chips through the vessel. Alternatively, a vertical, pressurized steaming bin with a downward flow of chips could also be used. Low-pressure steam can be used to heat the chips and drive off the air. Because the vessel is pressurized above atmospheric pressure, temperatures greater than 100°C can be used for the decontamination of the wood chips; these are similar to the temperatures and pressures of autoclaving. The contained unit will also significantly reduce steam use because excess steam does not readily escape from the system.

With the higher temperatures and pressures, the surge bin for decontamination time may or may not be needed. Previous work has shown that short-time steaming with good surface exposure is effective for decontamination. However, some surge capacity between the operations may still be desirable to isolate the effects of short-term shutdowns and process variations in the sequence. Our current systems use a holdup time of between 5 and 20 minutes during steaming, which is sufficient to handle the variation in the chip flow as well as provide adequate decontamination time. The amount of surge capacity will depend on the decontamination needs, operational requirements, and space availability. Again, to increase the effectiveness of the decontamination step, the surge bin could also be pressurized to achieve higher temperatures. It is also possible that the surge bin could be directly connected to the steaming vessel, thus pressurizing as one unit. A second valve at the end of the vessel would release the chips back to atmospheric pressure and the next operation.

Cooling and Inoculation

Cooling and inoculation will likely take place at atmospheric pressure. Mills that use air conveyors to move the chips to the storage location are well suited for incorporation of this technology. The conveying air will naturally cool the chips during transport, thus requiring that the inoculation be done at the end of the conveying system and before the chips are placed into storage. Mills that depend on other conveying methods—such as belts or screw conveyors—will probably require the addition of some type of ventilation cooling to reduce the temperature of the chips. In our pilot-scale work, the cooling of the chips, through ventilation in a screw conveyor used for the transport of the chips, was very successful, reducing the temperature of the chips from nearly 100°C to ambient conditions within 20 seconds, during which the chips traveled a distance of 2 m. Ventilation may also be possible using belt conveyors, although this has not been tested on a laboratory or pilot scale. Special consideration must be given to the cleanliness of the air that is used in cooling, air conveying, and subsequent ventilation of the pile. After decontamination, the chips should not be exposed to possible contamination until inoculated and sent to the chip pile. The cooling air must be filtered to remove contaminants. However, a very simple filtering system suffices for this purpose. The filters used in the pilot-scale trials were inexpensive filters, similar to those used in home furnaces. In the pilot-scale trials, no contamination was detected at the bottom of the pile near the air inlet, indicating that no significant contamination had entered through the ventilation system.

In the pilot-scale operation, the inoculation was done in the same screw conveyor that was used for cooling. Inoculum (together with the necessary nutrients and additional water) was applied to the chips and then mixed in the screw conveyor. At the end of the screw conveyor, the chips were deposited into the pile. The screw conveyor provided sufficient mixing so that the inoculum was uniformly distributed over the chips. The use of belt conveyors has not been explored; therefore, we do not have information regarding the uniformity achieved by spraying inoculum on

chips passing on a belt. However, the Cartapip[™] product has been successfully applied in this fashion (Farrell et al., 1992).

Many mill chip yards are turning to radial-arm stackers and horseshoe-shaped piles in order to better control chip inventory in a first-in, first-out strategy. The biopulping treatment would fit well into a design such as this, because the radial arm could be located where the cooling and the inoculation occur, with the steaming taking place somewhere before this step. With this type of operation the handling of the chips is minimized after inoculation, thus reducing the possibility of contamination. Of course, the air to different zones of the pile would require individual controls for airflow rate.

Currently, it is estimated that losses of approximately 1% per month of wood occur in outside chip storage systems (Smook, 1982). This loss is mainly due to the blowing of fines, respiration of the wood, and microorganism activity. The blowing of fines and sawdust, as well as microorganism growth, can also cause environmental difficulties in the vicinity of the chip piles. Thus, indoor storage can be considered as an option for incorporating a biopulping operation into a mill. Enclosing the chip storage operation should significantly reduce blowing dust and other environmental hazards. Furthermore, better control of the environment for the growth of the fungus could be maintained throughout the year. Enclosing the chip storage would also allow the recovery of the heat produced by the fungus for use in conditioning the incoming air. The geometry of the enclosed storage would also reduce the blower costs. These factors could result in substantial energy savings, especially during the winter months in northern areas.

Ventilation Strategies

As shown in Figure 11.11, the temperature (and hence the heat production) rapidly increases during the third or fourth day of incubation, reaching a maximum and then slowly decreasing during the second week. This is also seen in Figure 11.16, which shows a maximum in the heat generation rate at about the fourth day of the incubation.

We have found that a two-step ventilation strategy is very effective in managing the temperature in the reactors. During the initial 3 days, during which little heat is generated, a low airflow rate is used to maintain a positive pressure in the pile. If necessary, this initial airflow can also be used to maintain or adjust the temperature of the pile to the proper range. That is, if the chips placed on the pile are too cool, the air, which should be within the optimum growth temperature range for the fungus, can be used to warm the chips.

After the third or fourth day, the airflow is increased to a higher level to remove the heat from the pile. The inlet air should be at the lower range of the fungus, and the rate of airflow just sufficient that the maximum temperature of the chips is near the upper limit for the fungus. Experience will verify the proper airflow rate, and changes can be made as the increase in temperature is detected. More complex air-handling strategies can also be envisioned. For example, the rate of airflow could

TABLE 11.6 Operating Costs and Energy Savings for a 200 Ton/Day Biomechanical Mill.

	kW · h/ton	\$/ton @ 0.05 \$/kW · h	
Power Cost			
Main blowers	27–44	1.35–2.20	
Other	7	0.35	
	34–51	1.70–2.55	
Steam Cost	10 ⁶ BTU/ton	\$/ton @ 2.0 \$/10 ⁶ BTU	\$/ton @ 6.0 \$/ 10 ⁶ BTU
Decontamination	0.48	0.96	2.88
Air preconditioning	0.36	0.72	2.16
	0.84	1.68	5.04
Inoculum Cost		\$/ton	
		0.30–1.00	
Refiner Savings	kW · h/ton	\$/ton @ 0.05 \$/kW · h	
25–30%	375–600	19–30	

be controlled to achieve a certain temperature in a key location in the pile or to maintain the maximum temperature in the pile below a certain value. Of course, the lengthy time delays between the control action and the change in temperature will have to be considered in setting up this system.

PROCESS ECONOMICS

The economic benefits of the biopulping process have been evaluated based on the process studies and engineering data obtained to date. The economic benefits gained through use of the process result from the following effects.

Refiner Energy Savings

The electrical power savings as a result of the chip fungal treatment are shown in Table 11.6. This represents a primary source of savings for the process and has been well quantified experimentally. The savings (2-week treatment) should be a minimum of 25% under worst-case conditions of wood species and minimal process control, whereas 30% is typically expected. Savings are shown in Table 11.6 for an average power cost of 0.05 \$/kW h. Rates often vary substantially with time of day or magnitude of peak usage. In these circumstances, the cost benefits of refiner load reduction could be even greater.

The reduction in power requirement has a further consequence that could be of great significance for some mill sites. Mills that are currently throughput-limited because of refiner power limits may assign substantial value to the removal of bottlenecks provided by biopulping.

Furnish Blend Advantages

The biopulping process affects the resulting refiner mechanical pulp properties, mainly through improved strength. This is advantageous in some common mill scenarios; for instance, where the product pulp is a blend of kraft, TMP, and groundwood. The kraft component is used to impart strength and is more expensive than the TMP and groundwood components. The improved strength of the treated pulp would allow the required strength in the blend to be achieved with a lower percentage of kraft pulp, and a higher percentage of bio-pulp and/or groundwood. For example, a 50/30/20 blend of kraft/TMP/groundwood might be replaced by either a 40/40/20 or a 40/30/30 blend. The exact blend in any application will have to be optimized to ensure that all product specifications are met. The lower cost of the bio-pulp and groundwood components relative to kraft could produce substantial savings. This could also remove a bottleneck in mills that are kraft-production limited, because total blended pulp rates could be higher for a given production rate of the kraft pulp component.

Environmental Advantages

The biopulping process itself is very benign environmentally. Only benign materials are used, and no additional waste streams are generated. Biopulping chip storage is more carefully contained. In some cases, required kraft pulp production might be reduced. Such features are in addition to the substantial amount of energy conserved by the process.

These advantages may be compared with the costs associated with implementing and operating the biopulping process. A preliminary assessment was conducted in the case of a 2-week treatment with a flat pile geometry, which is a feasible, although not necessarily optimized, configuration. The scenario pertains to year-round operation in a northern climate; a southern climate scenario would show somewhat lower costs because of some reductions in containment and air-handling requirements.

The results, presented in Tables 11.6 through 11.8, are based on a 200 ton/day (dry weight basis) throughput scale. Operating costs per ton should not depend significantly on the scale. Although there should be further savings in the capital requirements (per ton/day) for larger throughput, their extent is not certain at this stage of evaluation. Conservatively, the capital requirements are scaled linearly with throughput.

Table 11.6 summarizes utility savings and requirements. The range of blower power requirements reflects the differences between fungi. The cost of low-pressure steam may be quite site dependent, and two values are given to indicate a range. Table 11.7 summarizes estimates of the fixed and working capital requirements.

Table 11.8 summarizes the economic evaluation; it shows the cumulative extremes of the ranges in the preceding tables. The net savings ranges from 10 to 26 \$/ton, with an estimated capital investment requirement of $\$2.5 \times 10^6$. Simple rate-of-return numbers are also shown. Although the high end of the savings range is probably optimistic, the low end is almost certainly overpessimistic. In round fig-

TABLE 11.7 Capital Costs for a 200 Ton/Day Biomechanical Pulping Mill.

	10 ⁶ \$
Site construction	0.45
Equipment	
Steaming	0.35
Blowers	0.35
Air preconditioning	0.58
Other	0.12
Total	1.50
Other contingency	0.37
Inventory @ 10 d add.	0.30
Total	2.52

ures, net savings of at least 10 \$/ton, and a simple annual rate of return (ROR) on capital of at least 25%, are likely.

The numbers given are the result of a preliminary study and are subject to appropriate qualifications. Even so, a good deal of process research has been conducted to establish the operating costs and savings. The capital cost estimate is subject to some variability, in particular the costs associated with integrating the new facility into an existing site. Nevertheless, the ranges shown in Table 11.8 indicate that the biopulping process should more than pay for itself based on utility saving alone.

It is important to remember that the process economics summarized in Table 11.8 represent only part of the overall economic impact of the process. The additional potential advantages mentioned, concerning furnish blend economics, removal of bottlenecks, and environmental considerations, can strongly augment the overall economics of the process. These advantages are not quantitatively analyzed here because they are site-specific in their particulars. However, the economics associated with them may be quite significant, and they must not be overlooked. Silo-based systems also have to be considered more thoroughly from an economic standpoint.

TABLE 11.8 Economic Summary for a 200 Ton/Day Biomechanical Mill.

Operating costs	(8.59)–(3.68)	\$/ton
Refiner savings	19–30	\$/ton
Net savings	10.41–26.32	\$/ton
Capital costs	2.52 × 10 ⁶	\$
Savings simple ROR	0.29–0.72	
Savings @ 0.15 ROR	4.96–20.87	\$/ton

CONCLUSIONS

Our engineering and economic analyses indicate that the biopulping process is technologically feasible and economically attractive. Instrumented and insulated bioreactors constructed to mimic commercial-size chip piles have provided data on heat buildup and the rate of fungal action. On a pilot-scale level, methods for surface decontamination of wood chips, cooling, fungal inoculation, and controlling temperature and moisture throughout the chip bed, using conditioned air, have been developed. A complete process flowsheet has been established for commercial operation and tested on a pilot scale. Based on the electrical energy savings alone, the process appears to be economically feasible. The additional benefits of biopulping—better quality pulp, greater throughput, and environmental improvements—enhance the economic picture for this technology. Two different fungi were investigated here for biopulping efficacy. Although they produced similar results in regard to the energy savings during mechanical pulping, differences between the growth patterns of the two fungi could have a significant effect on the economic analysis.

Four-ton and 40-ton trials, in which the decontamination of chips, subsequent cooling, and inoculation were performed sequentially in screw conveyors, provided us results similar to those obtained using laboratory-scale bioreactors.

Although a great deal of work has been performed over the past nine years to bring the biopulping technology to this point, many questions remain. The most basic concern is the mechanism of biopulping. It appears that the two biopulping fungi discussed in this chapter have different mechanisms in their action on wood chemistry and structure. Although *C. subvermispora* has a distinct softening effect on chips, *P. subserialis* does not soften the chips as much, but still results in essentially the same energy savings with mechanical pulping. An understanding of the mechanism should facilitate the optimization of the process for both mechanical and chemical pulping.

A better understanding of the decontamination process is also needed. Steaming has been very effective in reducing the contaminant load to allow the colonization of the chips by the biopulping fungus. However, an understanding of the time and temperature relationships in decontamination would greatly improve optimization of the process. More aggressive biopulping fungi would reduce the need for the initial decontamination step. However, an initial decontamination would still be beneficial, because the reduced competition increases the efficacy of the biopulping fungus. Larger-scale trials, in conjunction with pulp and paper mills, are needed to further confirm the economic feasibility of biopulping.

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ENVIRONMENTALLY FRIENDLY TECHNOLOGIES FOR THE PULP AND PAPER INDUSTRY

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