Review of Environmental Impacts and Applications of Biotechnology in the Pulp and Paper Industry in Canada

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ABSTRACT

This thesis examines the environmental issues facing the Canadian pulp and paper industry and the potential application of biotechnology to solve some of these problems and contribute to a sustainable growth in the future.

The Canadian pulp and paper industry has recently been the focal point of criticism on pollution by the public and governments. This is because the industry utilizes vast amount of natural resources such as the forests, streams and rivers, which are shared by many Canadians. Under increasing public pressure, governments have begun to toughen regulations limiting the quantities of pollutants released by pulp and paper mills into the environment. There is also widespread public perception that the forest resources are not being managed properly to ensure future utilization and enjoyment by all Canadians. Although the pulp and paper industry has spent millions of dollars modifying processes and installing waste treatment facilities, these are only short-term solutions to meet government standards. In the long run, the industry must be more proactive and develop a strategy for sustainable growth and to rid itself of the image of air and water polluter. Such a strategy would include the development of new processes that are less polluting than current technologies and make the best use of natural resources. Biotechnology has a promising potential in meeting these criteria. Biotechnology can offer a wide scope of applications including:

- Plant biotechnology: silviculture, reforestation, replacement of chemical pesticides with biological control agents.

- Biopulping and biobleaching: reduce the amount of polluting chemicals used in the production of pulp.

- Effluent treatment: micro-organisms can be selected to treat mill effluent more effectively.

- By-product conversion: wood waste can be hydrolyzed by enzyme to sugar, then fermented to ethanol that can be used as a renewable transportation fuel. One of the federal government's objective outlined in the Green Plan is to stabilize the total carbon dioxide emission in Canada. The substitution of gasoline by biomass ethanol would contribute significantly to this goal.

In this thesis, a process simulation model was developed using Lotus 123 to evaluate the economic feasibility of coupling a wood waste-to-ethanol conversion plant to a pulp mill. The model has been useful in identifying the key parameters that have the most significant impact on the process economics.

Although current economic conditions do not favour the bioconversion of wood to ethanol, this process merits support from both government and the forest products industry because it can potentially make a positive environmental contribution. This support could be in the form of more funding for research and development, a "green" tax credit for biomass ethanol, and possibly a "pollution" tax for fossil fuels.

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1.0 INTRODUCTION

1.1 Overview of the Canadian Pulp and Paper Industry

Canada is the world's largest exporter of pulp, paper and other forest products. Canada's share of world exports of pulp, paper and other forest products is 21%, approximately double that of Sweden or the U.S., the closest competitors[1]. In 1988, the industry's net contribution to Canada trade balance was $19.6 billion. The contribution by the pulp and paper industry was $13.8 billion, $4 billion higher than the total Canadian net merchandise trade surplus.

The pulp and paper industry contributes significantly to the economies in British Columbia, New Brunswick, and Northern Ontario. It is a major industrial component in every region of Canada with the exception of Prince Edward Island and Southern Saskatchewan[2]. It is the most important or only source of income for about 175 different towns or communities with combined residence of about 250,000 people. It is estimated that pulp and paper mills, and related logging operations provide direct employment for 173,000 Canadians.

The industry is highly capital-intensive at the mature stage, cyclical, and highly dependent on international markets. It is vulnerable to swings in the business cycle and to changes in international exchange rates. The healthy earnings of 1987 and 1988 financed record-level capital spending programs, mainly in expansion of capacity to produce tissue, printing and writing

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[1]Canadian Pulp and Paper Industry Annual Report, 1989, p. 18.

[2]Sinclair W.F., "Controlling Pollution from Canadian Pulp and Paper Manufacturers: A Federal Perspective", Environment Canada, March 1990, p. 10.

papers. In 1989, the operating capacity averaged 92.5% for the industry as a whole. In 1990, the operating capacity is expected to drop to slightly below 91.3% due to additions in capacity and the recession. The world demand for paper and paperboard is expected to increase in the next decade to more than double the current size of the Canadian industry's capacity. The opportunities for growth are tremendous, providing the industry can secure funds for expansion and long-term wood supply for the mills.

1.2 The Environmental Issue

Today, the Canadian pulp and paper industry faces two important issues: (i) remaining competitive in a global economy and (ii) protection of the environment. These two issues are related. In order to achieve a sustainable growth and competitiveness the industry must, among other things such as modernization, expanding production facilities and improving productivity, deal with the environmental issue. The pulp and paper industry, as a significant user of natural resources (forest and water) and a major source of pollutants, has the potential to cause major adverse effects on the environment. The pollutants discharged from pulp and paper mills affect both water and air qualities, and to a lesser extent land. In Canada, it has been estimated that the pulp and paper industry is responsible for 50% of all the waste dumped into the nation's waters[3]. The industry is the cause for seven of seventeen areas of concern in Ontario identified by the Great Lakes Water Quality Board. It accounts for approximately 5.6% of the common air contaminants from known industrial sources.

The liquid effluent from pulp and paper mills, if not treated properly before being discharged to natural water bodies, can have three major undesirable impacts:

1. Lowering dissolved oxygen levels necessary for aquatic life.

2. Adding chemical compounds which can have adverse effects on aquatic organisms and fish.

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[3]Sinclair W.F., *op. cit.*, p. 34.

3. Depositing suspended solids (fibres, clay, etc.) on the bottom of the river or lake. These sludge beds exert a demand on the oxygen resources of the natural waters; anaerobic decomposition of the sludge produces odour problems; and gases from anaerobic decomposition processes float suspended solids to the water surface.

Recent tests have shown that traces of dioxins and furans exist in the effluent of many pulp mills. A fillet sample from one fish out of 15 tested from the Athabasca and Wapiti Rivers contained more than the federal government's limit of 20 parts per trillion for dioxins and furans[4]. Traces of dioxins have been found in paper products such as coffee filters, milk cartons and disposable diapers. These chemicals, suspected of causing cancer, are formed when high levels of chlorine are used in bleaching. With increasing public awareness and demand for safer consumers' products and tougher regulations for industrial waste disposal, governments are under greater pressure than ever to tighten existing laws and step up enforcement. Without direct government intervention, the costs imposed on society by pollution and misuse of resources are not fairly paid by industry and its consumers. These hidden costs are seldom included in the production costs or reflected in the prices paid by the end users. Therefore, the environmental issue should not be limited to environmentally friendly or recyclable products, but a total approach to sustainable development should be sought. The idea of sustainable development, first articulated by the World Commission on Environment and Development (the Brundtland Commission) in 1987, is the primary motive for the federal government's Green Plan[5]. Sustainable development meets the

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[4]Pulp and Paper, Vol. 64, No. 8, 1990, "News Scan", p. 37.

[5]"The Green Plan - A National Challenge", Environment Canada, Cat. No. En. 21-86/1990, p. 1.

needs of the present generation without compromising the ability of future generation to meet their own needs. The Canadian Pulp and Paper Association, in its Environmental Statement in June 1989[6], has also endorsed the concepts of "... sustained yield forestry and environmental management..."

[6]Canadian Pulp and Paper Industry Annual Report, 1989, p. 1.

1.3 Focus of the thesis

This thesis reviews the structure and basic technology of the Canadian Pulp and Paper Industry and its environmental protection practice. It examines the potential application of biotechnology in improving processes, products and waste treatment. A computer simulation model is presented for studying the technical and economic feasibility of alternative uses of wood waste.

Biotechnology can be broadly defined as the application of biological processes, via microbial, plant or animal cells, or their constituents, to provide goods or services[7]. The major cause of pollutants from conventional pulp and paper technology is the use of chemicals in the pulping and bleaching processes. These chemicals also cause undesirable reactions which produce toxic chemicals. An example is the formation of chlorinated organic compounds, including dioxins and furans in the bleaching of certain pulps using chlorine. The attractiveness of using biological processes lies with their specificity, i.e., undesirable reactions resulting in toxic by-products are avoided. Therefore, in general biological processes are less damaging to the environment and can potentially offer the pulp and paper industry a solution to sustainable development.

This thesis is divided into two parts. In the first part, a general overview of pulping and bleaching processes where biotechnology can be applied to improve product quality and reduce pollution is introduced. In the second part, a more specific analysis is presented in the form of a cost/benefit study on the conversion of wood waste to ethanol in a sulphite

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[7]Roe L. and Furguson J., "Provincial Governments' Biotechnology Expenditures & Activity 1985-86", Ministry of State Science and Technology, Strategic Technology Branch, Nov. 1986, p. 2.

mill. A spreadsheet simulation model is used to evaluate the technical and economic feasibility of alternative processes. Process simulation is increasingly recognized as a useful tool for studying complex processes, identifying and carrying out sensitivity analysis on key process and economic parameters. It is also particularly useful for estimating preliminary capital investment and production cost of new products under development, and for cost/benefit evaluation against alternate options.

2.0 BACKGROUND and LITERATURE REVIEW

2.1 Key Players in the Environmental Issue

This section reviews the key players and their perspectives with regard to the environmental impacts caused by the pulp and paper industry.

2.1.1 The public and consumers

In the 1980's Canadians became increasingly more aware of the negative impact of pollution on the environment and public health, thanks to environmental activists' campaigns and wide media coverage. According to a recent Maclean's/Decima survey[8], 68% of Canadians polled named the environment as the most important issue facing the nation. There are signs indicating that consumers are more selective and willing to spend a little more on products that are perceived as environmentally friendly. This "green" movement is widespread and growing steadily. There is a growing demand for environmentally friendly and recyclable products. In an Angus Reid Poll taken in April 1990, about 80% of respondents would look for biodegradable and "friendly" products, and avoid styrofoam and packaging[9].

Industries and big businesses were often singled out as the major polluters. Changes in consumer preferences are felt not only in consumer products but also in large industries such as petroleum, pulp and paper. The pulp and paper industry received significant negative public reactions regarding dioxins found in certain chlorine-bleached product and high pollutant levels in mill

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[8]Fulton E. Kaye, "The Right to Know", Maclean's, Vol. 103, No. 38, September 17, 1990, p. 75.

[9]Cu-Uy-Gam Mirian, "Eco-labelling becoming new industry", The Financial Post, June 4, 1990, p. 38.

effluents. Many businesses were able to change their products and marketing strategies quickly to meet this new consumer demand. An example is the Loblaw's "green" product lines: phosphate-free detergent, cloth diaper, organic fertilizer, etc. The pollution problems can be categorized broadly into three major areas: air pollution, solid waste and water pollution.

Air pollutants originate from many sources. Hydrocarbons, carbon dioxide, ozone and nitrogen oxides from vehicle exhaust cause urban smog and are linked to respiratory illness. Acid rain killed an estimated 14,000 lakes and damaged 150,000 more in Canada[10]. It is also suspected of contributing to respiratory problems in children. Acid precipitation can also increase the level of toxic metals - such as aluminum, copper and mercury - in untreated drinking water supplies. The major source of acid rain is sulphur dioxide emitted from coal-fired generating stations and nonferrous ore smelters. Another culprit is nitrogen oxides which usually come from vehicles and fuel combustion. There is also growing concern about the potential global warming effect caused by "green house" gases such as carbon dioxide, methane, nitrous oxide which trap solar heat. The atmospheric carbon dioxide level has increased rapidly in the past few decades due to the burning of fossil fuels and the destruction of large tracts of rain forests which act as a carbon dioxide sink. In 1987, among total emissions of 128 million tonnes of CO_2 in Canada, approximately 30% were due to transportation sources, 20% from power generation, 23% due to natural gas combustion, 6% from the combustion of spent pulping liquors, and 5% from wood combustion[11].

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[10]Cu-Uy-Gam Miriam, "Acid rain: Outlook sunnier", The Financial Post, June 26, 1989, p. 32.

[11]Jaques A.P., "National Inventory of Sources & Emissions of CO_2 (1987), Draft Report", Environment Canada, June 1989, p. viii.

Public perception is that cutting down trees has a negative impact on the environment. The clear-cut practice of the forest products industry has created a negative public image. The forest products industry is often scrutinized for its past record of poor management of forest resources and current logging of old-growth forests. Environmentalists charged that clear cutting of old growth forests destroy the ecosystems. Protesters have tried to block plans by MacMillan Bloedel to harvest centuries-old timber on Meares Island, off the west coast of Vancouver Island, and in the Carmanah Valley on Vancouver Island. The Maclean's/Decima survey showed that 56% of Canadians polled think logging of mature forests should be halted, even if it meant fewer jobs in the forest industry and higher prices for wood and paper products.

Garbage is increasingly become a major problem for large urban centres. Toronto's garbage dump site will be full in three years[12]. Finding new dump sites presents problems because many communities are now less willing to take someone else's trash. And this only offers a short-term solution since more new sites, located at even further distances, will have to be found. This has sparked talks about the "three R's" program: reducing the amount of garbage produced, re-using materials directly (for example, refilling beer bottles), and recycling. Today, the "blue boxes" programs in many cities recycle paper, glass and metal. Since paper makes up the bulk of municipal waste, governments are encouraging paper recycling. In the U.S. news print must contain a minimum of 50% recycled material. Although there is no such legislation in Canada, more and more businesses are using recycled paper products to improve corporate environmental image.

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[12]Israelson David, "Toronto at the top among Canada's trash heaps", Ottawa Citizen, October 21, 1990, p. C4.

The forest product industry also has a solid waste disposal problem. Most of the waste are in the form of bark, sawdust, shavings, and rejected fibres. Some mills burn the solid waste to produce steam or electricity. Others landfill the waste. These methods of disposal cause air and water pollution respectively. Most biomass boilers do not have a high combustion efficiency when burning wet fuel such as rejected fibres from the primary clarifier, thus emitting undesirable gases and particulate into the atmosphere. Leaching of chemicals from bark and rejected fibres buried in landfills into ground water, streams and rivers is another concern because it may contaminate the drinking water source of communities living nearby.

Water pollution probably receives the most public attention because 84% of Canadians drink municipally treated water, whether from the surface or under-ground[13]. According to a Gallup poll published in October 1989, 95% of those polled were concerned about the quality of drinking water[14]. Most often, the major sources of water pollution come from industrial wastes being discharged directly into water bodies. Most existing municipal water treatment systems are designed to remove bacteria and some organic wastes, but they cannot effectively remove inorganics and many toxic chemicals. About one in every six Canadian households now use either bottled water or a home treatment system to remove chemicals and other undesirable elements from their drinking water[15]. In Montreal, where many residents are uneasy about the fact that the severely polluted St. Lawrence River is the source

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[13]Ohlendorf-Mofat Pat, "Is your water safe to drink", Chatelaine, Vol. 63, No. 11, November 1990, p. 54.

[14]Nichols Mark and Jensen Holger, "Danger in the water", Maclean's, Vol. 103, No. 3, January 15, 1990, pp. 30-33.

[15]Walmsley Ann, Wickens Barbara and Quinn Hal, "Alternatives to tap water", Maclean's, Vol. 103, No. 3, January 15, 1990, pp. 36-37.

of their drinking water, the ratio is as high as one in every three households. Many people switched from tap water to spring water to avoid chlorinated organic chemicals known as trihalomethanes, that are formed by the reaction between chlorine used as a disinfectant in water and organic materials. Studies in the U.S. had shown that there is a slightly higher risk of cancer among people living in areas where water is chlorinated. Traces of organochlorines, including dioxins and furans, detected some chlorine-bleached paper products such as milk cartons and baby diapers have recently attracted a lot of public attention. Although the regulations and limits on chemicals discharged in plant effluent are being toughened, environmentalists and other critics charge that governments often tolerate pollution because they are unwilling to come down hard on industries that provide jobs and tax revenues.

Public perceptions, whether logical or not, can create a formidable force that industries must not ignore. The following are just a few of many examples.

McDonald's Restaurants of Canada Ltd. bowed to public pressure and stopped serving burgers and other sandwiches in polystyrene foam boxes[16]. The company said that it stopped using foam containers because of the public perception that these containers are harmful to the environment, even though the polystyrene industry had stopped using chlorofluorocarbons (CFCs), the chemicals which are suspected of destroying the earth's ozone layer, since January 1989. The public outcry has proven to be a major obstacle for the proposed Alberta-Pacific Forest Industries mill in Northern Alberta. The company had to scrap the original plan to use chlorine bleaching to win approval from the federal-

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[16]Fox John, "McDonald's no-foam plan stuns Lily", The Financial Post, Nov. 5, 1990, p. 3.

provincial review board[17]. Environmentalists charged that the cattle farming contributes to global warming and water pollution[18]. They blamed that the prime reason for cutting rain forests, which act as vast CO_2 sinks, is to create grazing land for more cattle. Furthermore, manure pollutes streams and rivers. As well, each of the approximate 1.3 billion cows in the world belches out as much as 400 litres of methane, a potent greenhouse gas, every day - enough for the U.S. Environmental Protection Agency to label cattle a possibly significant contributor to global warming. Although this kind of protest has not resulted in any significant impact on the beef market, it drew public and governments attention that may eventually influence the way the cattle industry raise their stock.

Public demand on protection of the environment together with wide media coverage of alleged environmental harm done by the forest products industry have exerted tremendous pressure on government to toughen pollution regulations and enforcement and forced pulp and paper companies to change the way of doing business. The increasing demand for recycled newsprint and chlorine-free pulp have forced several companies to modify their mills to process recycled paper and to import old newsprint from the U.S.A. New pulping and bleaching processes are being employed to reduce the level of pollution discharged into the environment. Secondary waste treament facilities are being installed in some older mills at great costs.

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[17]Pulp & Paper, Vol. 64, No. 6, 1990, "News scan", p. 33.

[18]Precker Michael, "Cows - Environmentalists blame cows for destroying the water, rain forests and global warming", The Ottawa Citizen, December 2, 1990, p. C4.

2.1.2 Government

Because the Canadian Pulp and Paper Industry is responsible for 50% of all the waste dumped into the nation's waters, most of the regulations pertaining to the industry have focused on water pollution. There is a substantial overlap between the different levels of government and among agencies in air and water pollution control. To date, the development and enforcement of pollution abatement regulations have appeared to be a bureaucratic nightmare. The respective pollution control responsibilities of the federal and provincial governments have generally been vague. Although Environment Canada is now, and will likely remain, the principal environmental authority within the federal government, it is not the only federal agency with authority for waste control. Other departments which share such authority include, but are not limited to, Indian and Northern Affairs, Transport Canada, and Agriculture Canada. To complicate the matter further, the federal government uses the Fisheries Act as the legislative base for effluent regulations. The Department of Fisheries and Oceans Canada, which is responsible for administering the Fisheries Act, is less concerned with pollution abatement standards than with the effect of pollution on fish. Over the years, this has led to some disagreement between Fisheries and Oceans personnel and Environment Canada personnel[19].

The pulp and paper effluent regulations were passed into law in November 1971[20]. Internal process controls were recommended rather than external treatment to reduce effluent discharges. The effluent regulations have two requirement standards and three levels of compliance. The requirement standards are based on a

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[19]Sinclair W.F., *op. cit.*, pp. 103-105.

[20]*Ibid.*, p. 93

distinction between "old mills", built prior to November 24, 1971, and "new mills" built subsequently. The three levels of compliance include more stringent standards for new mills, and somewhat less restrictive targets for old mills.

The effluent regulations were augmented by the air emission guidelines for the pulp and paper industry in 1979. Under the authority of the Clean Air Act, Environment Canada established air emissions guidelines developed in conjunction with the provinces and industry[21]. Like the effluent, the guidelines are national in scope and based on technology that has been proven to be economically feasible. Federal air emission guidelines are not regulations that can be enforced under law. They are national guidelines designed to help the provinces establish standards that are comparable nation-wide. The provinces are responsible for air emissions from industrial plants located within their boundaries.

The parameters most commonly used to monitor the pollution levels of the mill effluents are:

- Total suspended solids (TSS): mainly fibres.

- Biochemical oxygen demand (BOD). BOD is a measure of oxygen required to oxidize the organic matter in a sample through the action of micro-organisms contained in the sample.

- Chemical oxygen demand (COD). COD is a measure of oxygen required to oxidize the organic matter in a sample through the reaction with strong oxidizing agents. A COD of a waste is generally higher than the BOD because more compounds can be chemically oxidized than can be biologically oxidized.

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[21]Sinclair W.F., *op. cit.*, pp. 93-94.

The BOD, COD, and TSS are often expressed in terms of kilogram per tonne of pulp produced by the mills.

- Toxicity to fish. The standard laboratory test for the acute lethal toxicity of pulp and paper mill effluents is the 96-h LC_{50} (median lethal concentration) fish bioassay[22]. The test involves placing groups of rainbow trout in a range of concentrations of effluent, diluted with fresh water (to which the fish are acclimated), and observing their survival throughout a 96-h test period. Samples of effluent identified as "non-toxic" are those in which more than 50% of the fish exposed to full-strength effluent for 96 h survive. The higher the LC_{50} value for a sample, the less its toxicity.

- Absorbable organic halides (AOX). These are chlorinated organics resulting from bleaching of pulp using chlorine and chlorine compounds. The AOX contributes to most of the toxicity in the bleachery effluent.

The main parameters used to monitor the common air contaminants from the pulp and paper industry include[23]:

- Particulate matter

- Sulphur dioxide

- Total reduced sulphur (TRS). The TRS compounds consist mainly of hydrogen sulphide, methyl mercaptan, dimethyl sulphide, and dimethyl disulphide.

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[22]D. McLeay and Associates Ltd., "Aquatic Toxicity of Pulp and Paper Mill Effluent: A Review", Environment Canada Report No. EPS 4/PF/1, April 1987, pp. 35-40.

[23]Sinclair W.F., *op. cit.*, p. 35.

The federal effluent regulations require each mill to measure and keep record of its discharge flows, and to sample for BOD, TSS, and toxicity to fish. Government employees also randomly collect samples of mill discharge and conduct laboratory analyses.

The liquid effluent from pulp and paper mills, if not treated properly before discharged to natural water bodies, can have three major undesirable impacts:

1. Lowering dissolved oxygen levels necessary for aquatic life.
2. Adding chemical compounds which can have a toxic effect on fish.
3. Depositing suspended solids (fibres, clay, etc.) on the bottom of the river or lake. These sludge beds exert a demand on the oxygen resources of the natural waters. And anaerobic decomposition of the sludge produces odour problems. Gases from the anaerobic decomposition process float suspended solids to the water surface.

The largest group of pollutants in pulp mill effluent that demand oxygen are organic in character. Most existing laboratory tests do not measure the quantity of organic matter in the effluent directly, but rather relate it to the amount of oxygen required to oxidize it. The methods commonly used are BOD and COD. The federal toxicity standard is often used to measure the toxicity of the mill effluent on local fish. Organochlorines, including dioxins and furans, are also subjected to regular monitoring for pulp mills using chlorine in bleaching. The average amount of organochlorines produced per tonne of pulp is 3 kg. Both B.C. and Quebec governments want to reduce this level to 1.5 kg/t by 1994[24]. Meeting these requirements is expected to cost the BC pulp and paper mills (18 out of a total of 22 are affected) $1 billion.

Environment Canada have encouraged the use of internal environment control over external control. External pollution control facilities, while can be put into operation more rapidly than internal production processes can be changed, do not foster a clean process concept, i.e., it is better not to generate the pollutants in the first place. Internal control encourages the use of modern technology which helps to maintain the competitive position of the Canadian industry. This is particularly true for the pulp and paper industry which depends on a large export market. The demand for environmentally friendly products is on the rise, especially with the European market. Buyers are also seeking out products from mills using processes which are less disruptive to the environment.

An important part of the overall strategy used to control the discharge of waste material is the referral system used between different levels of government and among agencies at the regional level. Seven provinces (excluding British Columbia, Quebec and Newfoundland) have established accords with the federal government by which the provinces assume the lead role for enforcement, but they also agree to enforce requirements at least as stringent as those required under federal regulations[25].
The federal government realized that many older mills would have needed substantial equipment upgrading and process improvement in order to meet the new regulations. The pollution abatement method via internal control, i.e., improving processes to

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[24]Cu-Uy-Gam Miriam,"Tighter toxic limits pressure pulp sector", The Financial Post, June 26, 1989, p. 33.

[25]Sinclair W.F., *op. cit.*, p. 95.

minimize the amount of discharged pollutants, was preferred over external control, i.e., reducing the pollutant levels to a safe limit by external treatments such as aerobic and anaerobic digestion. To assist the industry in developing environmentally acceptable processes and modernizing older mills, several incentive programs were offered[26].

- Accelerated Capital Cost Allowance (ACCA): which allows depreciation for tax purposes of up to 50% each year on the capital expenditures made on facilities and equipment. This program was first applied to water pollution control in 1965, and extended to air pollution control in 1970. In 1972, the ACCA was extended further to include all primary manufacturing equipment. The ACCA does not change the total taxes paid, but allows extended use of tax funds which eventually have to be paid.

- Co-operative Pollution Abatement Research: A total of $10.6 million was granted to the industry during the life of the program from 1971 to 1979.

- Development and Demonstration of Pollution Abatement Technology: This shared-cost program was initiated in 1975. A total of $15 million was spent by the industry and federal government.

- Demonstration of Resource and Energy Conservation Technology: The program was initiated in 1979. So far only $200,000 was granted to one mill in Quebec.

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[26]Sinclair W.F., *op. cit.*, pp. 96-98.

- Pulp and Paper Modernization Program: This shared-cost program was initiated in 1979 under which the participating provinces (Ontario, Quebec, and the Atlantic provinces) and federal government share some of the cost. A total of $3.1 billion was invested. The federal government's contribution was approximately $276 million; the provinces contributed $241 million; and the balance was invested by the industry.

More recently, the federal government have established a series of policies, legislations and action plans to protect human health and the environment from pollution. These are:

(i) The Green Plan (1990)

The goal of the Green Plan[27] is to ensure that the activities of businesses, individuals, communities and government are consistent with the concept of sustainable development. In establishing this overall environmental policy, federal government plans to consult with the public and businesses and develop concrete measures to achieve the ultimate goal: "to make Canada, by the year 2000, the industrial world's most environmentally friendly country". The five-year environmental plan, costing $3 billion and subjected to annual re-assessment, covers the following major areas:

- Clean air, land and water
- Sustaining renewable resources
- Parks and wild life
- The Arctic
- Global warming, ozone depletion, acid rain

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[27] "The Green Plan: A National Challenge", Environment Canada, 1990.

(ii) <u>The Canadian Environmental Act (CEPA) (1988)</u>

Under CEPA[28], toxic substances (chemicals, living organisms, or products of biotechnology) are controlled from development and production, through transportation, distribution and usage, to ultimate disposal.

(iii) <u>The Canadian Acid Rain Control Program (1988)</u>[29]

With the signing of seven federal-provincial acid rain agreements, Canada now has in place new standards design to cut in half the SO_2 and NO_x emissions from sources within Eastern Canada by 1994. The Canadian and U.S. governments signed an agreement on March 13, 1991 designed to reduce acid emission in both countries by 50% by the year 2000.

(iv) <u>The Federal Water Policy (1987)</u>[30]

The overall objective of the federal water policy is to encourage the use of fresh water in an efficient and equitable manner consistent with the social, economic and environmental needs of present and future generations. The federal government recognizes that the Constitution Act does not contain direct reference to the water resource. Hence, the provinces exercise propriety rights and have the authority to legislate in water resources within their borders. The provinces delegate some of this authority to municipalities. The federal government has propriety rights regarding federal lands and water in the territories,

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[28]The Canadian Environmental Act, Environment Canada, 1988.

[29]"Stopping Acid Rain - The Canadian Program", Environment Canada, 1988.

[30]"Federal Water Policy", Environment Canada, 1987.

national parks, and Indian reserves.

(v) Canada's Environmental Choice

Environment Canada's Environmental Choice Program, in an effort to help consumers in identifying products which are less harmful to the environment, issue the EcoLogo - three birds entwined to resemble the maple leaf - to the manufacturers of goods that conform to criteria[31]. Companies can apply to Environment Canada to have their products evaluated for environmental soundness. If the government guidelines are met the companies can be licensed to display EcoLogo symbols on their products. So far, at least 24 companies have met the government standards[32]. The EcoLogo products include fine paper made from recycled paper and insulation made from recycled wood-base cellulose.

The federal government is also studying proposals on "emission trading" system, permits or credits are distributed to polluters in an area, allowing them to discharge certain amounts of a compound based on an overall pollution target for that region[33]. Other considerations include: subsidies to promote environmentally beneficial products, "green" taxes on polluting products, and natural resources pricing systems that reflect the environmental costs of their extraction.

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[31]Cu-Uy-Gam Miriam, "Eco-labelling becoming new industry", The Financial Post, June 24, 1990, p. 38.

[32]Pulp and Paper, Vol. 64, No. 11, 1990, "News Scan", p. 33.

[33]Fox John, "A Green plan for smog credits", The Financial Post, December 17, 1990, p. 3.

All provinces have passed legislation requiring environmental assessment on major industrial projects. The provinces (except Quebec) also have or are developing long-term plans for conservation of sustainable development for national resources[34]. Ontario developed a comprehensive program called the Municipal- Industrial Strategy Abatement (MISA)[35] in 1987 aiming to control waterways. The development of MISA involved inputs from Environment Canada, the general public and businesses.

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[34] McIlroy Anne, "Toward a cleaner Canada - The Uncertain Path", The Ottawa Citizen, October 20, 1990, pp. I1-I6.

[35] "Municipal-Industrial Strategy for Abatement - The Public Review of the MISA and the Ministry of the Environment's Response to it", Ontario Ministry of the Environment, January 1987.

2.1.3 Canadian Pulp and Paper Industry

The Pulp and Paper Industry has been trying to improve its public image regarding environmental issues. In its 1989 Annual Report[36], the Canadian Pulp and Paper Association has committed itself to:

- "Excellence in sustained yield forestry and environmental management"
- "Multiple use and sustained yield"
- "Work with governments in the development of regulations and standards based on sound, economically achievable technologies".

In a statement released on January 1991 regarding the impact of the forest industry's activities on global climate change[37], particularly on the carbon dioxide cycle, the Canadian Pulp and Paper Association stated that it "supports an international effort to understand and address the subject of global climate change". It also commits to energy conservation, fuel substitution, renewable forest resource and recycling pulp and paper products.

According to The Canadian Pulp and Paper Association, the industry has made a significant effort in cleaning up its operation. From 1960 to 1988 pulp and paper companies spent $2.3 billion on air and water pollution abatement. Over this time the quantity of suspended solids in the liquid effluent of the mills was reduced by more than 91% per tonne, and the amount of dissolved solids by 74% per tonne. The reduction in pollution

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[36]Canadian Pulp and Paper Industry Annual Report, 1989, p. 1.

[37]Canadian Pulp and Paper Association, "A Statement by the Pulp and Paper Industry - Global Climate Change", Jan. 1991.

in the whole reflects the fact that some of the older sulphite mills, which generated the most pollutants per tonne of pulp produced, were shut down, and new expansions have higher pulp yields and generate less pollutants. Currently, the focus is on limiting trace levels of dioxins, furans, and other chlorinated organics found in bleachery effluent. Research has shown that these organochlorines are formed when chlorine is used in the bleaching stage. Companies are modifying their processes to reduce or eliminate the use of chlorine. At the same time they express concern that tough government regulations may undermine profitability.

Despite this significant effort to improve environmental practices, some sectors of the industry apparently still have a long way to go to meet future government's tough regulations. The Sinclair Report[38] stated that "less than ideal progress has been made during the last 17 years in bringing the pulp and paper industry into compliance with federal regulations". A large proportion of the mills have not yet achieved compliance with the minimum standards. Between 1970 and 1986, as the industry's average production increased by 31%, the annual emissions of common air contaminants (particulate, carbon monoxide, nitrogen oxide and hydrocarbons) increased by about 60%. In the same period, sulphur dioxide emission dropped by 12%. The average daily effluent toxic, BOD, and TSS discharges were reduced by 37%, 36%, and 52% respectively. The 5-year average trend of capital investment in air and water pollution control dropped slightly from 15% to 13% of total capital investment.

[38]Sinclair W.F., *op. cit.*, p. 164.

The industry is aware of the sensitive issue of sustainable development of the forestry resources. However, past mistakes by the industry and the provincial governments, who have the jurisdiction over the forest resources, have resulted in the industry still relying heavily on old growth forests for its wood supply. Effort is being made to regenerate the forests with silvicultural techniques. In 1988, 450,000 hectares were seeded compared to 165,000 hectares seeded in 1978[39]. More areas are being prepared and tended. However, because it takes at least 50 years for new second growth of a softwood forest to establish before commercial cutting, the sustainable development for the industry as a whole would not likely be achieved for some time. The pulp and paper companies tried to forestall the problem by acquiring large sawmills to secure fibre supply[40].

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[39]Canadian Pulp and Paper Industry Annual Report, 1989, p. 25.

[40]Fletcher Anne, "Forest renewal a haunting issue", The Financial Post, December 10, 1990, p. 5.

2.2 Pulp and Paper Market

2.2.1 Products

The industry produces a broad range of products:

- Bleached Kraft pulp for writing papers, food and milk containers.
- Thermo-mechanical pulp for newsprint, mechanical printing papers, and paperboards.
- Unbleached Kraft pulp for wrapping papers, bags, and some paperboards.
- Specialty sulphite pulp for applications in photo film, rayon and pharmaceutical products.
- Recycled paper for newsprint, mechanical printing papers and paperboards.

2.2.2 Current sales and market

In 1989, the Canadian shipments of pulp, paper and paperboard were 24.85 million tonnes. These shipments had a value of about $20 billion, with exports accounting for $15 billion. Canada's share of world exports of pulp, paper and other forest products is 21%, double that of Sweden or the United States, the two closest competitors. The breakdowns of shipments by product and by area are shown in **Table 1** and **Table 2** respectively. The operating capacity for the printing and other papers sectors was expected to decline from 89% in 1989 to 86% in 1990 . The packaging papers and paper board sectors are expected to operate at 92%, and the market pulp also at 92%.

In 1990, because of the recession, the industry suffered poor revenues, especially in market pulp, and eroded profits[41] (**Table** 3). The industry blamed the drop in earnings on low pulp prices, high interest rate and the high Canadian dollar.

The growing demand for recycled paper and chlorine-free bleached pulp by the U.S. market, which makes up half of all shipments, will have a significant impact on future production methods employed by Canadian companies.

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[41]Pulp and Paper Canada, extracted from "Industry News" Vol. 92, No. 1, 1991, p. 9; Vol. 91, No. 10, 1990, p. 7; Vol. 91, No. 7, 1990, p. 7.

Table 1 Shipments by product (thousand tonnes)

Newsprint	9,665
Mechanical printing papers	1,611
Book and writing papers	1,550
Kraft papers	518
Tissue and special papers	497
Containersboard	1,940
Boxboard	729
Wood pulp	9,219
Total	25,729

Source: Canadian Pulp and Paper Annual Report (1989)

Table 2 Shipments by area (thousand tonnes)

CANADA	5,741
UNITED STATES	13,005
UNITED KINGDOM	906
WESTERN EUROPE	2,403
JAPAN	1,467
LATIN AMERICA	553
ALL OTHERS	1,654
Total	25,729

Source: Canadian Pulp and Paper Annual Report (1989)

Table 3   **First three quarters sales and earnings for Canadian pulp and paper companies in 1989 and 1990**

Companies	Sales, $M		Earnings, $M	
	1989	1990	1989	1990
Abitibi-Price	2456	2345	68	21
Canadian Pacific Forest Products	2160	1898	103	12
Canfor	679	673	83	4
Cascades	506	605	21	13
Crestbrook	202	170	27	12
Domtar	1919	1793	54	-61
Donohue	486	456	35	21
Fletcher Challenge	1061	837	97	57
MacMillan Bloedel	2487	2307	207	65
Noranda Forest	3643	3516	162	-38
Perkins	55	57	3	3
Repap	869	921	66	14
Rolland	339	312	-2	-3
Scott	326	371	11	11
Tembec	186	180	27	12
Weldwood	590	518	56	14

Source: Pulp and Paper Canada, 92:1 (1991) p. 9; 91:10 (1990) p. 7; 91:7 (1990) p. 7.

2.2.3 Future growth

The Canadian Pulp and Paper Association[42] predicted that pulp and paper shipments from Canada could reach 35 million tonnes by the year 2000 as a result of the Canada-U.S. Free Trade Agreement, the hoped-for further dismantling of the trade barriers under GATT, and emerging market opportunities in Eastern Europe and East Asia.

Although the demand for pulp and paper continues to grow strongly, new pulping capacity coming on stream in the next several years will not be absorbed easily[43]. Coupled with the onset of the 1990 recession, the result would inevitably be a typical cycle of bust and boom as observed in the past.

The fastest growth will be in printing, writing paper and tissue. The emphasis will continue to focus on quality, recycling, and environmentally friendly products and processes. There will be a significant increase in demand for chlorine-free bleached pulp as well as recycled newsprint. Because Canada exports more pulp and paper than we consume domestically, in order to meet the requirement of recycled paper content required by law in several importing countries, notably the U.S., the industry will likely have to import waste paper from abroad.

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[42]Canadian Pulp and Paper Industry Annual Report, 1989, p. 22.

[43]Per Gundersby and Jan Rennel, "New Market Pulp Capacity Means Producers May Face Trying Times", Pulp and Paper, Vol. 64, No.8, August 1990, p.p. 120-124.

2.3 Basic Environmental Protection Technology of the Pulp and Paper Industry

This section provides a brief summary of the major areas of waste treatment that currently are of most concern to the industry. For a more in-depth study readers are referred to the works of Springer[44] and McCubbin[45,46].

In general, the industry must meet the government regulations in the areas of: effluent discharges, gaseous emissions and solid waste disposal. A typical schematic flow diagram of a pulp and paper mill using chemical pulping process (such as sulphite or Kraft) is represented in **Figure 1**. Environmental protection measures can be classified as internal control or external treatment. Internal control involves modification of processes or equipment to minimize or eliminate the pollution. Whereas, external treatment relies on add-on waste treatment facilities to improve the quality of the discharges. For pulp mills that discharge high effluent volumes, internal control is generally more cost effective than building expensive waste treatment systems.

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[44]Springer Allan M., "Industrial Environmental Control - Pulp and Paper Industry", John Wiley & Sons, 1986.

[45]McCubbin Neil, "The Basic Technology of the Pulp and Paper Industry and its Environmental Protection Practice", Environment Canada Training Manual EPS 6-EP-83-1, 1983.

[46]McCubbin Neil, "State of the Art of the Pulp and Paper Industry and its Environmental Protection Practices", Environment Canada Report EPS 3-EP-84-2, 1984.

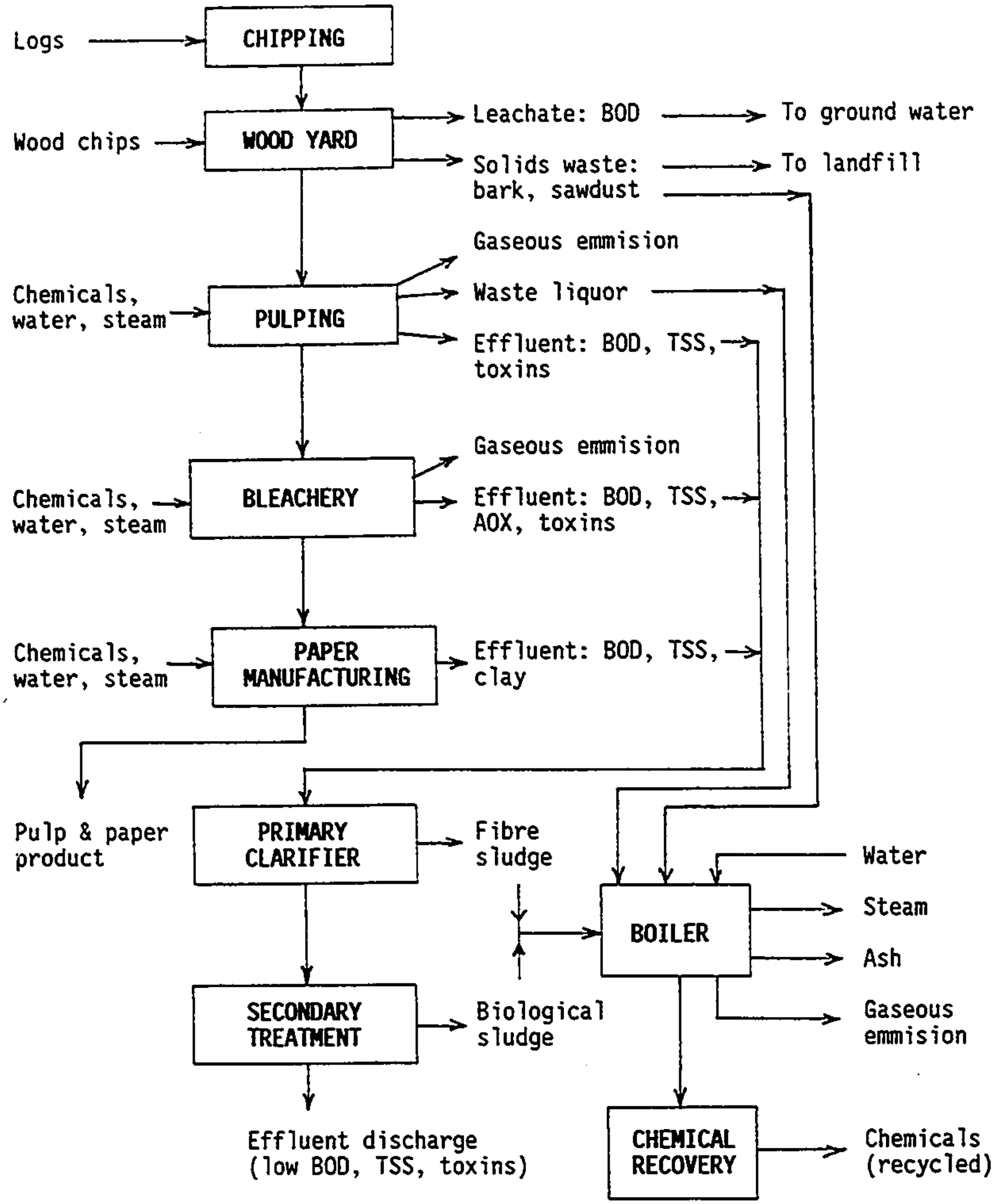

Figure 1 **Flow diagram of a typical chemical pulp and paper mill**

2.3.1 Effluent discharges

The quantities and properties of the discharges vary considerably depending on the process employed at each individual mill. The typical raw waste loads for different pulping processes are shown in **Table 4**. The levels of TSS and BOD must be reduced below limits set by environmental regulations. Each province set its own standards based on guidelines from Environment Canada. These standards are specific to the types of process used by the mills and also to the different steps in each process. For example, there are standard values for washing of logs, debarking, cooking, bleaching, and drying of pulp. For BOD, the standards are lower in the summer than in the winter. From **Table 4**, it is evident that mill effluents require treatment to reduce the BOD and TSS levels below government standards. The enforcement of these standards are sometimes dependent upon the local environmental and economic conditions. Unless the pollution limits are grossly exceeded, governments tend to extend the deadlines of compliance to older mills which show progress in cleaning up their effluent discharges rather than shutting down the mills and create unemployment problems.

Table 4 Typical raw waste loads for various pulping processes*

Products	Effluent (M^3/t)**	BOD*** (kg/t)	TSS*** (kg/t)
Bleached Kraft (dissolving pulp)	241	55 (16)	113 (14)
Bleached Kraft (market pulp)	171	40 (16)	71 (14)
Bleached Kraft (paperboard, tissue)	151	38 (16)	70 (14)
Bleached Kraft (fine papers)	133	32 (16)	82 (14)
Unbleached Kraft	53	17 (10)	110 (10)
Groundwood (chemimechanical)	113	95 (15)	52 (12)
Groundwood (thermomechanical)	99	28 (10)	48 (12)
Groundwood (papers)	91	17 (10)	52 (12)
Sulphite (papers)	220	126 (53)	89 (14)
Sulphite (market pulp)	244	123 (94)	33 (14)
Sulphite (dissolving pulp)	247	243 (94)	92 (35)
Non-integrated fine paper	63	11 (3)	31 (3)
Non-integrated tissue	96	12 (3)	34 (3)

* Extracted from "Industrial Environmental Control Pulp and Paper Industry", Allan M. Springer, John Wiley & Sons, 1986, p. 22.

** Cubic meter per metric ton of pulp produced.

*** Values in parentheses are Quebec daily standards (BOD values are for summer months, standards for winter months are normally twice as high). Source: Gazette Officielle du Quebec, Jan. 21, 1981, Vol. 113, No.3, pp. 195-199.

Legend: BOD: Biochemical oxygen demand
TTS: Total suspended solids

Referring to **Figure 1**, logs are debarked then chipped at the pulp mills. Many mills also buy wood chips from nearby sawmills. Normally, an inventory of wood chips supplying several months of production is stored on concrete or asphalt pads in the wood yard. Depending on storage time, rain and melting snow can leach soluble components of wood chips which then can permeate into the ground. Some mills landfill waste bark which, when decays, causes contamination of surface as well as ground water.

The major source of water pollution come from the pulping and bleaching operations. Untreated waste liquor and bleach plant effluents contain high levels of BOD, toxic chemicals and fibers (**Table 4**). Effluent from paper manufacturing section contains lower levels of BOD, generally about 11 kg/t of pulp.

Generally, the suspended solids (mainly fibres) are removed by sedimentation clarifiers, often referred to as primary clarifiers. A removal efficiency of suspended solids of 80-90% is achieved at most mills. The suspended solids being removed contain a certain amount of associated BOD. In a few mills, an air floatation clarifier is used. A flocculent is normally added to promote the settling of suspended solids, thus improving the removal efficiency. The fibres removed from the clarifier are de-watered by filter and screw presses before being landfilled or burnt in boilers tc generate steam.

After being treated in the primary clarifier, the effluent is sent to a biological treatment system, sometimes referred to as secondary treatment system, to lower the BOD content to an acceptable level. The main organism in a biological waste treatment system is a dynamic population of bacteria. The two most common biological treatment systems used in the pulp and paper industry are:

- Aerated stabilization basins: These usually are large ponds having a 5-10 day retention time, and equipped with aeration devices. The BOD removal ranges from 80% to 90%. However, this system is not effective in cold climate regions as the BOD removal drops to about 50% at temperature below 18 °C. Other drawbacks with this system is the enormous space required for the basins and the discharge of suspended biological sludge (50-200 mg/L) with the treated effluent.

- Activated sludge process: This process is normally used where space is limited or the aerated stabilization process. There are a varieties of design of the activated sludge process providing BOD removal in the 80-85% range. Generally, the system consists of two main parts: (i) aerated stabilization basin and (ii) secondary clarifier. The retention time is 3-8 hours due to the high biological sludge concentration (2,000-5,000 mg/L) in the aerated basin. The excess biological sludge is removed from the secondary clarifier. This sludge is very difficult to de-water and usually must be mixed with primary sludge, bark or sawdust in order to be successfully de-watered. The de-watered secondary sludge is incinerated or land filled.

The pulp and paper industry have been developing new effluent treatment techniques to achieve: lower costs, smaller space requirements, lower sludge production, ability to remove toxins as well as BOD. Some of the major emerging secondary treatment techniques include:

- Anaerobic treatment
- Rotating biological surface
- Fixed-film activated sludge
- Aerated activated carbon filter
- Reverse osmosis

2.3.2 Gaseous emissions

The major airborne pollutants from pulp and paper mills include:

- Particulate: The Kraft pulping process is the major source of particulate emissions. A typical Kraft mill emits particles ranging in size from less than 1 micron to 30 microns from chemical recovery furnace and wood-burning boilers. Large particulate can settle out of the air near the mill site causing soiling, staining. Chemical salts can cause corrosion problems. Material of smaller particle sizes is of more concern because it remains airborne for long periods of time, creating haze and causing respiratory problems.

- Reduced sulphur compounds: these compounds, commonly referred to as total reduced sulphur (TRS), are emitted mainly from Kraft mills and cause nauseous odour at concentrations of only a few parts per billion. Thus minimization of odour is a major air problem facing Kraft mills.

- Sulphur dioxide: is a major pollutant from sulphite mills as well as Kraft mills. Plants near mills emitting high level of sulphur dioxide can suffer damage. Sulphur dioxide emission also contributes to the acid rain problem.

- Chlorine compounds: chlorine is used in various forms as a bleaching chemical in pulp and paper processes.

2.3.3 Solid waste disposal

The pulp and paper industry generates a wide variety of solid wastes. Depending on the types of feedstock (logs or wood chips) and the pulping process employed, each mill will generate different types and quantities of solid wastes. The major solid wastes that require final disposal are:

- Bark: For mills receiving logs as feedstock, bark accounts for about half of all solid wastes. In the past bark was disposed of by landfill or by burning in a tepee burner. Both these methods have become less acceptable in many regions. Tannin and phenolic compounds can be leached from bark, buried in landfill site, into ground water, streams and rivers. Burning bark in open-air tepee burner generates high emissions of particulate, carbon monoxide and hydrocarbons.

- Primary clarifier sludge: The primary clarifier removes 80-90% of TSS in the mill effluent (Table 3). Most of the solids are rejected knots and fibres. The sludge is de-watered to 40-50% solid using a filter press before being disposed of by landfill or burning.

- Secondary clarifier sludge: As described in section 2.3.1, the biological sludge from the secondary treatment system is usually mixed with the primary clarifier sludge and bark or sawdust to facilitate de-watering. The mixture is either burnt in biomass boilers to generate process steam or landfilled.

- Ash: Ash from biomass boilers is generally landfilled. This waste stream is normally small and does not pose a major disposal problem.

2.4 Overview of Applications of Biotechnology

Biotechnology has been recognized by many industrialized countries that it can offer many promising solutions for food, health, energy, and environmental problems. The following examples are only a few of many applications of biotechnology.

In the food and beverage industry, improvement in product quality and process efficiency are being made with the use of enzymes. The use of genetically engineered organism greatly reduces the cost of production of pharmaceuticals. In health care, companies are rushing to develop monoclonal antibody (an antibody that reacts with a certain antigen) for diagnosis or medical treatment. Biochemicals (enzymes or fungi) will replace chemical herbicides and insecticides that are toxic to human and harmful to the environment. Micro-organisms and enzymes can be used in certain chemical production such as ethanol, oil and fat products and synthetic resins. In agriculture, biotechnology application include: plant breeding, and development of high yield and disease-resistant stock. Genetic engineering will some day help produce very low fat cattle and mass produce growth hormones for farm animal and fish. In the forest products industry, biochemicals will eventually replace chemicals that are harmful to the environment.

The U.S. has been a leader in biotechnology since the 1970s. However, other countries have been catching up. In Japan, many government departments, including the Ministry of International Trade and Industry, the Ministry of Agriculture, Forestry and Fisheries, and the Ministry of Health and Welfare, are eager to promote biotechnology in their specific areas[47]. In the early

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[47]Duncan Davies and Frances Pinter, "Industrial Biotechnology in Europe - Issues for Public Policy", London & Dover, N.H., U.K., 1986, pp. 59-64.

1980s, many Japanese firms rushed to by new biotechnology products and processes from western companies. At the same time, research and development was strongly promoted in governmental research institutes, universities and private sector. It was estimated that the markets for Japanese biotechnology industry will reach 15 trillion yens - or approximately Can$ 125 billion - (compared to 112 trillion yens for all Japanese industries using conventional technologies) by the year 2,000 (Table 5).

Table 5 **Projected markets for Japanese biotechnology products in year 2,000**

	(billion yens)	(% of total)
Food	4,247	28.31
Pharmaceuticals & agrochemicals	3,293	21.95
Chemicals	2,598	17.32
Resource, energy & utilities	2,167	14.44
Agriculture, forestry & fisheries	2,004	13.36
Electronics & machinery	604	4.02
Pulp & paper	90	0.60
Total	15,003	100.0

Source: Duncan Davies and Frances Pinter, "Industrial Biotechnology in Europe - Issues for Public Policy", London & Dover, N.H., U.K., 1986, pp. 59-64.

The European Community developed a "Biotechnology Action Programme" to seek collaboration and open up opportunities for research and development in biotechnology[48].

In Canada, biotechnology, except in the health care, food and beverage industries, is still in the early development stage. In 1983, the Canadian Government announced a National Biotechnology Strategy. The long-term objectives of the Strategy were[49]:

- to provide policy and programme guidance to enhance scientific research and industrial applications,
- to encourage skilled human resource development,
- to foster effective collaboration and communications, and
- to help create an economic and regulatory climate conductive to commercial biotechnology investment and activity.

The Ministry of State for Science and Technology (now Industry, Science and Technology Canada) was given the responsibility of implementing the Strategy. Many provinces are integrating their approach to biotechnology within an overall advanced technology strategy. Interaction between the provinces and the federal government is through the National Advisory Committee. There are approximately 110 organizations in Canada involved in biotechnology research, development or manufacturing[50].

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[48]Karl-Heinz Narjes, "European cooperation in biotechnology", Trends in Biotechnology, Vol. 5, May 1987, pp. 118-119.

[49]Roe R. and Ferguson J., "Provincial Governments' Biotechnology Expenditures & Activity 1985-86", Ministry of State Science and Technology, Strategic Technology Branch, November 1986, p. 1.

[50]Ministry of State Science and Technology - Biotechnology Unit, Strategic Technology Branch, "1986 Canadian Biotechnology Source Book", 1986.

Most (85%) employ less than 15 full-time researchers. A few organizations reported 50 to 200 researchers. The largest organizations are Allelix Inc., Institute Armand Frapier and Bio-Mega Inc., all have reported biotechnology expenditures over $5 million annually.

2.5 Applications of Biotechnology in the Pulp and Paper Industry

The environmental issue has encouraged the pulp and paper industry to develop new processes aimed at reducing the pollution levels in mill effluent. The areas received the most attention so far are in the effluent treatment and bleaching processes. Tougher regulations on levels of BOD and toxins in liquid effluent have forced many existing mills to install secondary effluent treatment systems. The demand for chlorine-free bleached pulp is continually rising. Most new bleaching installations employ hydrogen peroxide and oxygen instead of chlorine and chlorine dioxide. These non-chlorine bleaching processes also produce lower quantities of toxic chemicals.

Biotechnology can potentially offer a wider scope of applications in the pulp and paper industry. The attractiveness of biological process lies in its specificity in providing the desired products with minimal formation of toxic by-products. Excellent reviews of potential applications of biotechnology in the pulp and paper industry have been published by several authors[51,52,53]. The applications include: plant biotechnology, biopulping, pulp modifications, effluent treatment and by-product conversion. These are briefly summarized below.

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[51]Paice M.G., Jurasek L. and Bourbonnais, "Biotechnology in the pulp and paper industry", PPRIC Miscellaneous Report MR 212, July 1991.

[52]Kirk Kent T., "Advances in Biotechnology in Pulp and Paper Manufacture: Overview of the 1989 International Conference", Tappi Journal, Vol. 72, No. 5, 1989, pp. 33-43.

[53]Trotter Patrick C., "Biotechnology in the pulp and paper industry: a review", Part 1: Tappi Journal, Vol. 73, No. 4, 1990, pp. 198-203; Part 2: Tappi Journal, Vol. 73, No. 5, 1990, pp. 201-205.

i) Plant biotechnology

Plant biotechnology has a great potential in silviculture and reforestation. It provides new methods for plant breeding and developing new plant varieties that meet the requirements of the pulp and paper industry.

Wood characteristics, such as specific gravity and chemical composition, can be tailored to a certain extent via strain selection, mutagenesis or genetic recombination[54]. For example, if the content of lignin in wood can be reduced and its characteristics altered to facilitate its removal by pulping processes, the economic gains would be enormous. Less energy and chemicals would be required to pulp such an ideal species. Furthermore, the pollution level released from the pulp manufacturing processes would also be reduced.

The use of chemical pesticides for plant protection can be reduced or even eliminated by using biological control agents that are benign to the environment.

ii) Biopulping

Biopulping is based on the ability of white-rot fungi to degrade lignin in wood. Research in this area has shown that fungal treatment of wood chips in rotating-drum bioreactor result in an energy savings of approximately 50% in subsequent mechanical refining. Pulp yield are in excess of 90% and lignin removal range from 3% to 37% after a four-week pretreatment. Handsheet strength properties of biopulped aspenwood increase, with burst index increasing to

[54]Giles Kenneth L. and Morgan Walter M., "Industrial-scale Plant Micropropagation", Trends in Biotechnology, Vol. 5, February 1987, pp. 35-39.

a maximum of approximately three times that of control. Brightness and light scattering decrease. Properties were comparable to those obtained from chemi-thermomechanical pulps.

The resin content in wood chips can be reduced by fungal treatment. A dilute solution of fungal is sprayed onto the chips as they are being loaded into chip piles. A residence time of about a week is generally required for the enzyme action to take place inside the chips. The reduction of resin in wood chips prior to pulping and bleaching is an alternative method to reduce toxic compounds in the mill effluent. Some of the toxic compounds are formed as chlorine-based bleaching chemicals react with resin in the wood.

Fungal treatment of wood chips is very slow and the desired effect of de-resination and de-lignification cannot be attained without the use of chemicals. Therefore, biopulping can never replace chemical and mechanical pulping but it should be considered as an option to reduce chemical and refining energy requirements. Furthermore, because the fungal activity is drastically reduced at low temperature, biopulping is not practical in the winter for Canadian mills.

The pitch/resin content of pulp can be reduced with treatment with lipase enzyme. In addition to the potential cost saving for using lipase, the reduction in the amount of chemical or talc added to control pitch also likely results in lower COD and suspended solid level in the mill effluent.

iii) Pulp modifications

Pulp modifications using enzymes include bleaching, altering surface properties, removing hemicellulose, lowering pulp viscosity. Biobleaching currently cannot substitute chemical bleaching, rather the pretreatment of certain types of unbleached pulps has been shown to reduce the quantities of bleach chemicals such as chlorine and chlorine dioxide. Hardwood kraft pulp can be partially delignified by white-rot fungi, thus effect a reduction in the requirement of bleaching chemicals. Similar results can also be obtained with the removal of hemicellulose from unbleached pulp by hemicellulase enzymes.

Treatment of un-bleached Kraft pulp by xylanase enzyme has been demonstrated in laboratory to reduce the requirement of chlorine and chlorine dioxide in the bleaching stage by up to 30%. This has a significant environmental advantage because of the expected reduction in the AOX level in the effluent. High cost of xylanase is currently a major obstacle for its commercial use. Enzyme bleaching must compete with other alternatives - such as oxygen, hydrogen peroxide and ozone - that are commercially proven.

iv) Effluent treatment

Reduction of BOD and toxicity levels by biological treatments have probably received the greatest attention. Although secondary waste treatments, such as the activated sludge process, have been in commercial use for a long time their efficiencies could be further improved by optimizing the bacterial cultures for a particular effluent. Conventional activated sludge systems are effective in reducing BOD but remove only up to about 65% of AOX. Application of biotechnology includes selecting micro-organisms that are effective in breaking down organochlorine compounds.

v) By-product conversion

Although by-product conversion is currently receiving little attention, its potential for commercialization is, except for biological effluent treatment, as important as biopulping or product modifications.

Glucose and mannose in spent sulphite liquor can be fermented to ethanol by baker's yeast. Research has shown that xylose, which is present in large quantity in hardwood hemicellulose, can also be fermented to ethanol. The BOD of the spent sulphite liquor is reduced by approximately half if all the sugars are utilized[55].

Primary clarifier sludge and sawdust can be hydrolysed to fermentable sugars by acid or enzymes. In this way the volume of solid waste can also be reduced. Therefore, by-product conversion may be considered as a form of waste treatment. This area of application is examined in greater details in the following case study.
The case study examines the technical and economic feasibility of incorporating a wood hydrolysis plant to an existing spent sulphite fermentation plant. Both acid and enzyme hydrolysis options are evaluated. A computer process simulation model was developed using Lotus 123 spreadsheet to facilitate the analysis.

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[55]Wilson, J.J., Nishikawa, N.N., Deschatelets, L., and Nguyen, Q., "Ethanolic fermentation of spent sulphite liquors - a technical and economic evaluation", Forintek Canada Corp. 1990. Final report contract file #051SZ.23283-8-6103, Alternative Energy Div., Energy, Mines and Resources Canada.

2.6 Process Modelling

Computer simulation of complex chemical or biochemical processes is increasingly used by scientists and engineers for planning and designing experiments, evaluating processing options and estimating costs. In general, process simulation programs can be developed using three different tools[56]: high-level programming languages, modular simulation packages and spreadsheet programs.

(i) High-level programming languages

High-level programming languages such as BASIC, FORTRAN, Pascal and C can be used to write process simulation programs[57]. The advantages of using these programming languages are: flexibility in solving almost any types of problems, low cost.

The disadvantages are: the user must write the program in its entirety and this can be very tedious for complex processes; the user must have extensive programming experience; graphic outputs require considerable additional effort; and any process modification could result in considerable re-writing of the program.

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[56]Schroderus S.K., Herschmiller D.W. and Bruce D.M., "Selecting the right simulation tool for the job", Pulp and Paper Canada, Vol. 92, No. 2, 1991, pp. 27-32.

[57]Kuriychuk M.G. and Gallupe R.T., "An application of microcomputer-based decision support to ion exchange column performance appraisal", Pulp and Paper Canada, Vol. 91 , No. 12, 1990, pp. 153-156.

(ii) Modular simulation packages

There are many flowsheet simulators currently available on the market. Some simulators, such as Aspen Plus and Process, are sophisticated and intended for process design and analysis. These simulators are increasingly being taught in chemical engineering process design courses[58]. Modular simulation programs commonly used in the pulp and paper industry are GEMS, MASSBAL, MAPPS and CADSIM[59].

The greatest advantage of modular simulation packages is that users do not need to write the programs. Complex process simulations can be assembled from individual modules that are reasonably simple to set up. Sophisticated packages contain extensive error tracing capabilities, look-up tables of physical constants and sub-routines to handle a varieties of calculations, such as mass and heat balances. Because of the modular construction of the simulation program, it can be readily modified for new process configurations.

The disadvantages of simulation packages are: high cost and users require considerable training and practice before they can use the program efficiently.

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[58]Harris T.J. and Jackson B.W., "Creative and Innovative Problem Solving Using Flowsheet Simulators", Canadian Chemical News, June 1990, pp. 19-21.

[59]Schroderus S.K., Herschmiller D.W. and Bruce D.M., "Selecting the right simulation tool for the job", Pulp and Paper Canada, Vol. 92, No. 2, 1991, pp. 27-32.

(iii) Spreadsheet programs

Simple simulation models can be easily constructed using spreadsheet programs, such as Lotus 123, and Excel. Many engineers find spreadsheet programs easy to use and adequate for most calculations required in process simulation and cost calculation. These low-cost programs also offer flexibility in producing graphs and reports.

Process modelling using spreadsheet programs generally lack the sophistication of the modular simulation packages. Generally, spreadsheets are suitable for simulations involving voluminous, sequential calculations. Users tend to treat unit operations as "black boxes". However, these models can be effectively used to estimate the technical and economic feasibilities of processes under the early stage of development where not all processing steps are well defined. And they are particularly suitable for evaluating the relative costs of process options[60]. There have been several simulation models on bioconversion of wood to ethanol developed using spreadsheet programs.

These models, which are briefly described below, simulate large, stand alone wood ethanol plants using enzyme hydrolysis processes. Whereas, the case study presented in this thesis studies the feasibility of adding a small wood hydrolysis, using either acid or enzyme process, to an existing ethanol plant.

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[60] McCormick Douglas, "Play with purpose: modelling biotech processes", Biotechnology, Vol. 6, No. 8, 1988, pp. 887-892.

The Arthur D. Little Study[61] investigated the feasibility of installing an ethanol plant with a production capacity of 21 million litres per year from hardwoods (400 tonnes/day wood input) in New York State. The total capital investment for the plant was estimated to be U.S.$60.6 million in 1984. Steam explosion was selected as the pretreatment method. Hydrolysis of cellulose to sugar is by enzyme, which is produced on site using cheese whey as substrate. The selling price, which includes capital related charges, was estimated at U.S.$1.34/L. Subtracting credits for co-generated electricity and stillage as animal feed, the selling price was reduced to U.S.$1.02/L. The study identified sugar yield, enzyme production cost and credit for residual lignin as having the most significant impact on the process economics.

The L. J. Douglas Study[62] is based on a hypothetical plant utilizing 1,000 tonnes/day of aspenwood to produce approximately 91 million litres of ethanol per year. The total capital investment was estimated to be $121 million in 1988. The model proposes burning residual solids to supply all the energy requirements for the plant and selling surplus electrical. Very high enzyme production yield from lactose was assumed. As a result of large scale operation and low enzyme production cost, the proposed selling price

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[61]Nystrom John M., Greenwald Gail C., Hagler Robert W., and Stahr Jennifer J., "Technical and Economic Feasibility of Enzyme Hydrolysis for Ethanol Production from Wood", Arthur D. Little, Inc., Final Report C-50569 to New York State Energy Research and Development Authority, and Solar Research Energy Research Institute, 1984.

[62]Douglas Larry J., Entropy Associates, Inc., "A Technical and Economic Evaluation of Wood Conversion Processes", prepared for Energy, Mines and Resources Canada, Contract File No. 23283-8-6091, August 8, 1991

(including capital recovery charges) was estimated to be $0.48/L.

The Forintek Model[63] studies a conceptual ethanol plant with a production capacity of 49 million litres per year based on an input of 500 tonnes/day of aspenwood. The total capital investment was estimated to be $80 million, and the selling price $0.78/L. Enzyme is produced from steam exploded wood. Unlike the above models, this model includes xylose fermentation which increases the total ethanol yield by approximately 30%.

Based on these models, the conversion of wood to ethanol is currently not economically viable. However, this process warrants another appraisal, as presented in the following case study, because of the unique situation at Tembec where an ethanol plant is already in place. In this case, since no installation of ethanol fermenters and distillation capacity is required, conversion of wood to ethanol is simplified to hydrolysis of wood to fermentable sugars.

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[63]Nguyen Q. A. and Saddler J. N., "An Integrated Model for the Technical and Economic Evaluation of an Enzymatic Biomass Conversion Process", Bioresource Technology, Elsevier Science Publishers Ltd., 35 (1991), pp. 275-282.

3.0 CASE STUDY : BIOCONVERSION OF WOOD WASTES TO ETHANOL

3.1 Background

Temeco Enterprises has recently started up an ethanol fermentation plant at the Tembec pulp mill complex in Temiscaming, Quebec. The plant utilizes spent sulphite liquor (SSL) as feedstock and has a annual production capacity of 18 million litres of 95% industrial ethanol. The SSL, a waste liquor from the adjacent ammonium-based acid sulphite pulp mill, contains sugars that contribute to high BOD in the effluent. It is estimated that the BOD content of the SSL will be reduced by approximately 30% after the ethanol fermentation. The schematic diagram of the ethanol plant is shown in **Figure** 2. Weak spent sulphite liquor from the pulp mill is concentrated from 10 wt% to 20 wt% in a series of evaporators and sent to the fermenters where the sugars are fermented to ethanol. The fermented liquor is sent to the distillation unit for ethanol recovery. The spent liquor from the distillation, now depleted of sugars, is returned to the evaporators for further concentration to 50 wt% solution which is then either burnt to generate process steam or sold as a by-product.

The pulp mills at the complex (one sulphite, one chemical thermomechanical and one paperboard) generate approximately 40 oven-dry tonnes per day (OD tonnes/d) of waste fibres which have an average cellulose content of 70%. This solid waste is presently being landfilled; but it will eventually be burnt in a biomass boiler to generate steam. The existence of the alcohol plant plus the negative cost (landfill cost) and high cellulose content of this waste may make it an attractive feedstock for a sugar conversion process. The conversion of wood waste to sugar can be carried out via either an acid hydrolysis or an enzyme hydrolysis process. The resulting sugar solution can be added directly to the existing ethanol fermenters (**Figures** 2).

This case study investigates the technical and economic feasibility of installing a hydrolysis unit to convert this fibre waste to sugar, thus increasing the sugar feed to the alcohol plant. Using a Lotus 123 spreadsheet, a process simulation model was developed to facilitate calculations for material and energy balance, cost estimation. The model is intended to be used by project managers to develop a strategy for the utilization of wood waste, to carry out sensitivity analyses on key process and economic parameters and to compare the wood-to-ethanol conversion option with other alternatives, such as burning to produce steam and electrical power.

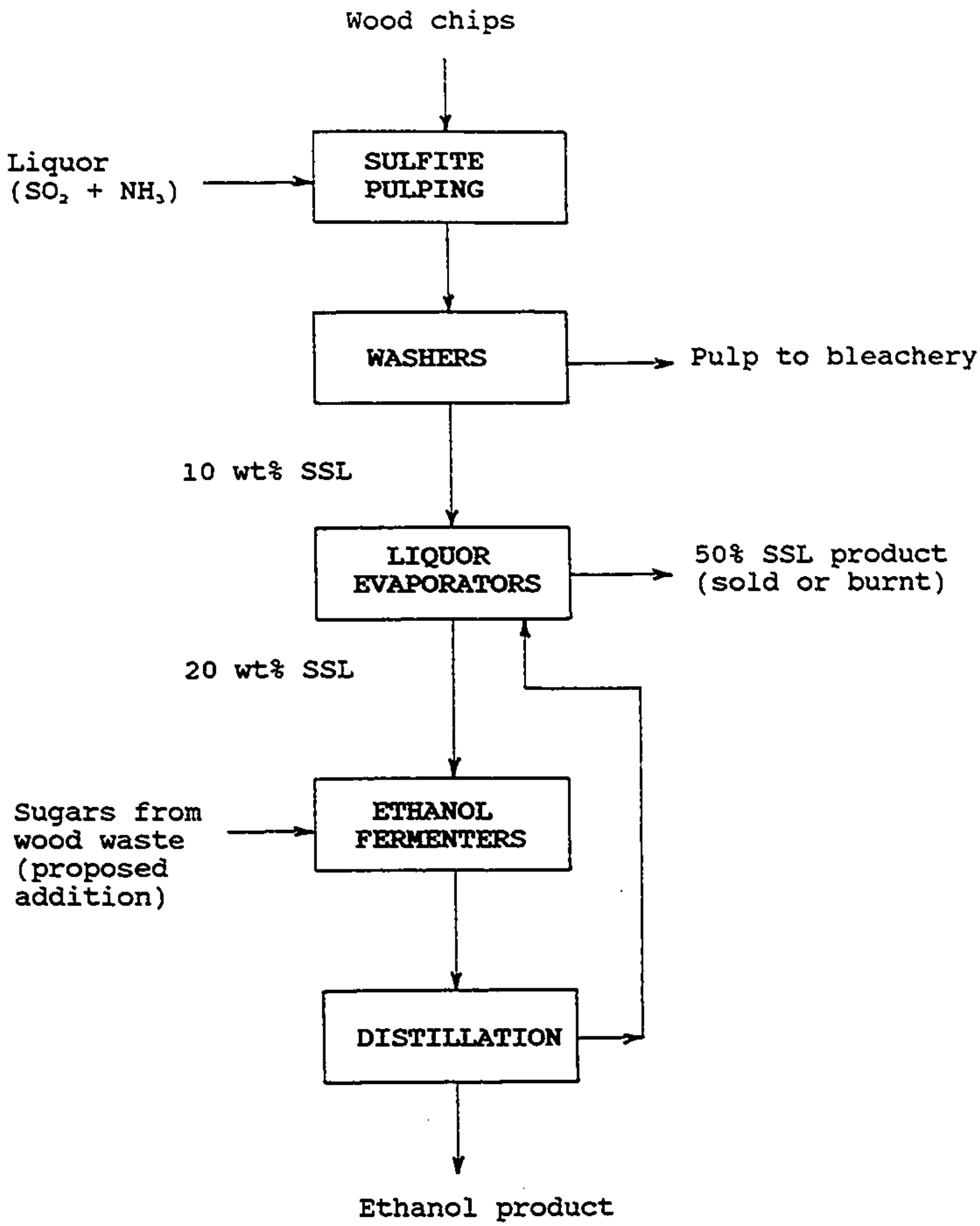


Figure 2 Production of ethanol from spent sulphite liquor

3.2 Description of the Model

Two processing options are evaluated: (i) enzyme hydrolysis and (ii) acid hydrolysis. The construction of the process model using spreadsheet first requires the development of a conceptual process flowsheet that specifies all major equipment. Next, mathematical equations are developed to calculate the material and energy balance for each unit operation. Cost estimations are then calculated based on the equipment selected and the material and energy balance. Single-parameter sensitivity analysis is carried out to study the effect of each input variable on the unit production cost of ethanol. And finally, the effect of uncertainties in input variables on production cost is predicted using the Monte Carlo Simulation technique.

3.2.1 Process description

As the model focuses on the conversion of wood waste to fermentable sugars, only the hydrolysis processes, namely acid and enzyme hydrolysis, are described.

(a) Steam pretreatment and enzyme hydrolysis

The enzyme hydrolysis process consists of the following steps: feedstock preparation, steam pretreatment and enzymatic hydrolysis (**Figure** 3). This process is described below.

(i) Feedstock preparation

The wet primary clarifier sludge must be de-watered with a screw press to lower the moisture content to approximately 55 wt%. The de-watered sludge is then conveyed to the acid impregnation system.

(ii) Steam pretreatment

The purpose of steam pretreatment is to make the cellulose in the waste fibres more accessible to enzyme attack. Sulphur dioxide (SO_2) is added to the sludge in the acid impregnation system which consists of a in-line mixer and a screw conveyer. The SO_2-to-wood weight ratio is approximately 0.015. Batch digesters are employed in the steam pretreatment. SO_2-impregnated fibres are fed by gravity into two digesters which operate in parallel. The digesters are constructed of corrosion resistant high-nickel. Each digester has a working volume of 1.15 M^3 (40 ft^3) and can process about 110 oven-dry (OD) kg of chips per cooking cycle, assuming the bulk density of the solid waste is 96 OD kg/M^3 (6 lb/ft^3). Steam is injected into the digesters via nozzles located at the bottom and the top. At the end of a cooking cycle the content of the digester is discharged into a blow tank where excess steam is quenched with water.

(iii) Enzyme hydrolysis

A two-stage batch hydrolysis system is used. The hydrolysis reactors are essentially tall cylindrical vessels with side-entry mixers. An enzyme solution is mixed in with the steam treated wood and the mixture is pumped into the top of the first hydrolysis reactor. The amount of enzyme required is expressed in international unit per gram of cellulose, IU/g. The partially hydrolysed wood slurry is pumped from the bottom of the first reactor to the top of the second reactor. The final hydrolysate slurry is drawn from the bottom of the second reactor to a drum washer where the sugar is washed from the fibres and sent to the ethanol fermenters, and the residual solids are then mixed with the biological sludge from the secondary treatment (Figure 1) before being conveyed to the biomass boiler to be burnt.

(b) Acid hydrolysis

The acid hydrolysis process consists of the following steps: feedstock preparation, acid impregnation and hydrolysis (Figure 4).

(i) Feedstock preparation

This step is similar to that required for enzyme hydrolysis described previously.

(ii) Acid impregnation

The de-watered wood waste is impregnated with warm dilute sulphuric acid solution in a variable pitch screw-conveyor. Uniform acid penetration of the fibres is essential for obtaining good sugar conversion in the hydrolysis stage.

(iii) Acid hydrolysis

Acid hydrolysis is carried out in two batch digesters operating in parallel. Direct steam is used to heat the acid-impregnated fibres. At the end of the cook, the content of the digester is discharged into a blowtank where water is added to form a slurry. The sugar solution is then separated from the residual solids using either a continuous centrifuge or a vacuum drum filter.

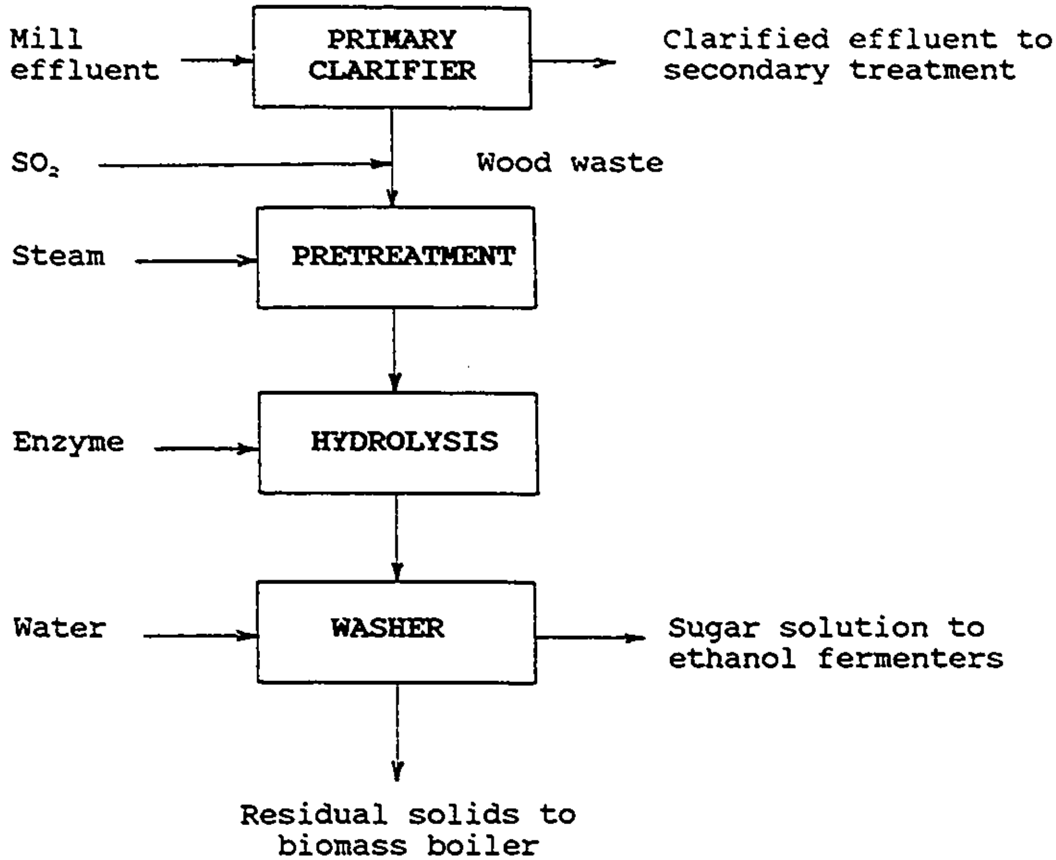


Figure 3 Steam pretreatment and enzyme hydrolysis of wood waste to fermentable sugar

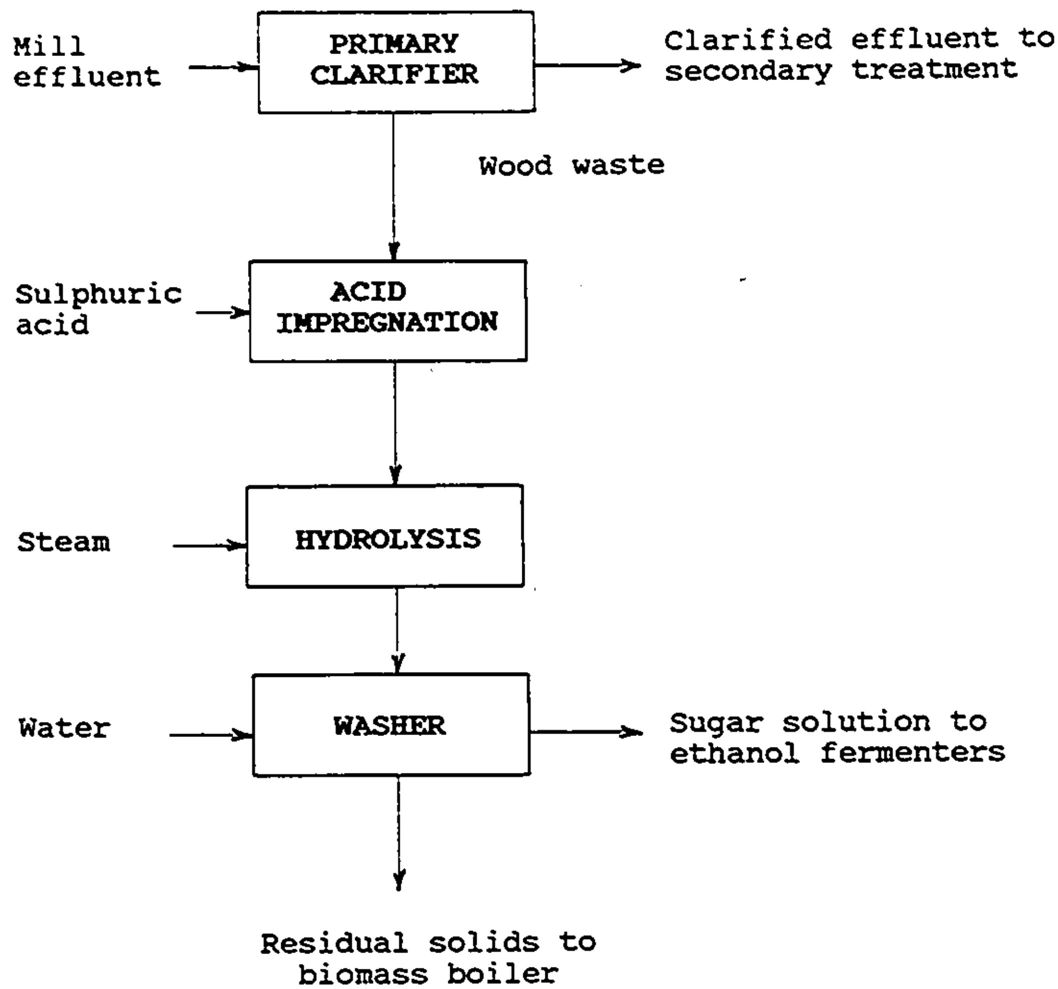


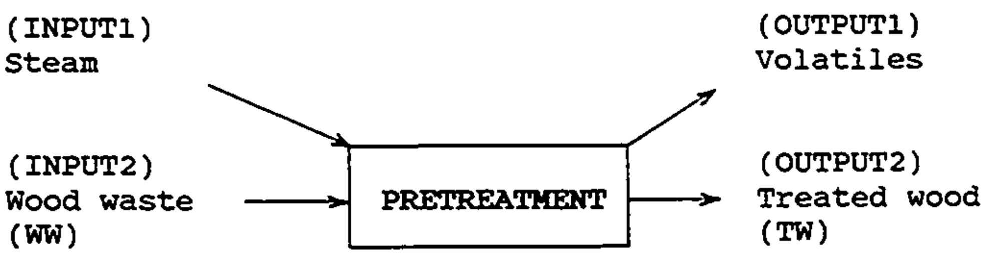
Figure 4 Acid hydrolysis of wood waste to fermentable sugar

3.2.2 Material and energy balance

Material and energy balance for each unit operation is necessary for the determination of the quantity, size and energy consumption of the equipment required in for each processing step as shown in Figures 3 & 4. The process is essentially represented by a series of mathematical equations representing the flow of materials from feedstock to end products. The major components in each stream are also calculated so that product yields can be determined.

As an example, the conversion of wood waste to sugars via an enzyme hydrolysis process (Figure 3) involves two major steps: pretreatment and enzyme hydrolysis. One of the major components of interest is the cellulose in the original wood which is made accessible to enzyme in the pretreatment step then converted to sugar (glucose) in the hydrolysis step.

The material balance for cellulose in the pretreatment step is illustrated below. Notations are assigned to various streams.



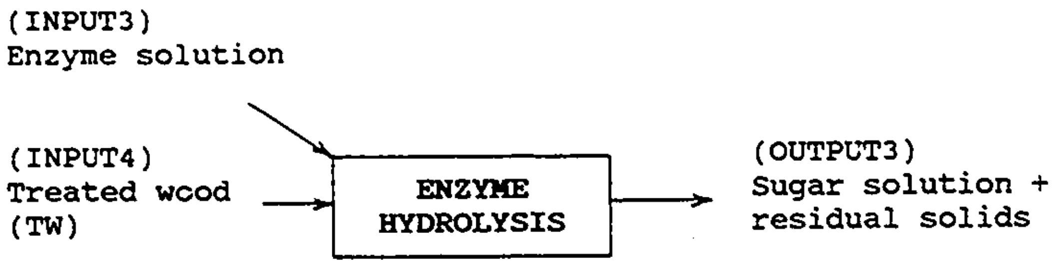
WW = 40 tonnes/day
cellulose content = 70 %

Solids recovery = 95%
Assume no cellulose loss

<u>Material balance for cellulose (in tonnes/day)</u>:

Cellulose in INPUT2 = 0.70*WW = 0.70*40 = 28
OUTPUT2 or TW = 0.95*WW
Cellulose in OUTPUT2 = cellulose in INPUT2 = 28

For the hydrolysis step:



Cellulose in INPUT4 = 0.70*WW

80% conversion yield (YG)

<u>Material balance for cellulose (in tonnes/day)</u>:

Cellulose in INPUT4 = 0.70*WW
Cellulose in OUTPUT3 = 0.70*WW*(1-0.8) = 0.14*WW
Sugar (glucose) in OUTPUT3 = 0.70*WW*0.8*1.11 = 0.622*WW

Where 1.11 is the conversion factor for hydrolysis of cellulose to glucose.

Material balance calculations for other streams and components such as water hemicellulose and lignin are carried out in a similar fashion. The material balance equations developed for the model are presented in **Appendix A**.

Parameters that have significant impact on equipment size and energy consumption, thus production cost, form input variables for the model (**Table** 6). For example, high enzyme loading in the hydrolysis step or low sugar conversion yield would result in high unit production cost. These variables can be changed to study their effect in the production cost of ethanol. Several of these parameters have impact on others; for example, high enzyme loading would increase the sugar conversion yield. These inter-dependence between the input variables are determined from laboratory data. A base case is established using best current technologies. The estimation of the base case production cost of ethanol helps managers set target values for various parameters in order to produce ethanol at a competitive cost.

Table 6 Input variables for the computer simulation model

DESCRIPTION OF PARAMETERS	VALUE	UNIT
Common to both hydrolysis processes		
Wood waste input (dry basis)	40	tonnes/day
Cellulose content in wood waste	70	weight %
Cost of wood waste	0	$/tonne
Ethanol yield from glucose	80	% theoretical
Cost of steam	4	$/giga joules
Cost of electrical power	0.04	$/kWh
Cost of ammonia	300	$/tonne
Service life of equipment	15	years
Debt fraction of capital investment	0.3	
Equity (stock) fraction of capital	0.7	
Interest rate on debt	12	% annually
Rate of return on stock	12	% annually
Income taxes	50	% gross income
Property taxes and insurance	2	% capital cost
Annual inflation rate	5	%
Enzyme hydrolysis		
Steam required for pretreatment	1	kg steam/kg wood
Sulphur dioxide (SO_2) required for pretreatment	1.5	kg SO_2/kg wood
Solids recovery after pretreatment	95	% of wood input
Solid loading in enzyme hydrolysis reactors	5	% weight/volume
Enzyme loading in hydrolysis reactor,	5	unit/g cellulose
Enzyme hydrolysis time	72	hour
Glucose yield from enzyme hydrolysis	80	% theoretical
Cost of enzyme	40	$/million units
Cost of sulphur dioxide	240	$/tonne
Acid hydrolysis		
Sulphuric acid required	0.03	g acid/g wood
Steam required for acid hydrolysis	1.5	kg steam/ kg wood
Glucose yield from acid hydrolysis	40	% theoretical
Cost of 96% sulphuric acid	140	$/tonne

3.2.3 Cost estimation

The production cost includes operating costs and variable capital costs. Because ethanol is sold in litres the unit for the production cost is expressed in cents per litre of ethanol produced (cents/L).

Production cost = Operating costs + Variable capital costs

Where:

Operating costs = Costs of raw materials, energy, labour and maintenance

Variable capital costs = (Costs of installed equipment) X (Capital recovery rate)

The estimations of these costs are explained below.

(a) Operating costs

Operating costs include: labour, raw material, energy, and maintenance. The costs of labour and maintenance are estimated for each processing step based on past operating experience on similar equipment. The raw material and energy costs are derived from the material and energy balance calculation.

Generally:

Raw material cost (Energy) = Raw material required (Energy) * Unit cost of raw material (energy)

(b) Variable capital costs

In this case study, the variable capital cost is defined as the cost of installed equipment multiplied by a capital cost recovery rate. Depending on the value of input variables, the size and cost of processing equipment may vary. For example, longer hydrolysis time would require larger reactors. The capital cost recovery rate takes into account costs of equity, long-term debts, taxes, depreciation, and inflation. The method of calculation is described below. The equipment list and corresponding costs are presented in **Appendix B**.

The variable capital cost is defined as:

Variable capital cost = (Installed cost of equipment) X (Capital recovery rate)

Where:

Cost of installed equipment = Purchase cost * Installation factor * Contingency factor

The installation factor includes: installation cost, engineering and contractor fees. The costs of various equipment and associated installation costs are obtained directly from the suppliers or estimated from historical data[64,65]. A 10% contingency is added to the installed cost.

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[64]Gruthie K.M., "Data and Technique for Preliminary Capital Cost Estimating", Chemical Engineering, March 24, 1969, pp. 114-142.

[65]Peters Max S. and Timmerhaus Klaus D., "Plant Design and Economics for Chemical Engineers", 4th edition, McGraw-Hill, Inc., New York, 1991.

The effect in varying size of the equipment on purchased cost of equipment can be estimated using the exponent method:

$$\text{Cost of equip. A} = \text{Cost of equip. B} * \left(\frac{\text{Capacity of A}}{\text{Capacity of B}} \right)^{EF}$$

Where: EF = exponent factor

The capital recovery rate (CRR) is defined as[66]:

CRR = LAIT + PTI + CRF

Where:

LAIT : Levelized annual income tax

PTI : Property taxes and insurance cost

CRF : Capital recovery factor

$$CRF = \frac{ROI * (1 + ROI)^n}{(1 + ROI)^n - 1}$$

n = Service life of equipment

ROI = Internal rate of return after inflation

$$ROI = \left(\frac{1 + WACC}{1 + INFLA} \right) - 1$$

WACC = Weighted average capital cost

WACC = (LTDEBTR * LTDEBTC) + (STOCKR * STOCKC)

$$LAIT = \left\{ CRF - \left(\frac{1}{n}\right) \right\} * \left\{ 1 - \frac{LTDEBTR * LTDEBTC}{ROI} \right\} * \left\{ \frac{TAX}{1 - TAX} \right\}$$

LTDEBTR = Long-term debt fraction of fixed capital cost

LTDEBTC = Long-term debt cost

STOCKR = Stock fraction of total fixed capital cost

= 1 - (long-term debt fraction)

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[66]Jeynes P.H., "Profitability and Economic Choice", Iowa State University Press, Ames, IA., 1978.

STOCKC = Return on stock

TAX = Income taxes

A more accurate method, as far as taxation issue is concerned, would involve the use of 25% declining balance capital cost allowance; however, for preliminary cost evaluation and optimization of process variables, the simpler method of capital recovery rate described above should be adequate.

A base case, which assumes a set of specific values for various technical and economic parameters, is established as a bench mark. The values of these parameters are based on current technology and market conditions. The costs of producing ethanol (95% by volume) from primary clarifier sludge are approximately 97 cents/L using enzyme hydrolysis and approximately 57 cents/L using acid hydrolysis. The components of the production costs are shown in **Table 7** and **Table 8** respectively. These cost breakdowns and the sensitivity analyses are useful to identify areas that require improvement and in setting improvement targets in order to achieve economically viable production costs. The required improvements are discussed in the sensitivity analyses below (section 3.2.4).

Table 7 Production cost of ethanol via enzyme hydrolysis (Base case)

Wood input = 40 tonnes/day

Ethanol production = 4.73*10^6 litres/year (338 litres/tonne)

Capital investment = $10.11*$10^6$

Operating cost	cents/L	% of total cost
Process steam	16.1	16.6
Chemicals	0.1	0.1
Enzyme	40.6	41.8
Electrical power	1.6	1.6
Labour	4.6	4.7
Maintenance	2.0	2.0
Variable capital cost		
Pretreatment	13.6	14.0
Enzyme hydrolysis	18.6	19.2
Total production cost	97.2	100.0

Table 8 Production cost of ethanol via acid hydrolysis (Base case)

Wood input = 40 tonnes/day

Ethanol production = $2.37*10^6$ litres/year (169 litres/tonne)

Capital investment = $\$3.15*10^6$

Operating cost	cents/L	% of total cost
Process steam	21.6	38.0
Chemicals	6.3	11.1
Electrical power	1.1	1.9
Labour	9.2	16.2
Maintenance	4.1	7.2
Variable capital cost		
Acid hydrolysis	14.6	25.6
Total production cost	56.9	100.0

3.2.4 Sensitivity analyses

Because of the uncertainty in the values of the input variables, sensitivity analyses are carried out in the economic evaluation of these hydrolysis processes. Two types of sensitivity analyses were performed: single-parameter and Monte Carlo Simulation.

(a) Single-parameter sensitivity analysis

Single-parameter sensitivity analysis is employed to study the effect of each parameter on the production cost. In this analysis, the value of a input variable (as listed in **Table 6**) is changed while other variables are held constant at the base case values. The model then calculates the corresponding production cost of ethanol. A series of analyses was run on key variables, i.e., wood input, cost of wood waste, cellulose content in wood waste, glucose yield, ethanol yield, substrate concentration in enzyme hydrolysis, and cost of enzyme. The results are tabulated in **Appendix B** and interpreted below.

Wood waste input (plant capacity)

The process economics favours large plant capacity (**Figure 5**). Considering the current market price of industrial ethanol of about 52 cents/L, enzyme hydrolysis process is not economically viable. The production cost of ethanol via the acid hydrolysis process can potentially be reduced to about 50 cents/L with higher wood input. Since the quantity of wood fibres recovered from the primary clarifier will not increase much beyond 40 tonnes per day, the only option to increase the feedstock throughput is to use sawdust and shavings from nearby lumber mills. The drawback of using sawdust is that the cost of buying and trucking the material to the site would negate the economies-of-scale advantage.

Effect of cost of wood waste

In the base case study, it is assumed that the cost of wood waste is zero. Currently, this cost is negative because Tembec has to truck the waste to landfill site. However, if instead of being landfilled or converted to sugar, the waste is entirely burnt in a biomass boiler to produce process steam, a net fuel value of approximately $15/tonne must be assigned as a feedstock cost. This would make the hydrolysis option even more unattractive. The effect of cost of wood waste on the ethanol production cost is shown in **Figure 6**.

Effect of cellulose content in wood waste

The glucose concentration in the hydrolysate is directly proportional to the cellulose content in the wood waste. The higher the cellulose content the lower the unit production cost of ethanol (**Figure** 7). The average cellulose content of the primary clarifier sludge is currently about 70% because of the high content of good fibers. However, the cellulose content is expected to come down as the sulphite mill is improving its fibre recovery system, i.e., most of the good fibers are recovered. As a result, the sugar yield from each unit mass of waste would be reduced and the unit production cost of ethanol would go up.

Effect of glucose yield

Glucose yield is the quantity of glucose obtained from the hydrolysis step. Theoretically, one unit mass of cellulose yields a maximum theoretical value of 1.1 unit mass of glucose. The higher the glucose yield the lower the unit cost of ethanol. It is well known that glucose yield from dilute acid hydrolysis of wood is limited to less than 60% theoretical. The glucose yield from enzyme hydrolysis can reach 90% theoretical. However, the yield depends on many factors, such as the effectiveness of pretreatment, hydrolysis residence time, substrate concentration and enzyme loading. The effect of glucose yield on the ethanol production cost is shown in **Figure 8**.

Effect of ethanol yield

Theoretically, 0.51 kg of ethanol can be obtained from 1 kg of glucose. However, less than theoretical ethanol yield is expected because of the presence of inhibitory chemicals in spent sulphite liquor. Yeast inhibitors are also produced by the acid hydrolysis of wood, but not the enzyme hydrolysis. **Figure 9** shows the effect of ethanol yield on the ethanol production cost.

Effect of solid loading in enzyme hydrolysis reactor

Research has shown that the concentration of solid (treated wood) in the hydrolysis reactor has a significant impact on the hydrolysis efficiency and glucose yield. Generally, the glucose yield increases with decreasing solid concentration because of lower end-product inhibition. However, low solid concentration results in large hydrolysis reactor volume (i.e., higher capital cost) and low product concentration (i.e., higher energy requirement to recover the product), and ultimately higher production cost (**Figure 10**).

Effect of enzyme loading in hydrolysis reactor

Enzyme loading in the hydrolysis step has a significant effect on the total production cost (**Figure 11**). The key criteria for a viable enzyme process is to keep the enzyme requirement very low. There are a lot of uncertainties in estimating the enzyme loading required because the enzyme activity can vary with different substrate. For example, pretreated hardwood is generally more susceptible to enzyme attack than softwood. It is unlikely that the enzyme loading can be reduced much below the level of

5 unit/g cellulose as used in the base case. One method of reducing the net enzyme loading is to recycle the enzyme from the digested substrate to incoming feed. But more research is required to prove that this concept is feasible.

Effect of cost of enzyme

As shown in **Figure 12**, the cost of enzyme has a pronounced effect on the production cost of ethanol. In fact, one of the main reasons for the conversion of wood to ethanol are currently uneconomical is the high cost of enzyme. Although enzymes are being used commercially in detergent and in the food processing industry, no bulk enzyme is currently available commercially for cellulose hydrolysis. The cost of enzyme of $40/million units used in this model is projected from pilot plant data. In order for the enzyme hydrolysis to be commercially viable, the enzyme cost must be lower than $10/millions units. This target can potentially be achieved if the enzyme is produced on site to eliminate cost of concentration the enzyme solution and transportation cost.

Fig. 5 Effect of Wood Waste Input (Plant capacity)

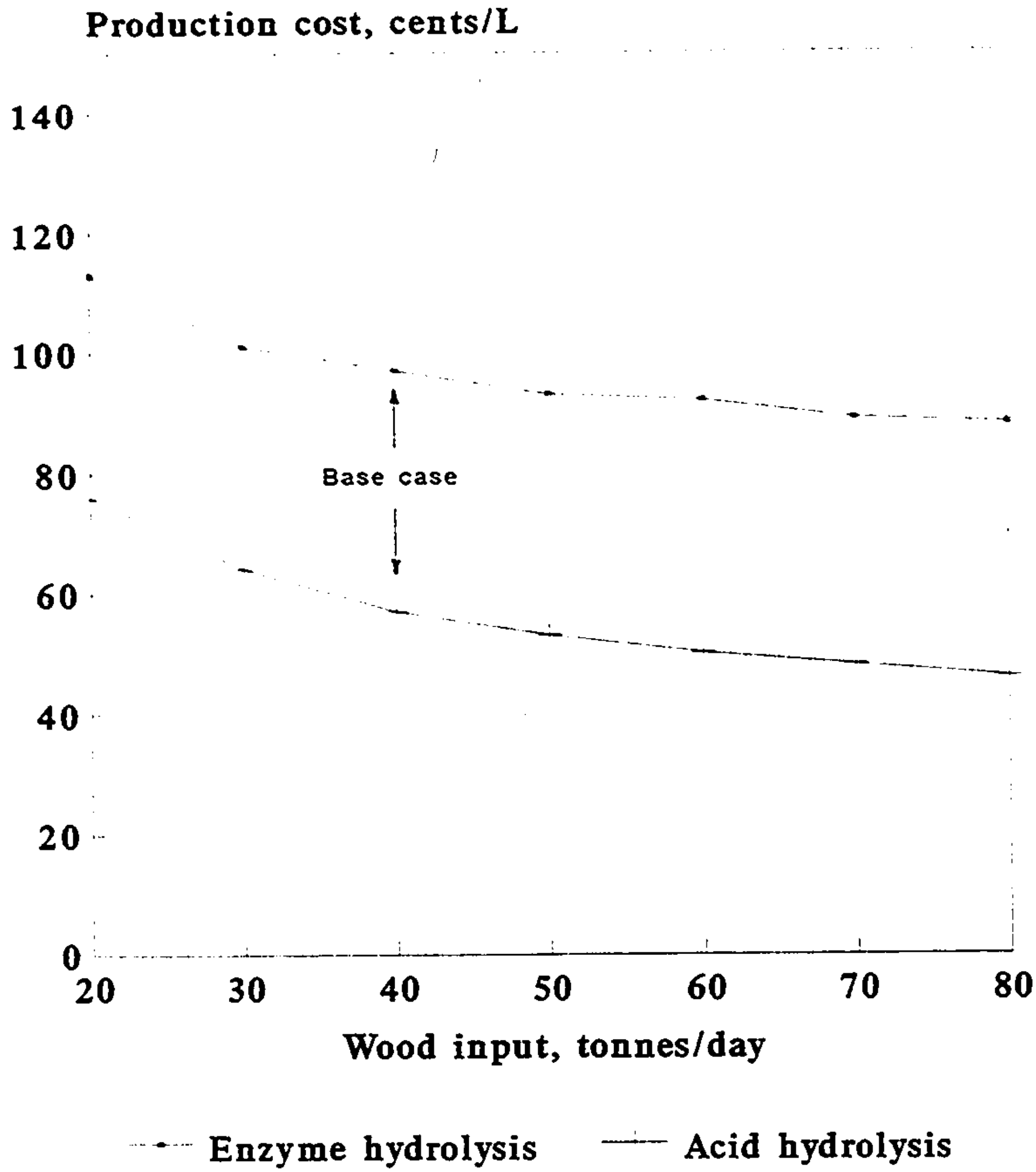


Fig. 6 Effect of Cost of Wood Waste

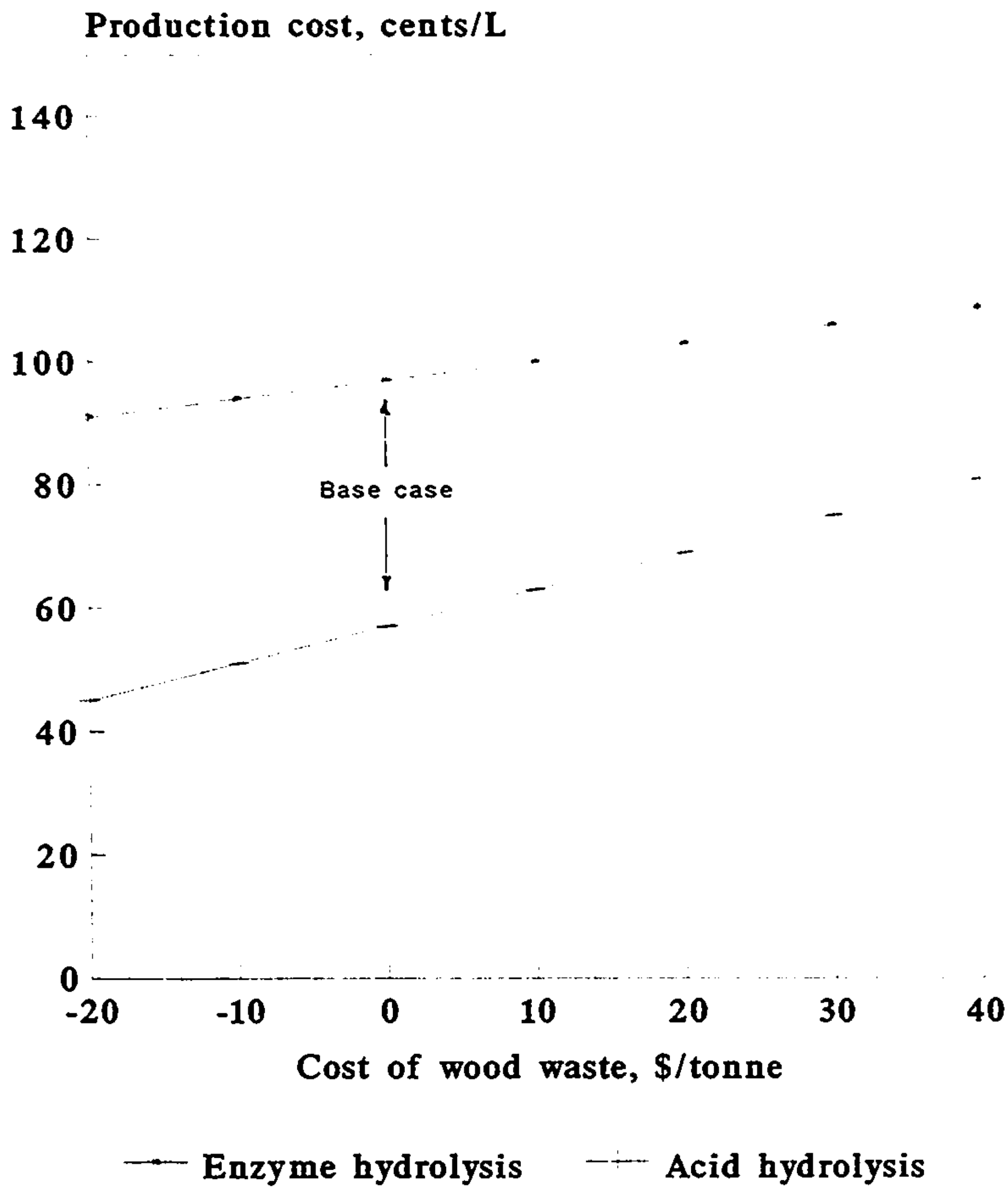


Fig. 7 Effect of Cellulose Content in Wood Waste

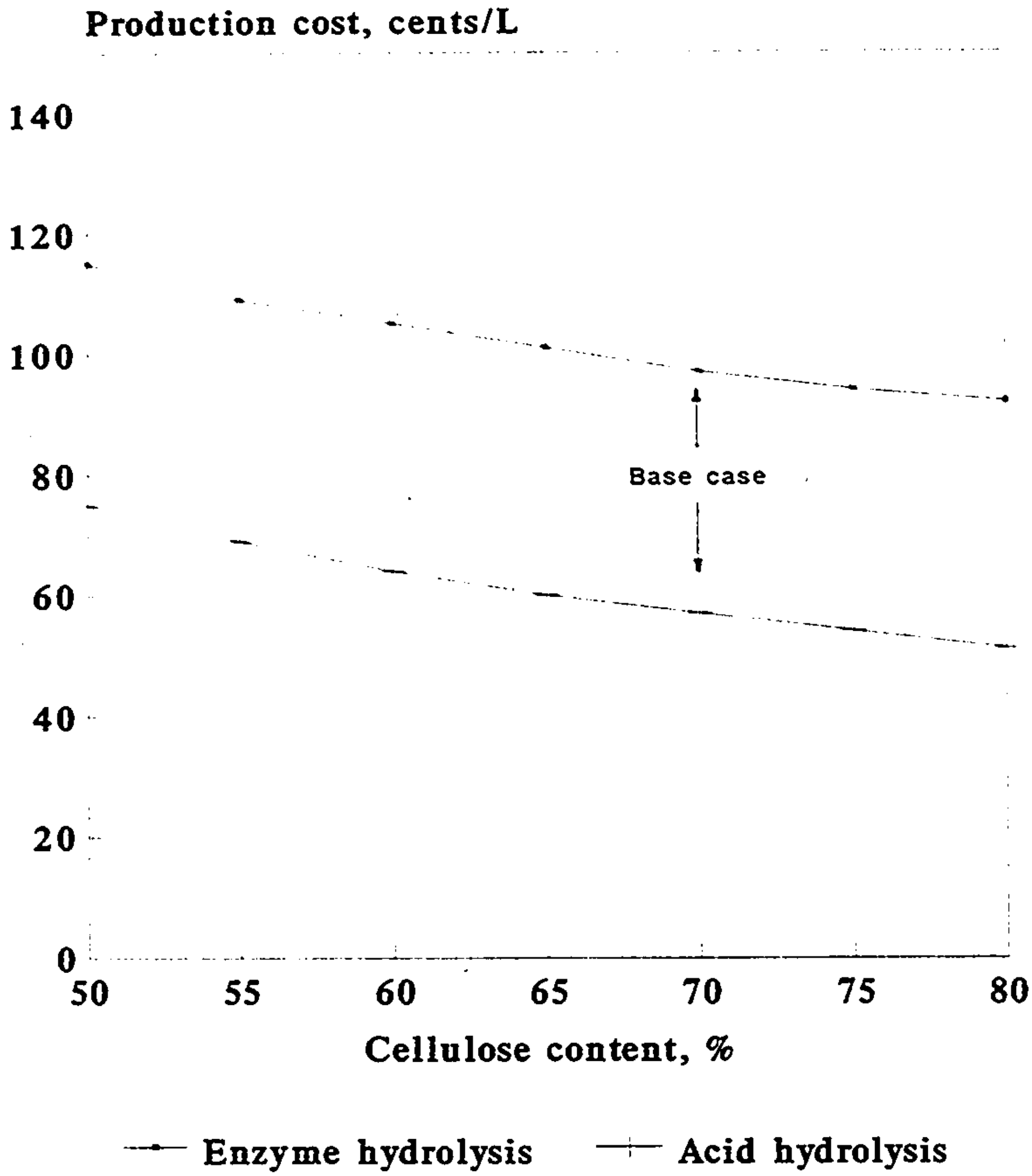


Fig. 8 Effect of Glucose Yield

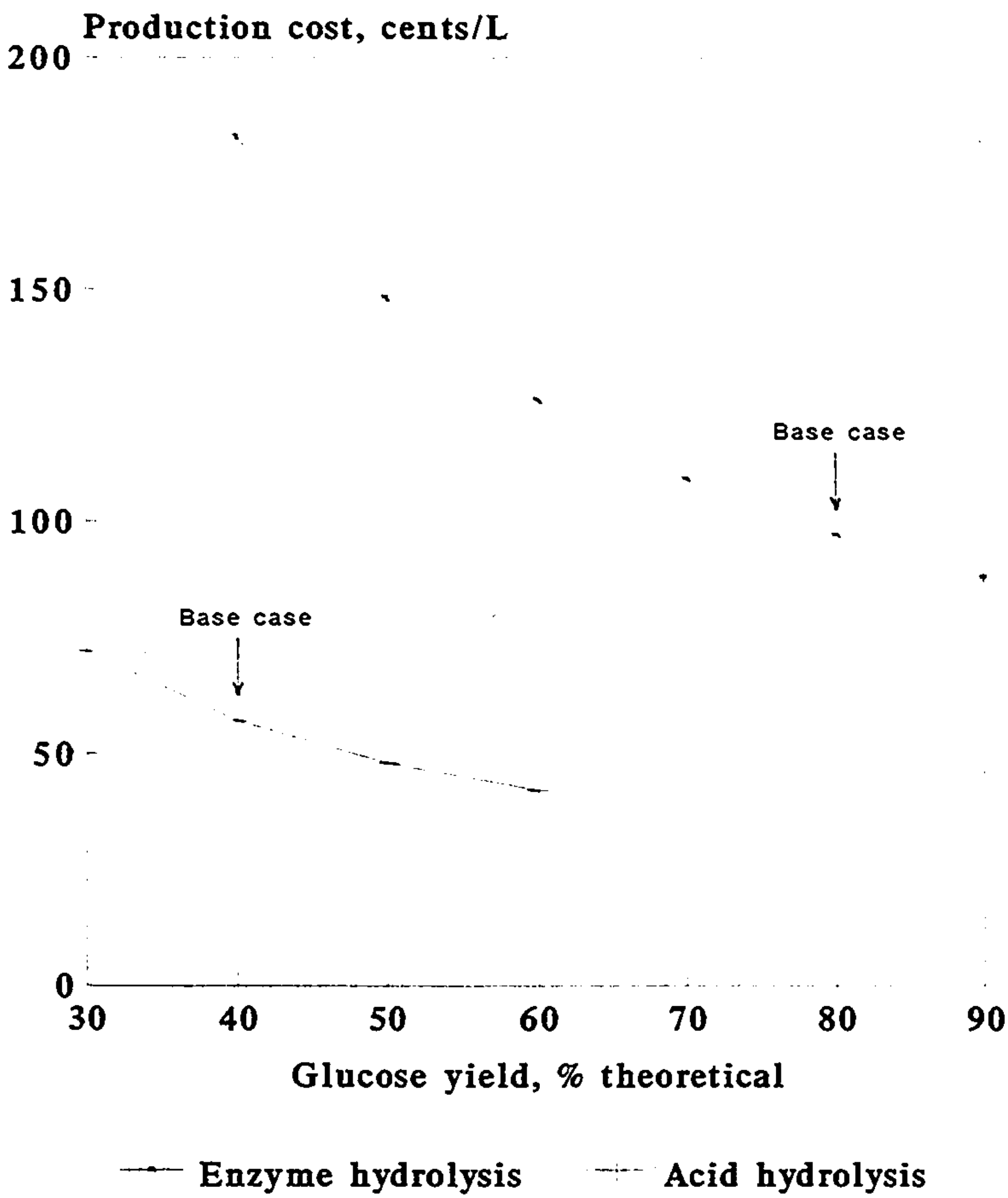


Fig. 9 Effect of Ethanol Yield

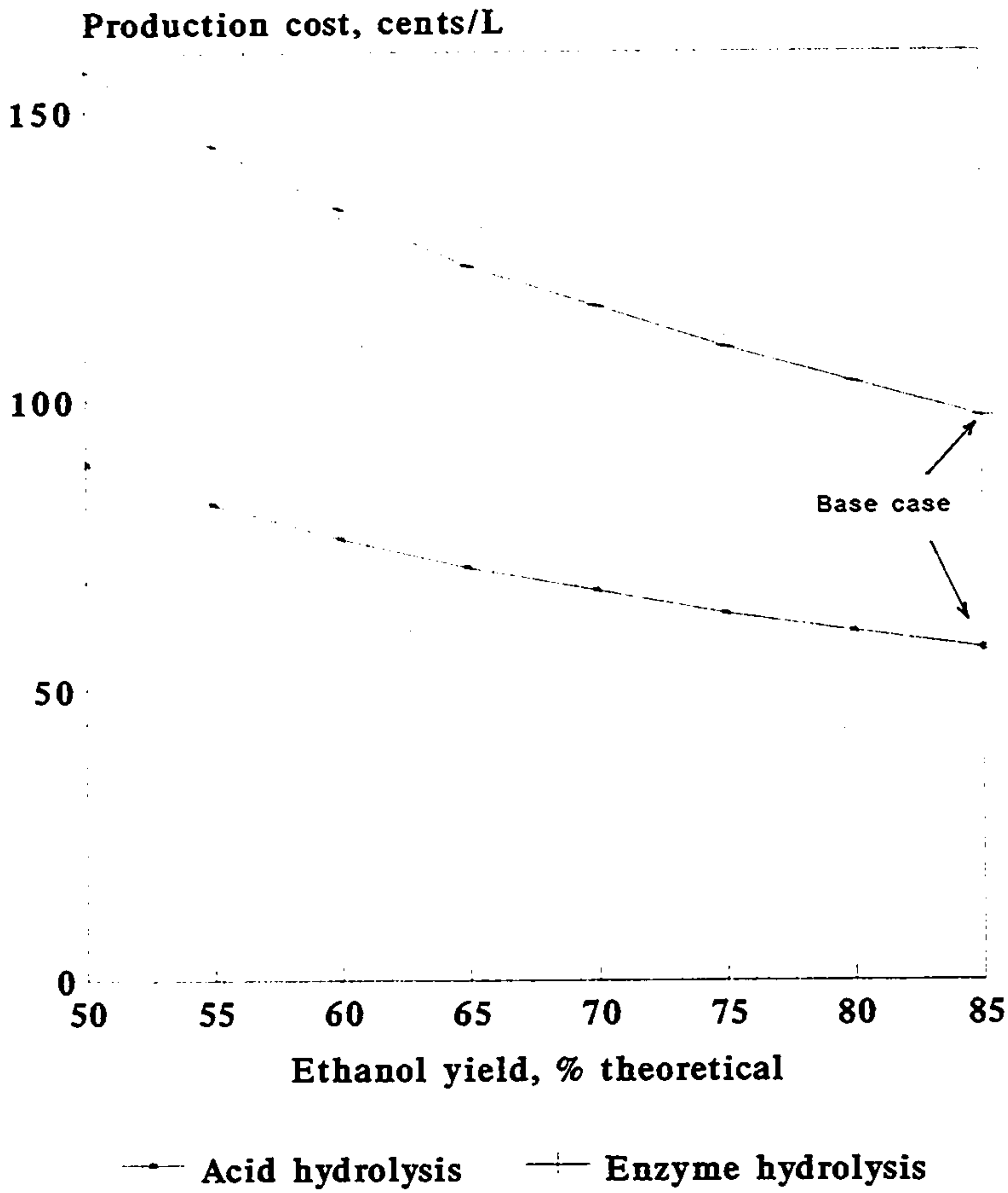


Fig. 10 Effect of Solid Loading in Enzyme Hydrolysis Reactor

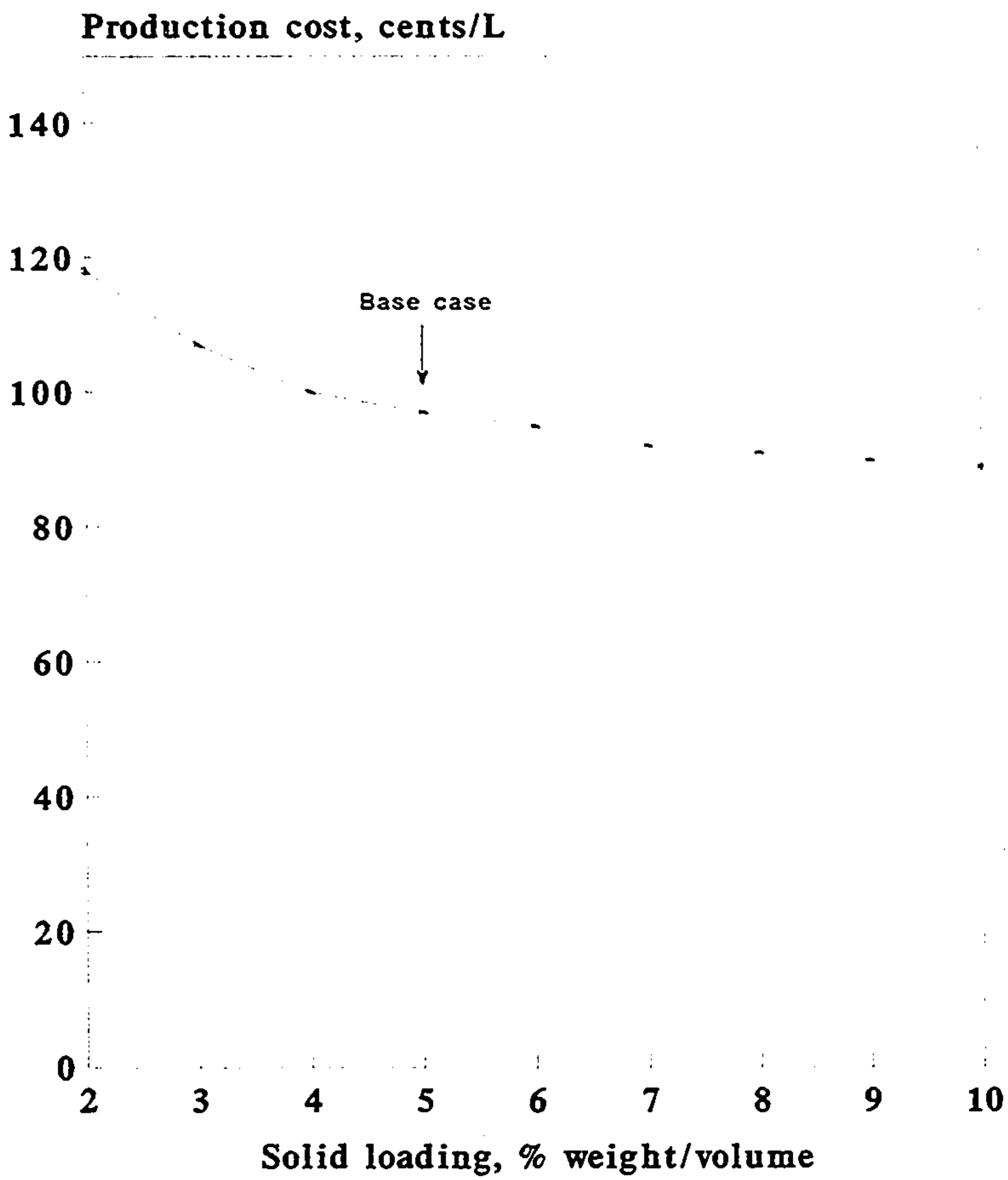


Fig. 11 Effect of Enzyme Loading in Hydrolysis Reactor

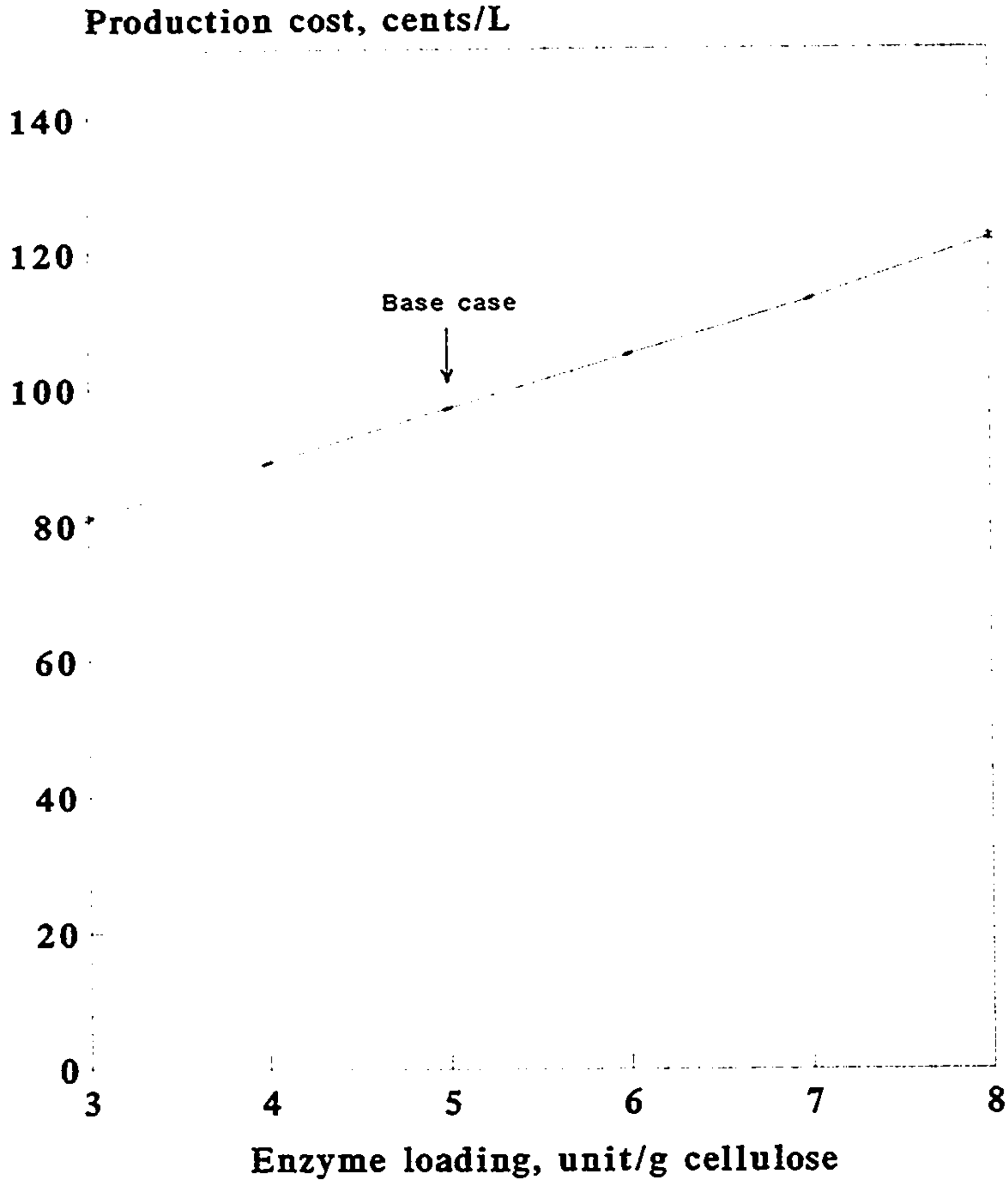
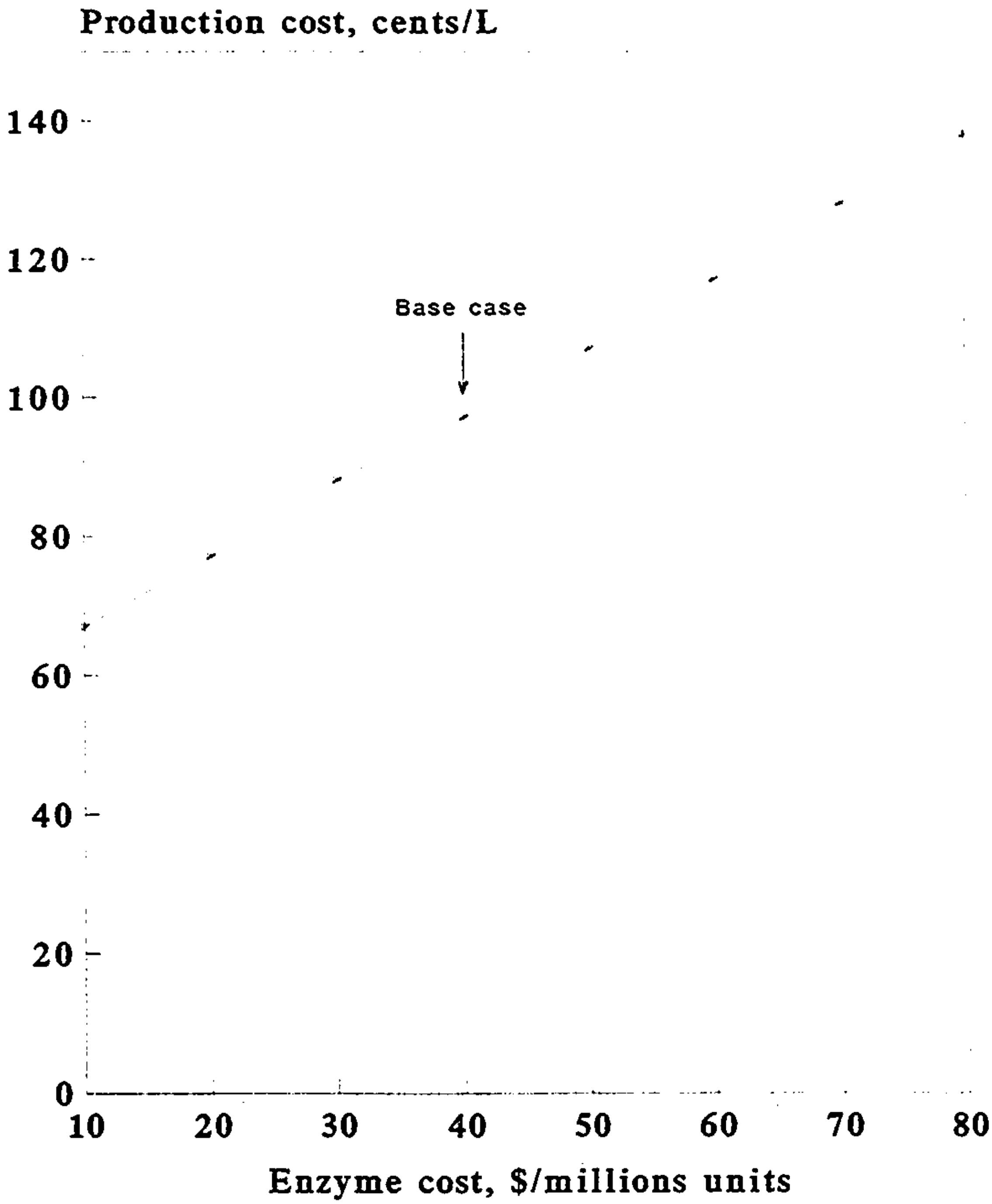


Fig. 12 Effect of Cost of Enzyme



(b) Monte Carlo Simulation

There are certain risks involved in predicting the input parameters for the model due to the variation in laboratory results, the uncertainty in projecting laboratory and pilot plant data to commercial plant operation, and the interaction between the parameters. These risks, occurring where input variables vary concurrently, can be simulated using the Monte Carlo Simulation technique, which is basically a multiple-parameters sensitivity analysis.

In the Monte Carlo Simulation, the variation in the values of input variables is simulated by means of random numbers. Random numbers can be used to simulate random samples without actually carrying out a large number of laboratory experiments. A normal distribution is assumed for the random samples. By assigning the means and standard deviations to the input variables, a cumulative-frequency distribution for the price of ethanol can be determined. The Monte Carlo Simulation technique is described below.

To carry out a Monte Carlo Simulation each input variable must first be transformed to a random normal distribution.
The transformation takes the form of the following equation:

$$Y = M + (S * RN)$$

Where: Y: randomized input variable
M: mean value of input variable
S: standard deviation
RN: normally distributed random number

There are many ways to generate normally distributed random numbers, such as the Box-Muller, Polar, Rejection and Sampling method[67,68]. The Sampling method was found to be easy to use with the spreadsheet environment and gives good approximation of normally distributed variates, i.e., mean and standard deviation of approximately 0 and 1 respectively. The application of the Sampling method using spreadsheet program is described below.

An approximation of normal random distribution of numbers can be generated using the @RAND function in Lotus 123 as illustrated in **Table 9** below. An array of 12 by N random numbers is constructed. The random numbers in each row are added together then 6 is subtracted from the sum. The number of rows, N, is selected between 300 and 500. If a large numbers of input variables are to be transformed, the number of random numbers that can be used in the simulation may be limited by the size of the computer RAM. For this case study, a distribution using 400 random numbers is generated for each variable used in the simulation.

Table 9 Generating an approximate normal distribution of random numbers

@RAND (col. 1)		. . . .	(col. 12)	@SUM (col. 1 to 12)	@SUM-6
0.366	0.468	0.764	0.639	6.468	0.468
0.611	0.926	0.826	0.166	6.846	0.846
0.202	0.733	0.084	0.693	6.330	0.330
0.636	0.725	0.830	0.881	6.365	0.365
:	:	:	:	:	:
:	:	:	:	:	:
:	:	:	:	:	:
Copy to 400th row					400th row

[67]Law Averill M. and Kelton W. David, "Simulation Modeling and Analysis", McGraw-Hill Book Co., N.Y., 1982, p. 258.

[68]Watson Hugh J. and Blackstone John H., Jr., "Computer Simulation", John Wiley & Sons, Inc., N.Y., 1989, p. 120.

The random numbers generated by this method have a range from -6 to +6, and closely fit a normal distribution. Because of this narrow range no unrealistic variables are generated by the transformation. An example of transforming the cost of enzyme is illustrated in Table 10.

Table 10 **Transformation of the enzyme cost to an approximate random normal distribution**

Input variable	Random number	Randomized variable (Y)
mean = 40	0.468	34.7
sigma = 5	0.846	42.8
	-0.668	38.1
	0.365	41.1
	:	:
	:	:
	:	:
	400th row	400th row

Transformation of other variables are carried out in a similar fashion. A new set of random numbers is generated for each transformation. Once the transformation is completed, the randomized values of each variables are group together in a table with each column containing random values of a variable (Table 11). A simple macro is written to input these values into the appropriate cell addresses of the variables and calculate the ethanol production cost. The final result is a simulated distribution of the production cost.

Table 11 Random values of variables used in a Monte Carlo Simulation of cost of ethanol production via enzyme hydrolysis

	Transformed variables					
No	VCE	YGE	CCEL	CENZ	CCH	Production cost (cents/L)
1	35.77	80.47	67.50	4.38	4.54	90
2	43.30	83.47	67.21	4.31	6.31	90
3	34.83	75.68	66.29	4.07	4.15	92
4	31.19	77.41	69.70	4.93	5.85	98
5	42.43	77.32	70.12	5.03	5.24	100
6	40.03	78.49	70.57	5.14	5.26	97
7	39.00	76.60	69.24	4.81	4.33	102
8	35.56	80.17	70.36	5.09	4.71	93
:	:	:	:	:	:	:
:	:	:	:	:	:	:
400	:	:	400th row		:	:

Legend:
VCE: Cost of enzyme, $/million units
YGE: Glucose yield from enzyme hydrolysis, % theoretical
CCEL: Cellulose content in wood waste, %
CENZ: Enzyme loading, unit/g cellulose
CCH: Solid loading in enzyme hydrolysis reactor, % w/v

Monte Carlo Simulations of the ethanol production cost for the enzyme and acid processes were performed, using 400 trials for each selected parameter used. Five parameters were selected for the enzyme hydrolysis, and three for the acid hydrolysis (**Table 12**). The resulting ethanol production cost distributions are shown in **Figure 13** and **Figure 14**. For enzyme hydrolysis, the estimated average production cost is 97 cents/L and the standard deviation is 7 cents/L. The acid hydrolysis yields an average production cost of 57 cents/L and a standard deviation of 3 cents/L. The cumulative probabilities of production costs are shown in **Figure 15**.

Table 12 Monte Carlo Simulation Parameters*

Parameter	Mean	Sigma	Unit
Enzyme hydrolysis			
Cost of enzyme	40	5	$/million units
Cellulase loading	5	0.5	unit/g cellulose
Glucose yield	80	2	% theoretical
Cellulose content	70	2	weight %
Solid loading	5	0.5	% (weight/volume)
Acid hydrolysis			
Glucose yield	40	2	% theoretical
Cellulose content	70	2	weight %
Ethanol yield	85	2	% theoretical

* Other variables are kept the same as in the base case (Table 6)

Fig. 13 Distribution of Ethanol Cost for Enzyme Hydrolysis Process

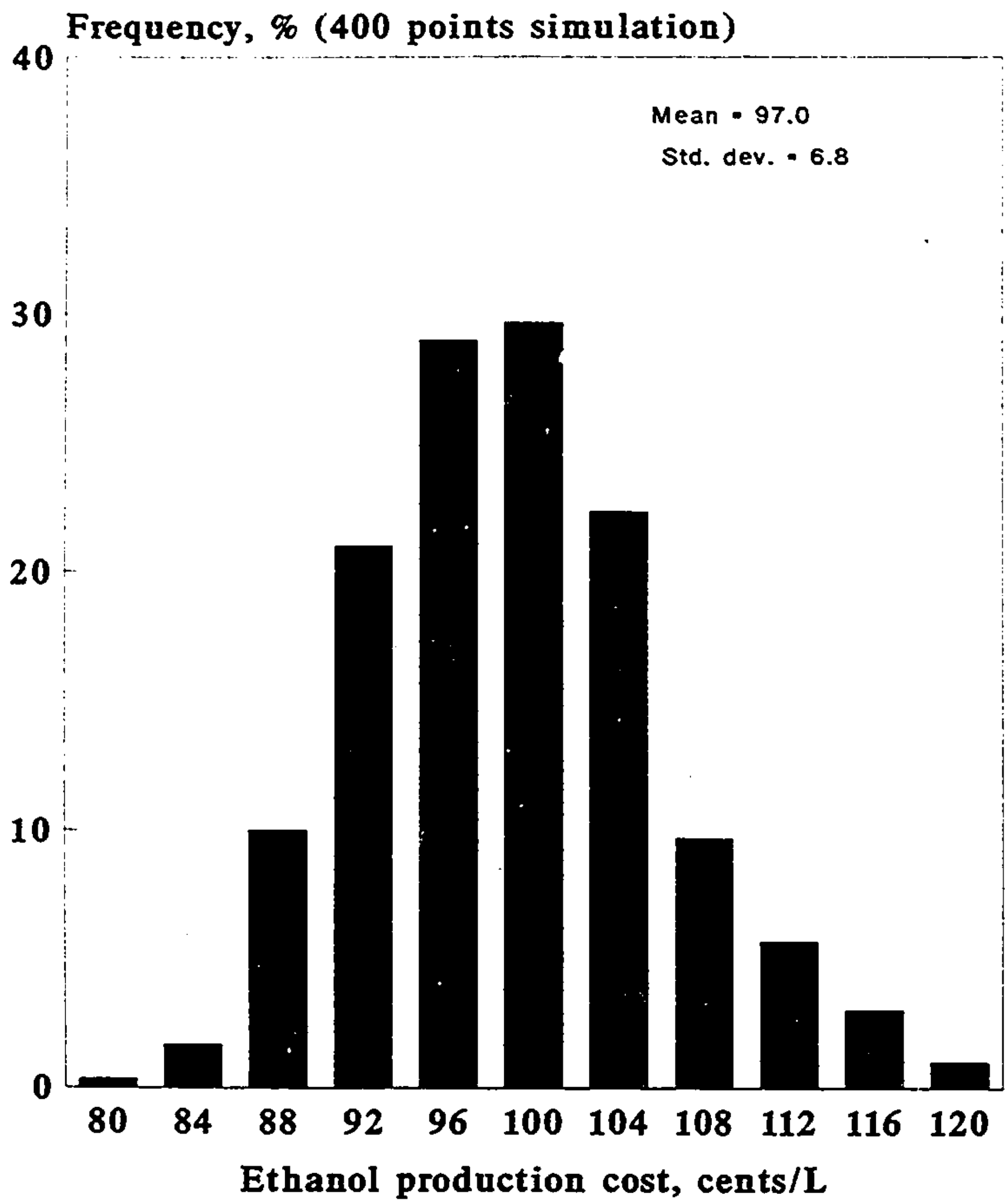


Fig. 14 Distribution of Ethanol Cost for Acid Hydrolysis Process

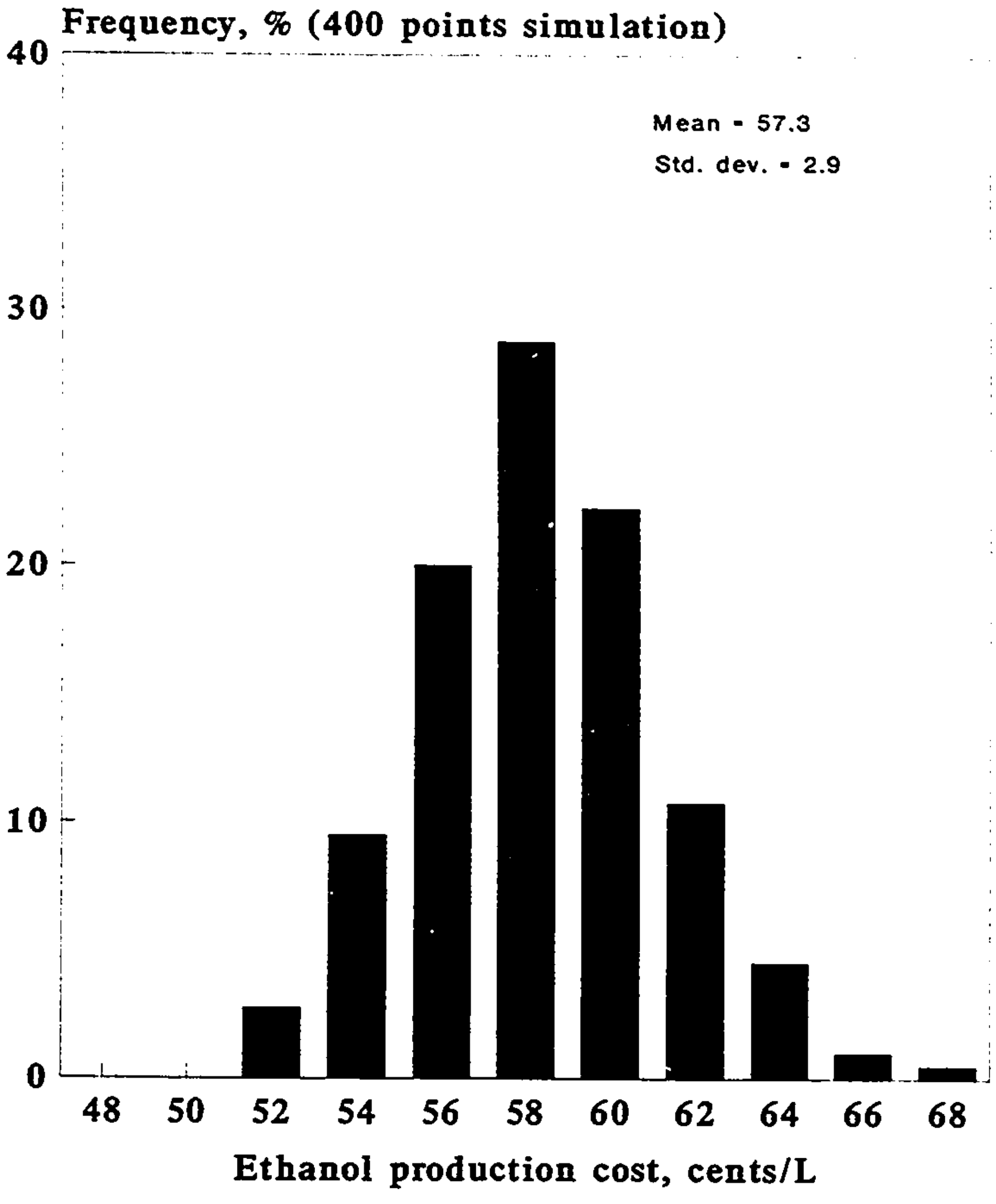
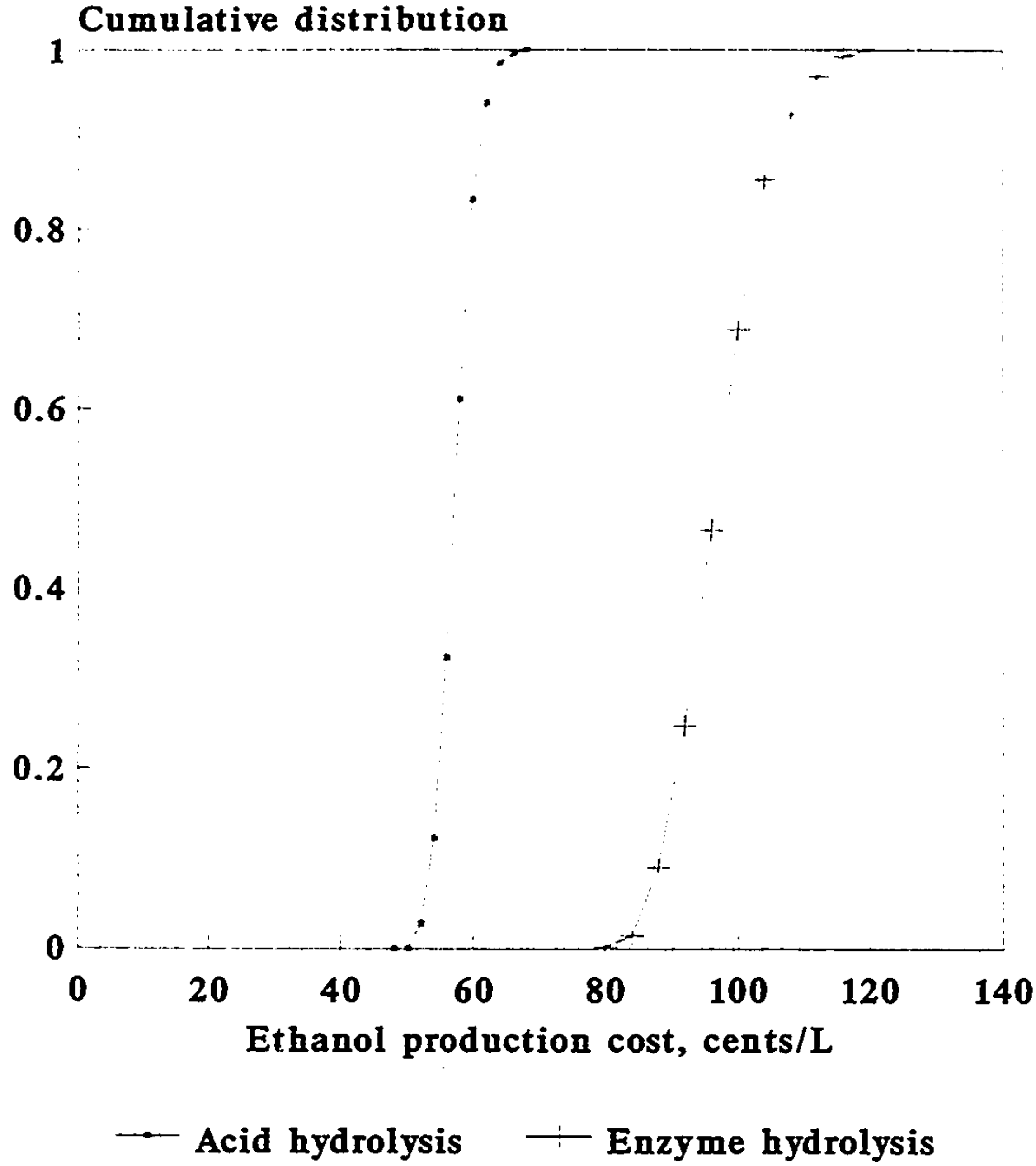


Fig. 15 Monte Carlo Simulation of Ethanol Production Costs



4.0 CONCLUSION AND EXTENSION

The model has been an effective tool for evaluating the technical and economic feasibility of the conversion of wood waste to ethanol without the expense of extensive laboratory and pilot plant testing. It has been useful to Tembec project managers in developing a research and development program for utilizing wood waste generated at the mills. The modelling approach gives an overview of alternative processes and a better focus on key parameters and their impact on the process economics. This type of process simulation can also be applied in preliminary evaluation for other capital projects or process modifications. The main advantages of using spreadsheet to build simulation models were: inexpensive, easy to use and update, and flexibility in reporting.

Researchers in the bioconversion field actively use computer simulation as a tool to evaluate their processes and achieve better focus for optimization effort. The factors having a significant impact on the economics of conversion of wood waste to ethanol are: cost of feedstock, cellulose content of feedstock, plant scale, enzyme cost (if an enzyme hydrolysis process is chosen), glucose yield, ethanol yield, and market price of ethanol. Acid hydrolysis is less expensive than enzyme hydrolysis, but the environmental impact of using an enzyme process is probably more favourable.

Although the conversion of wood waste to ethanol is currently not economically viable, it should deserve support of the forest products industry and the government because of its environmental merits. The current market price for industrial ethanol is approximately 52 cents/L. However, the market for industrial ethanol in Canada is only about 35 million litres per year. If ethanol is used as a transportation fuel additive, the volume can be quite large. Gasoline sales in Canada for 1989 was about

34.7 billions litres[69]. If 1% of all gasoline is to be replaced by ethanol, the volume would be 347 million litres annually. The problem is that fuel ethanol must be price competitive with gasoline, which currently has a whole sale cost of about 25 cents/L.

With the rapid advancement in research in biotechnology, the efficiency of converting wood to ethanol via enzyme process is expected to improve significantly. It is estimated that a large scale (50 millions litres/year or more) plant could potentially produce ethanol for approximately 50 cents/L within the next 5 years. At this price level, ethanol is viable as a motor fuel only if crude oil costs more than US$45/barrel. Since the price of oil is expected to remain stable and below US$25/barrel for the foreseeable future, fuel ethanol would need government subsidies of approximately 30 cents/L to be viable as an alternative to gasoline.

On the positive side, fuel ethanol produced from wood is a renewable source of energy. The federal government's Green Plan concludes that the goal of stabilizing production of carbon dioxide, a green house gas, will depend largely on cut back on the use of fossil fuel. In the past, the federal government's policy with regard to fuel ethanol was to let market forces dictate its use. Now, the government is moving towards providing incentives for conversion to alternative fuels such as propane, natural gas, methanol and ethanol[70]. Of all these alternative transportation fuels, biomass ethanol does not give a net contribution of CO_2 because forestry resource is renewable. Taking the environmental factor into consideration, there are

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[69]National Petroleum News Factbook, 1990, p. 85.

[70]Fagan Drew, "In search of alternatives", The Globe and Mail, March 30, 1991, pp. B1-B2.

external diseconomies of consumption[71] when fossil fuels are burnt. By using wood waste as a source for fuels, i.e., burning in biomass boilers or converting to ethanol, the forest products industry could be in a strong position in providing an alternative for stabilizing CO_2 emission in Canada. If the concept of pollution tax and credit is applied here, then a pollution tax must be charged to fossil fuel and a credit given to biomass ethanol. However, because global climate change is an international issue, such actions need cooperation among nations to achieve effective solutions. The encouraging news is that several European countries including Germany and Sweden have begun to impose "carbon" taxes on gasoline and promote the use of renewable energy such as biomass ethanol. Let's hope that this sensible initiation may eventually spread to North America.

Social changes have made the environment one of the key factors in choosing a product. Biotechnology offers a vast potential to the pulp and paper industry for making its processes and products environmentally friendly. If the industry is to be proactive it must consider actively develop and utilize this technology to get rid of its polluting and smoke stack image, and transform to a new high-technology and "green" industry.

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[71]McGuigan James R. and Moyer R. Charles, "Managerial Economics" 4th edition, West Publishing Company, St. Paul, MN., 1986, pp. 632-649.

APPENDIX A

Material and Energy Balance

Lotus 123 Spreadsheet Model for the Simulation of
HYDROLYSIS OF WOOD WASTE

July 17, 1991 Q. Nguyen

Input	40	oven-dry tonne of wood per day	
Output			
Acid hydrolysis	2,367,223	L 95 wt% ethanol/yr	169 litres of ethanol per tonne of wood
Enzymatic hydrolysis	4,734,447	L 95 wt% ethanol/yr	338 litres of ethanol per tonne of wood

INPUT PARAMETERS

PROCESS

Wood	1,667	Wood input, oven-dry (OD) kg/h
MCW	60	Moisture content of wood, wt% (wet basis)
HPPRE	1	High pressure steam requirement for pretreatment, kg/kg OD wood
HPAH	1.5	High pressure steam requirement for acid hydrolysis, kg/OD kg substrate
SO2	1.5	SO2 content in impregnated wood chips, wt%
rG	95	Solids recovery after steam pretreatment, % of wood input
cCH	5	Substrate loading in enzymatic hydrolysis fermenters, wt%
cENZ	5	Enzyme loading, IU/g cellulose
tCH	72	Enzymatic hydrolysis time, hour
ccel	70	Cellulose content in original input wood, wt%
H2SO4	0.03	Sulfuric acid content in acid-impregnated wood, wt ratio
MCWI	70	Moisture content of steam treated wood, wt%
yGe	80	Glucose yield from enzymatic hydrolysis of wood, % theoretical
yGa	40	Glucose yield from acid hydrolysis of wood, % theoretical
yEC6	85	Ethanol yield from glucose, % theoretical
WTYPE	1	Type of wood waste: WTYPE = 1 for clarifier sludge; WTYPE = 0 for sawdust
PRE	1	Pretreatment ?: YES = 1; NO = 0
ACID	0	H2SO4 hydrolysis: ACID= 1; Enzymatic hydrolysis: ACID = 0
VCW	0	Cost of wood, $/OD tonne
VCE	40	Enzyme cost, $/million IU (0.6 IU/mg protein)
VCA	140	Cost of 96% sulfuric acid, $/tonne
VCSO2	240	Cost of SO2, $/tonne
VCNH3	300	Cost of ammonia, $/tonne
VCST	4	Cost of process steam (125 psi), $/GJ
VCS	0.011	Cost of process steam (125 psi), $/kg
VCEP	0.04	Cost of electrical power, $/kWh

ECONOMIC

LIFE	15	Service life of equipment, years
LTDEBT	0.3	Long-term debt, fraction of total borrowings (long and short terms)
LTDC	0.12	Interest rate of long-term debt
STOCK	0.7	Common stock, fraction of total fixed-capital investment (common stocks and debts)
STOCKC	0.12	Common stock cost
TAX	0.5	Income tax rate
PTI	0.02	Annual property tax and insurance, fraction of fixed-capital investment
INFLATE	0.05	Annual inflation rate
ODPY	350	Number of operating days per year

MATERIAL AND ENERGY BALANCE (Basis: 1 hour)

PRETREATMENT

WWood	4,167	Wood waste input (wet weight), kg/h
MSO2	25	SO2 requirement, kg/h
HP	1,667	High pressure steam requirement, kg/h
WSEW	6,333	Wet steam exploded wood.
SEW	1,583	Dry steam exploded wood, kg/h
SEWW	4,750	Water in wet exploded wood, kg/h
CELLU	1,143	Cellulose in exploded wood, kg/h

ENZYMATIC HYDROLYSIS

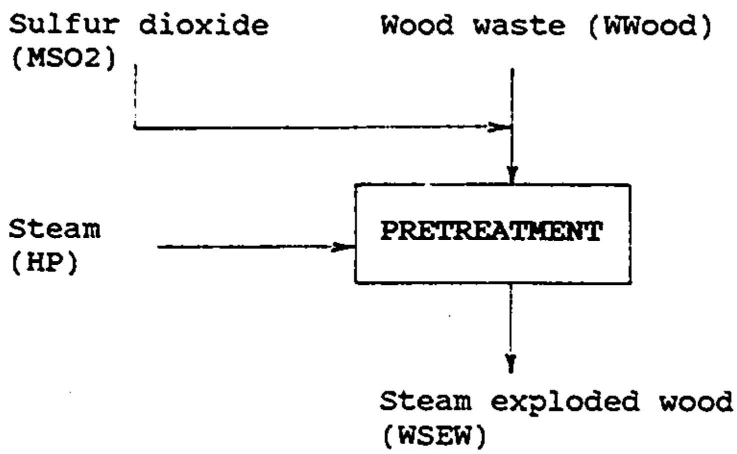
ENZ	5.72E+06	Total enzyme required, IU/h
WHYD	31,667	Hydrolysis slurry, kg/h
WI	1,667	Substrate in slurry, kg/h
HYDW	30,000	Water, kg/h
ENC6	1,036	Glucose production, kg/h
WELIG	1,625	Wet solid residues, kg/h
ELIG	650	Dry solids in residues, kg/h
ELIGW	975	Water in residues, kg/h
EBEER6	30,450	Beer, kg/h
EETC6	450	Ethanol, kg/h
EWB6	30,000	Water, kg/h
ECEC6	1.5	Ethanol concentration in beer, wt%
EEC6	564	Ethanol (95 wt%) from cellulose, L/h
ECCO2	430	Carbon dioxide production, kg/h
LPS2	6,001	Steam required for ethanol distillation, kg/h
EYETOH	338	Ethanol yield, L/OD tonne wood

ACID HYDROLYSIS (SINGLE STAGE)

MSO4	52	Sulfuric acid (technical grade) requirement, kg/h
AHHP1	2,500	High pressure steam requirement, kg/h
WSEW1	5,000	Wet steam exploded wood.
SEW1	1,330	Solids in steam exploded wood, kg/h
SEWW1	3,670	Water and condensables in wet exploded wood, kg/h
WAHC1	3,867	Water to blow tank, kg/h
AHS1	8,867	Acid hydrolysis slurry, kg/h
ANC61	518	Glucose, kg/h
ALIG1	1,149	Residual solids (non-glucose), kg/h
WAHS1	7,200	Water, kg/h
NH3MA1	18	Ammonia required to neutralize the acid hydrolysate, kg/h
SULFATE	61	Ammonium sulphate, kg/h
ANC6S1	8,867	Glucose solution from centrifuge, kg/h
ANC61	518	Glucose, kg/h
WANC61	8,349	Water, kg/h
CANC61	6.2	Glucose concentration, wt%
PWAH1	1,149	Wash water, kg/h
WALIG1	3,829	Wet solid residues, kg/h
ALIG1	1,149	Dry solid residues, kg/h
ALIGW1	2,680	Water in residues, kg/h
ABEER61	8,574	Beer, kg/h
AETC61	225	Ethanol, kg/h
AWB61	8,349	Water, kg/h
ACEC61	2.6	Ethanol concentration in beer, wt%
AEC61	282	Ethanol (95 wt%) from cellulose, L/h
ACCO21	215	Carbon dioxide production, kg/h
LPS31	2,990	Steam required for ethanol distillation, kg/h
AETOH1	282	Total 95 wt% ethanol production, L/h
AYETOH1	169	Ethanol yield, L/OD tonne wood

Material and Energy Balance Equations

Referring to the conceptual process flow diagram for steam pretreatment and enzyme hydrolysis (Figure 3 on page 60), the material balance for the steam pretreatment is shown in the example below. Note that the notations for various streams and components, as listed in the input variables table above, are shown in parentheses. All calculations are based on one hour of flow of material input to simplify the cost estimation.



Wood waste input (wet basis), kg/h:

Wwood = 100*WOOD/(100-MCW)

Where: WOOD = Mass of wood waste input (dry basis), kg/h
MCW = Moisture content of wood waste, wt%

Amount of sulfur dioxide required, kg/h:

MSO2 = SO2*WOOD/100

Where: SO2 = Sulfur dioxide content in impregnated wood in wt%

Steam requirement, kg/h:

HP = HPRE*WOOD

Where: HPRE = kg of steam required to treat 1 kg of wood

Steam exploded wood (wet basis), kg/h:

WSEW = RG*WOOD/(100*(1-(MCW/100)-0.15))

Where: RG = Percentage of solids recovered after steam pretreatment
0.15 = Fraction of solid in wet exploded wood

Steam exploded wood (dry basis), kg/h:

SEW = RG*WOOD/100

Water in exploded wood = Wet exploded wood - Dry exploded wood

SEWW = WSEW - SEW

Cellulose in exploded wood (dry basis), kg/h

CELLU = 0.98*WOOD*CCEL/100

Where: CCEL = Cellulose content in original wood input, %
0.98 = Cellulose recovery fraction after steam pretreatment

The material and energy balance calculations for subsquent processing steps for the enzyme hydrolysis and for the acid hydrolysis process are computed in a similar fashion. The equations used in the spreadsheet model are listed in the following pages.

```
C62: 'MATERIAL AND ENERGY BALANCE (Basis: 1 hour)
B65: 'PRETREATMENT
B67: ^WWood
C67: (,0) 100*WOOD/(100-MCW)
E67: [W6] 'Wood waste input (wet weight), kg/h
B68: ^MSO2
C68: (,0) +SO2*WOOD/100
E68: [W6] 'SO2 requirement, kg/h
B69: ^HP
C69: (,0) +HPPRE*WOOD
E69: [W6] 'High pressure steam requirement, kg/h
B70: ^WSEW
C70: (,0) +RG*WOOD/(100*(1-(MCW/100)-0.15))
E70: [W6] 'Wet steam exploded wood,
B71: ^SEW
C71: (,0) +WOOD*RG/100
E71: [W6] 'Dry steam exploded wood, kg/h
B72: ^SEWW
C72: (,0) +WSEW-SEW
E72: [W6] 'Water in wet exploded wood, kg/h
B73: ^CELLU
C73: (,0) 0.98*WOOD*CCEL/100
E73: [W6] 'Cellulose in exploded wood, kg/h
B75: 'ENZYMATIC HYDROLYSIS
B77: ^ENZ
C77: (S2) @IF(PRE=1,CENZ*CELLU*1000,CENZ*(CCEL*WOOD)/100*1000)
E77: [W6] 'Total enzyme required, IU/h
B78: ^WHYD
C78: (,0) @IF(PRE=1,100*SEW/CCH,100*WOOD/CCH)
E78: [W6] 'Hydrolysis slurry, kg/h
B79: ^WI
C79: (,0) +WOOD
E79: [W6] 'Substrate in slurry, kg/h
B80: ^HYDW
C80: (,0) +WHYD-WI
E80: [W6] 'Water, kg/h
B81: ^ENC6
C81: (,0) +WOOD*CCEL/100*1.11*YGE/100
E81: [W6] 'Glucose production, kg/h
B82: ^WELIG
C82: (,0) +ELIG/0.4
E82: [W6] 'Wet solid residues, kg/h
B83: ^ELIG
C83: (,0) @IF(PRE=1,SEW-ENC6/1.11,WOOD-ENC6/1.11)
E83: [W6] 'Dry solids in residues, kg/h
B84: ^ELIGW
C84: (,0) +WELIG-ELIG
E84: [W6] 'Water in residues, kg/h
B85: ^EBEER6
C85: (,0) +EETC6+EWB6
E85: [W6] 'Beer, kg/h
B86: ^EETC6
C86: (,0) +ENC6*0.511*YEC6/100
E86: [W6] 'Ethanol, kg/h
```

```
B87: ^EWB6
C87: (,0) +HYDW
E87: [W6] 'Water, kg/h
B88: ^ECEC6
C88: (F1) 100*EETC6/(EETC6+EWB6)
E88: [W6] 'Ethanol concentration in beer, wt%
B89: ^EEC6
C89: (,0) +ENC6*0.511*YEC6/(0.95*100*0.8404)
E89: [W6] 'Ethanol (95 wt%) from cellulose, L/h
B90: ^ECCO2
C90: (,0) +ENC6*0.488*YEC6/100
E90: [W6] 'Carbon dioxide production, kg/h
B91: ^LPS2
C91: (,0) +EEC6*(10.6964-3.2913*ECEC6/100+0.4456*(ECEC6/100)^2-0.0216*(ECEC6/100)^3)
E91: [W6] 'Steam required for ethanol distillation, kg/h
B92: ^EYETOH
C92: (,0) 1000*EEC6/WOOD
E92: [W6] 'Ethanol yield, L/OD tonne wood
B94: 'ACID HYDROLYSIS (SINGLE STAGE)
B96: ^HSO4
C96: (F0) +WOOD*H2SO4/0.96
E96: [W6] 'Sulfuric acid (technical grade) requirement, kg/h
B97: ^AHHP1
C97: (,0) +WOOD*HPAH
E97: [W6] 'High pressure steam requirement, kg/h
B98: ^WSEW1
C98: (,0) +WWOOD-WOOD+AHHP1
E98: [W6] 'Wet steam exploded wood,
B99: ^SEW1
C99: (,0) +WOOD*RG*0.84/100
E99: [W6] 'Solids in steam exploded wood, kg/h
B100: ^SEWW1
C100: (,0) +WSEW1-SEW1
E100: [W6] 'Water and condensables in wet exploded wood, kg/h
B101: ^WAHC1
C101: (,0) +AHS1-WSEW1
E101: [W6] 'Water to blow tank, kg/h
B102: ^AHS1
C102: (,0) +SEW1/0.15
E102: [W6] 'Acid hydrolysis slurry, kg/h
B103: ^ANC61
C103: (,0) +WOOD*CCEL/100*1.11*YGA/100
E103: [W6] 'Glucose, kg/h
B104: ^ALIG1
C104: (,0) +WOOD-ANC61
E104: [W6] 'Residual solids (non-glucose), kg/h
B105: ^WAHS1
C105: (,0) +AHS1-ANC61-C114
E105: [W6] 'Water, kg/h
B106: ^NH3MA1
C106: (,0) +HSO4*2*17/98
E106: [W6] 'Ammonia required to neutralize the acid hydrolysate, kg/h
B107: ^SULFATE
C107: (,0) +HSO4*115/98
E107: [W6] 'Ammonium sulphate, kg/h
```

```
B108: ^ANC6S1
C108: (,0) +ANC61+WANC61
E108: [W6] 'Glucose solution from centrifuge, kg/h
B109: ^ANC61
C109: (,0) +ANC61
E109: [W6] 'Glucose, kg/h
B110: ^WANC61
C110: (,0) +WAHS1+PWAH1
E110: [W6] 'Water, kg/h
B111: ^CANC61
C111: (F1) 100*ANC61/WANC61
E111: [W6] 'Glucose concentration, wt%
B112: ^PWAH1
C112: (,0) +ALIG1
E112: [W6] 'Wash water, kg/h
B113: ^WALIG1
C113: (,0) +ALIG1/0.3
E113: [W6] 'Wet solid residues, kg/h
B114: ^ALIG1
C114: (,0) +ALIG1
E114: [W6] 'Dry solid residues, kg/h
B115: ^ALIGW1
C115: (,0) +WALIG1-ALIG1
E115: [W6] 'Water in residues, kg/h
B116: ^ABEER61
C116: (,0) +AETC61+AWB61
E116: [W6] 'Beer, kg/h
B117: ^AETC61
C117: (,0) +ANC61*0.511*YEC6/100
E117: [W6] 'Ethanol, kg/h
B118: ^AWB61
C118: (,0) +WANC61
E118: [W6] 'Water, kg/h
B119: ^ACEC61
C119: (F1) 100*AETC61/(AETC61+AWB61)
E119: [W6] 'Ethanol concentration in beer, wt%
B120: ^AEC61
C120: (,0) +AETC61/(0.95*0.8404)
E120: [W6] 'Ethanol (95 wt%) from cellulose, L/h
B121: ^ACCO21
C121: (,0) +ANC61*0.488*YEC6/100
E121: [W6] 'Carbon dioxide production, kg/h
B122: ^LPS31
C122: (,0) +AETOH1*(10.6964-3.2913*ACEC61/100+0.4456*(ACEC61/100)^2-0.0216*(ACEC61/100)^3)
E122: [W6] 'Steam required for ethanol distillation, kg/h
B123: ^AETOH1
C123: (,0) +AEC61
E123: [W6] 'Total 95 wt% ethanol production, L/h
B124: ^AYETOH1
C124: (,0) 1000*AETOH1/WOOD
E124: [W6] 'Ethanol yield, L/OD tonne wood
```

APPENDIX B

LIST OF EQUIPMENT

DESCRIPTION	QTY	UNIT COST ($)	SCALING EXPONENT	INSTALL. FACTOR	INSTALLED COST, $
PRETREATMENT					
Drag-chain conveyor	1	10000	0.6	1.3	12080
SO2 impregnation reactor	2	500000	0.7	1.6	1405843
Chip bin	1	70000	0.5	1.4	96305
Steam digester	2	600000	0.7	1.6	1687011
Blow tank	1	90000	0.7	1.4	110710
Steam condenser	1	20000	0.65	1.5	27108
Condensate pump	1	5000	0.7	1.4	6151
Process piping	1	50000	1.05		36118
Instrumentation	1	50000	N/A		65000
Electrical	1	40000	N/A		52000
Building, yard	1	300000	N/A		390000
			Total capital cost (Including contingency)		$4,277,158
ENZYMATIC HYDROLYSIS					
Hydrolysis fermenters	6	300000	N/A	1.4	3276000
Mixer	6	50000	N/A	1.4	546000
Acid, base tanks	2	7500	N/A	1.4	27300
Hydrolysate pumps	6	20000	0.7	1.4	147613
Centrifuge	1	336134	N/A	1.5	655462
Conveyor	1	15000	0.6	1.3	18120
Process piping	1	50000	1.05		36118
Instrumentation	1	100000	N/A		130000
Electrical	1	60000	N/A		78000
Building	1	300000	N/A		390000
			Total capital cost (Including contingency)		$5,835,075
ACID HYDROLYSIS (single-stage)					
Acid impregnation reactor	2	500000	0.7	1.6	878652
Acid hydrolysis reactors	2	600000	0.7	1.6	1054382
Blow tank	1	180000	0.7	1.4	158157
Slurry pump	2	20000	0.7	1.4	35146
Centrifuge	1	183849	N/A	1.5	239004
Conveyor	1	20000	0.6	1.3	18584
Process piping	1	75000	1.05		54177
Instrumentation	1	80000	N/A		104000
Electrical	1	50000	N/A		65000
Building	1	200000	N/A		260000
			Total capital cost (Including contingency)		$3,153,813

APPENDIX C

SINGLE-PARAMETER SENSITIVITY ANALYSIS RESULTS

Table C1 Effect of wood waste input (plant capacity)

Wood input (tonnes/day)	Production cost, cents/L Enzyme	Acid
20	113	76
30	101	64
40	97	57
50	93	53
60	82	50
70	89	48
80	88	46

Table C2 Effect of cost of wood waste

Cost of waste ($/tonne)	Production cost, cents/L Enzyme	Acid
-20	91	45
-10	94	51
0	97	57
10	100	63
20	103	69
30	106	75
40	109	81

Table C3 Effect of cellulose content in wood waste

Cellulose content (weight %)	Production cost, cents/L Enzyme	Acid
50	115	75
55	109	69
60	105	64
65	101	60
70	97	57
75	94	54
80	92	51

Table C4 Effect of glucose yield

Glucose yield (% theoretical)	Production cost, cents/L Enzyme	Acid
30	240	72
40	183	57
50	148	48
60	126	42
70	109	N/A*
80	97	N/A
90	88	N/A

* Glucose yield for acid hydrolysis is limited to less than 60%

Table C5 Effect of ethanol yield in fermentation

Ethanol yield (% theoretical)	Production cost, cents/L Enzyme	Acid
50	157	89
55	144	82
60	133	76
65	123	71
70	116	67
75	109	63
80	103	60
85	97	57

Table C6 Effect of cost of enzyme

Cost of enzyme ($/millions units)	Production cost, cents/L
10	67
20	77
30	89
40	97
50	107
60	117
70	128
80	138

Table C7 Effect of enzyme loading in hydrolysis reactor

Enzyme loading (unit/g cellulose)	Production cost, cents/L
3	81
4	89
5	97
6	105
7	113
8	122

Table C8 Effect solid loading in enzyme hydrolysis reactor

Solid loading (% weight/volume)	Production cost, cents/L
2	118
3	107
4	100
5	97
6	95
7	92
8	91
9	90
10	89

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