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State-of-the-Art of the Pulp and Paper Industry and its Environmental Protection Practices

Canada

Economic and Technical Review
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STATE-OF-THE-ART OF THE PULP AND PAPER INDUSTRY AND ITS ENVIRONMENTAL PROTECTION PRACTICES

prepared by

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for the

Environmental Protection Service
Environment Canada

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This report has been reviewed by the Environmental Protection Programs Directorate, Environmental Protection Service, and approved for publication. Approval does not necessarily signify that the contents reflect the views and policies of the Environmental Protection Service. Mention of trade names or commercial products does not constitute recommendation or endorsement for use.

READERS COMMENTS

This review is as complete as possible within the time constraints and budget available for its preparation. Readers who wish to comment on the content, or wish to suggest additions, are invited to address them to -

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ABSTRACT

The current technology for environmental protection used in the Canadian pulp and paper industry is reviewed. Recent process and equipment developments having a significant effect on the industry's effluents, atmospheric emissions and solid waste discharges are described, with emphasis on in-plant measures. Drawings, flowsheets, and typical process criteria are presented.

The overall capital and operating costs, as well as the energy conservation implications, of environmental protection measures are briefly discussed.

RÉSUMÉ

On examine les techniques actuellement utilisées dans l'industrie canadienne des pâtes et papiers pour protéger l'environnement. On décrit les dernières améliorations des procédés et de l'équipement, qui ont un effet significatif sur les effluents industriels, les émissions atmosphériques et les rejets de matières solides, en insistant sur les mesures prises à la source. Des dessins, des schémas de principe et des conditions opératoires sont présentés.

Les investissements et les frais d'exploitation, dans leur ensemble, de même que les questions d'économie de l'énergie liés aux mesures de protection de l'environnement font l'objet d'une courte discussion.

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Dr. S.D. Swan, Consultant, Senneville, Quebec wrote the section on forestry.

Dr. W.H. Rapson, Toronto, Ontario, reviewed the bleaching section and contributed a number of useful comments.

EXECUTIVE SUMMARY

The layout and subtitles in this executive summary follow the same sequence as the body of the report. All data are presented in SI units, in accordance with Canada's metric policy. Refer to the Appendix for conversions and further information.

Introduction

The pulp and paper industry in Canada includes about 130 mills, producing over 20 million tonnes of various grades of paper and pulp per annum. Newsprint and bleached kraft pulp are the predominant product categories, and most of the expansion expected over the next few years is expected to be in the production of thermomechanical pulp for newsprint. Thermomechanical pulp is replacing sulphite pulp for environmental reasons and will also increase newsprint production by a few percent. Much of the current capital expenditure in the industry is being directed towards improvements in product quality, protection of the environment, or energy conservation.

Wood Supplies and Preparation

The rate of forest harvesting in Canada is approaching the rate of growth of wood, and will surpass it in a few years if no corrective action is taken. The technology required to substantially increase the yield of Canadian forests is well known, but its application has been so far been relatively limited. In some areas, particularly in the East, softwoods are being harvested much more quickly than they are being replaced by forest regeneration.

The traditional seasonal delivery of logs to mills has largely been replaced by systems which approach a uniform rate of delivery all year round. River driving of logs is disappearing, and logging methods are being steadily mechanised.

Dry debarking processes have proven capable of reducing the effluent biochemical oxygen demand (BOD) and suspended solids from the wood preparation departments by 80 to 99%, and suitable for many grades of pulp. Most new mills use the dry debarking process to minimise effluents, and some older mills have converted from the traditional wet process to dry debarking for this reason. However, this does not necessarily bring a mill into compliance with the Federal Pulp and Paper Effluent Regulations (1972), since the Component Process Category allowance for wet drum barking is 5 kg/t wood, whereas it is only 2.5 kg/t wood for dry debarking with wood washing, and zero if there is no wood washing operation.

Pulping Processes

The most significant change in pulping practices in the last ten years has been the widespread use of **thermomechanical pulping** (TMP). This process produces mechanical pulp which is stronger than the traditional stone groundwood pulp, and therefore allows replacement of some or all of the sulphite pulp in newsprint with mechanical pulp, raising the overall yield on wood and reducing the effluent BOD substantially.

The principal recent development in sulphite pulping technology has been the development of several **higher yield** processes to replace the traditional low-yield sulphite pulp used for the production of newsprint. These processes reduce the BOD discharges substantially, while avoiding the need for chemical recovery systems.

Consolidated Bathurst Inc. and Canadian International Paper Co. have both developed ultra high yield variations of the previously established sulphite process, and have full scale systems in operation. Ontario Paper Co. has developed the OPCO process which replaces the traditional sulphite pulp in newsprint furnish with a treated thermo-mechanical pulp. The first full-scale mill using this process is presently under construction in Quebec.

No major changes have occurred in the past 10 years in the kraft pulping process, but the equipment used has been developed to increase the practical limits on pulp washing efficiency and reduce discharges of organic material due to foam and overflows. **Continuous digesters** incorporating **diffusion washers** have become widespread and other more recent equipment improvements are gaining acceptance. Most new mills have installed this equipment, which produces effluents with lower BOD and suspended solids than traditional equipment. Some older mills have replaced obsolete equipment to improve black liquor recovery and reduce effluent discharges.

Chemical Recovery

Recently installed kraft chemical recovery systems are more generously dimensioned than was normal in the past, which allows recovery and incineration of higher proportions of the residual organics removed from the wood in the pulping process. Most recently installed recovery systems use **low-odour** extended economy recovery furnaces, which reduce malodorous gas emissions and raise thermal efficiency compared with the traditional boiler with a **direct contact evaporator.** Several scrubbers have been installed for the recovery of particulates, hydrogen sulphide emissions and heat, mostly in older mills. In the chemical recovery area, most new installations are based on one large single line of equipment, rather than two or more smaller units in parallel. This simplifies operation and facilitates the application of modern computer control systems, stabilising the operation and reducing accidental discharges to the environment.

To overcome the capacity limitations of an older recovery furnace, one mill has installed a fluidised bed reactor in series with the recovery furnace to oxidise the organic material in a portion of the black liquor.

Most of the larger, low yield sulphite pulp mills have installed chemical recovery systems, primarily to reduce effluent BOD and toxicity. Fluidised bed reactors have been installed to incinerate waste pulping liquors in a few cases.

Pulp Washing and Screening

The design and operation of the washing and screening department is one of the key factors in minimising kraft mill effluent BOD and toxicity, and in recovering the maximum amount of energy from the waste liquor. The equipment used has changed radically over the past ten years, with diffusion washers and pressure screens becoming the industry standard for new installations as the washing and screening systems move towards a "pipeline" processing concept.

Continuous diffusion washers have become the predominant equipment for new kraft mill installations, and have facilitated the reduction of both continuous and accidental discharges of black liquor solids, reducing the raw effluent BOD and toxicity relative to the values common in effluents from older drum washing systems. They also eliminate the high volume emissions of malodourous gases which characterise the traditional drum type brown stock washer system.

Closed pressure screens have been installed in most of the newest washing and screening departments in both chemical and mechanical pulp mills. Although they have no direct environmental effect, accidental losses and foam overflows are lower than with the traditional open centrifugal screens. This is particularly important in the case of kraft pulp systems, since the foam can be a significant source of BOD and toxicity in the mill effluent.

Pressure diffusion washers and Fourdrinier type flat belt washers have been introduced, and both offer the potential for better washing than the conventional drum washers, with lower accidental discharges and lower malodorous gas emissions. It remains to be seen how they will compete with the diffusion washers on the market.

Bleaching

Many kraft mills have modified their bleach plants in the past ten years to reduce effluent flows, primarily to save energy. This generally reduces effluent treatment costs also, and may improve the efficiency of some effluent treatment systems slightly. Several mills have also added chlorine dioxide generation capacity and substituted chlorine dioxide for some of the chlorine in the first bleaching stage, with the objective of reducing effluent toxicity. One Canadian mill now uses an oxygen delignification stage prior to the bleach plant, which results in higher proportions of the organic residues from pulping being recovered and incinerated in the recovery boiler than in conventional kraft mills.

Complete recycle of bleach plant effluent using the Rapson-Reeve concept has been adopted by one mill in Ontario to avoid the need for a biological treatment system.

Papermaking

The most environmentally significant papermaking development in recent years has been the **replacement of low-yield sulphite pulp** by mechanical pulp and high-yield sulphite pulps in newsprint. This has reduced the BOD of newsprint mill effluents by up to 60%, although it does not usually bring the mill into compliance with the Federal Pulp and Paper Effluent Regulations, since the permitted BOD discharge for the less polluting high-yield sulphite and TMP processes is lower than it was for the traditional low-yield sulphite process.

A wide variety of pulp blends are now used for newsprint manufacture, as illustrated in the following table prepared from published data for operating mills.

Many mills have installed paper machines with twin wire formers or converted older Fourdrinier formers to twin-wire designs, with the objective of improving product quality. This type of machine generally raises the consistency of the white water system which tends to increase fibre losses. However, in most cases the mill white water system has been modernised simultaneously, so that there was a reduction in suspended solids discharge due to the installation of the twin wire formers.

A few of the recently built mills have installed centrifugal blowers instead of the traditional liquid ring vacuum pumps, which reduces effluent volumes and suspended solids discharges.

RANGE OF NEWSPRINT FURNISHES ON VARIOUS PAPER MACHINES

Machine No.	Speed (m/min)	Basis Weight (g/m^2)	Efficiency (%)	Pulp Type * (% of total) SGW	RMP	TMP	SCMP	LYS	HYS	SBK	BOD (kg/t)
1	1048	48.3	82	3	-	80	-	-	-	17	24
2	936	48.7	82	52	-	41	-	-	-	7	17
3	918	48.6	80	-	-	87	-	-	-	13	24
4	913	48.7	79	-	-	100	-	-	-	-	25
5	911	45.1	86	-	-	100	-	-	-	-	25
6	858	46.9	79	-	-	92	-	-	-	8	25
7	844	48.7	81	64	-	-	31	-	-	5	32
8	841	48.6	81	-	80	-	-	20	-	-	72
9	814	48.8	78	76	-	-	-	-	24	-	39
10	742	48.4	75	50	-	26	-	-	24	-	43
11	683	46.2	89	44	-	34	-	22	-	-	79
12	653	48.7	87	68	-	-	-	-	33	-	50
13	584	48.7	81	62	-	-	35	-	-	3	35
14	583	47.1	75	21	-	51	-	-	28	-	51

* SGW = Stone Groundwood; RMP = Refiner Mechanical Pulp; TMP = Thermomechanical Pulp; SCMP = Sulphonated Chemimechanical Pulp; LYS = Low Yield Sulphite Pulp (48% nominal yield); HYS = High Yield Sulphite Pulp; SBK = Semibleached Kraft Pulp.

Steam and Power Plants

The most significant development with respect to the environment has been the installation of a number of large, **modern hog fuel boilers.** These have effective emission control devices and usually replace older, smaller boilers and "teepee" wood waste burners, resulting in a substantial reduction in particulate emissions. Many of the hog fuel boilers replace oil burning facilities, either on-site or at a remote utility power station, leading to a net reduction in sulphur dioxide emissions, since hog fuel is sulphur free.

Characteristics of Total Mill Effluent

The characteristics of the effluent from a complete mill operation depend on the processes used, the operating practices, the equipment and the production rate. The following tables summarise typical effluent data, prior to any external treatment facilities, for bleached kraft pulp mills and for newsprint mills, which are the two predominant types of mills in Canada. The data in these tables are discussed in Section 9.

KRAFT MILL EFFLUENT BREAKDOWN

	Older Mill			Maximum In-plant Control		
	Flow (m^3/t)	SS (kg/t)	BOD (kg/t)	Flow (m^3/t)	SS (kg/t)	BOD (kg/t)
Wood Preparation (wet)	15	90	16	-	-	-
Wood Preparation (dry)	-	-	-	5	2	1
Pulping (non-process)	10	3	3	5	0.2	0.1
Washing and Screening	15	5	15	3	0.3	0
Contaminated Condensates	10	0	15	-	-	-
Evaporator (non-process)	20	0	5	3	0	1
Recovery Furnace/Power Boiler	15	0	0	5	0	0
Bleaching CEDED	75	1	25	-	-	-
Bleaching OC_dEDED	-	-	-	10	0.2	10
Recausticising (process)	2	10	5	0	0.1	0
Recausticising (non-process)	5	1	0	2	-	0
Pulp Dryer	15	10	1	3	0.2	0.1
Accidental Losses	20	30	30	10	5	5
TOTALS	202	150	115	44	8	17.2

External Effluent Treatment

There have been no major developments in effluent treatment technology affecting the classic parameters of suspended solids, toxicity, and BOD, although one new

NEWSPRINT MILL EFFLUENT BREAKDOWN (All quantities expressed per tonne newsprint)

	Older Mill			Groundwood +85% Yield Sulphite			TMP with Maximum In-plant Control		
	Flow (m^3)	SS (kg)	BOD (kg)	Flow (m^3)	SS (kg)	BOD (kg)	Flow (m^3)	SS (kg)	BOD (kg)
Wood preparation									
(wet)	15	40	8	13	35	7	-	-	-
(dry)	-	-	-	-	-	-	2	1	1
Sulphite pulping	100	1	75	20	1	25	-	-	-
Mechanical pulping	70	30	8	65	27	6	5	5	19
Papermaking	25	15	1	25	15	1	5	1	1
Non-process water	50	1	0	40	1	0	10	0	0
Accidental losses	20	10	0	15	7	0	5	2	0
TOTALS	280	97	92	178	86	39	27	9	21

system for removal of effluent colour has been commissioned at a Canadian mill. The reductions in discharges to receiving waters have been achieved by a combination of the in-plant measures discussed above and much more widespread application of the same effluent treatment technology that was used in the early 1970's. A number of mills have attained compliance with effluent control regulations through in-plant measures alone, and some others are implementing programs to do so.

Kraft Mill Odour Control

Many Canadian mills now collect and incinerate the highest concentration malodorous gases, those from the digester and evaporators. Most mills use their lime kiln as an incinerator, so that some energy is recovered, rather than using a dedicated incinerator as was practiced in the early 1970's.

Some mills also collect and incinerate the high volume, low concentration malodorous gases from other sources such as the black liquor storage tanks and the brownstock washer systems. These are burned in one of the boilers, but the practice is usually a net energy consumer, since relatively large volumes of wet air have to be handled with the malodorous gases.

Computer Applications

Process simulation models are being used increasingly for mill design, and have been used in several cases to design white water systems to minimise suspended solids discharges. Their principal environmental advantage is that they allow detailed analysis of the process design and operation of a mill, leading to more effective recycle of process wastes and reducing the accidental losses which characterise so many mill start-ups.

Computer control is used extensively in paper mills, and for control of digesters. It is also used in several other departments in a few mills to various degrees of sophistication. This is generally helpful in stabilising the process, and many of the parameters that are controlled by the computers allow better control of discharges. The improved process stability and increased operational supervision attainable with well-designed computer control systems tends to reduce accidental losses to sewer. However, no computer control systems have been installed primarily for environmental reasons. Several mills have computerised the preparation of the routine environmental reports required by regulatory authorities to reduce the paperwork burden.

Energy Implications

The total purchased energy consumption for the average pulp or paper mill in Canada is about 14 GJ/t product.

Generally, the application of environmental protection measures in the industry has had little effect on energy consumption. External treatment systems consume about 0.2 GJ/t product at most mills where they are installed, but most in-plant measures consume negligible energy and some result in minor energy economies. The effect of air pollution control systems on mill energy consumption is usually a very small proportion of the mill total.

There has been a reduction of over 25% in the total amount of oil burned in the pulp and paper industry in the past ten years, which has reduced sulphur dioxide emissions proportionately. This has been partly due to replacement with hog fuel, and partly due to energy conservation measures which have reduced the requirements for steam in the manufacturing process.

1 INTRODUCTION

1.1 Background and Definitions

This review summarises recent developments and presents data on the more advanced pulp and paper technology now available in Canada. For the purposes of this report, state-of-the-art is defined as a process, system or piece of equipment already operating in at least one full-scale installation or very large (over 100 t/d equivalent pulp) pilot plant. Some current research work which appears to be approaching commercialisation is also discussed briefly, and some data from the manual, "The Basic Technology of the Pulp and Paper Industry and its Environmental Protection Practices" (Report No. EPS 6-EP-83-1), has been repeated where appropriate. It is assumed that readers are familiar with the pulp and paper industry, or have access to the manual.

In accordance with Canadian government policy, all data are reported in the International System of units (abbreviated SI). Reference 1 provides a brief summary of the the conversion factors which are in frequent use in the pulp and paper industry, and references 2 and 3 provide extensive detail. Some convenient conversion factors and abbreviations are appended. The word "toxic" is normally used in the context of the Federal toxicity standard defined in Schedule D of the Pulp and Paper Effluent Regulations (1).

1.2 The Canadian Pulp and Paper Industry in 1983

The Canadian pulp and paper industry is in the midst of its worst economic period since the 1930's. The industry has historically been cyclic, and is to some extent dependent on the general economic situation in Canada, the United States and overseas, so there is reason to hope that the economic picture will improve in the medium term. The current numbers and types of mills in Canada are summarised in Table 1.

The current and estimated future capacities for all the significant grades of pulp and paper are shown in Table 2, which is based on data published by the Canadian Pulp and Paper Association, Montreal.

1.3 Status of Compliance with Environmental Regulations

The status of mills' compliance with the Federal Pulp and Paper Effluent Regulations (4) is summarised every second year in reports by the Environmental Protection Service, Environment Canada. The most recent was published in July 1982 (5). This indicated that slightly over half the mills, representing 57% of the total production,

TABLE 1 SUMMARY OF TYPES OF CANADIAN MILLS

	Paper & Board	Pulp Mill	Sulphite	Kraft	Semi-Chem.	Stone GWD	Other Mechanical	Misc.
Alberta	3	2		2	-	-	-	-
B.C.	11	26	1	17	-	6	3	2
Manitoba	4	4	1	1	-	2	-	-
N.B.	6	10	3	4	2	4	1	-
Newfld.	3	2	2	-	-	2	1	-
N.S.	5	5	2	-	-	3	2	-
Ont.	35	26	7	9	3	11	2	5
Que.	51	44	17	12	1	22	10	6
Sask.	-	1	-	1	-	-	-	-
TOTALS	118	120	33	46	6	50	19	13

were in compliance with suspended solids regulations, and about three-quarters of them, representing 72% of total production, were in compliance with BOD regulations. It is anticipated that about 80% of the mills, representing 80% of the total production of the pulp and paper industry in Canada, will be in compliance with the current regulations by 1986 (5).

No comparable nationwide reviews of the status of compliance with atmospheric emission regulations have been done.

TABLE 2 CANADIAN PULP, PAPER AND PAPERBOARD CAPACITY (1000 metric tonnes)

Grades	1981	1982	1983	1984
Pulp				
Dissolving and special alpha	303	316	320	324
Sulphite paper grades	2580	2518	2499	2479
Bleached	(461)	(467)	(484)	(495)
Unbleached	(2119)	(2051)	(2015)	(1984)
Sulphate paper grades	10220	10381	10662	10827
Bleached softwood	(6371)	(6518)	(6807)	(6948)
Semibleached softwood	(1106)	(1138)	(1122)	(1128)
Bleached hardwood	(955)	(953)	(952)	(986)
Unbleached	(1788)	(1772)	(1781)	(1765)
Semichemical	445	449	462	485
Mechanical for paper/board	8876	9600	10140	10395
Stone groundwood	(6413)	(6190)	(6333)	(6257)
Atmospheric refiner	(725)	(664)	(597)	(503)
Thermomechanical (TMP)	(1738)	(2746)	(3210)	(3634)
Mechanical for building paper/board	537	537	537	537
Groundwood and atmos. refiner	(231)	(231)	(231)	(231)
Defibrated and exploded	(306)	(306)	(306)	(306)
Total pulp capacity	**22961**	**23801**	**24620**	**25046**
Paper and Board				
Newsprint	9499	10020	10475	10500
Printing and writing	1679	1790	1952	2175
Kraft papers	566	553	558	558
Sanitary tissues and specialities	467	496	509	527
Containerboard	1884	1918	1988	2041
Boxboard	792	796	813	821
Total excluding building papers	**14878**	**15573**	**16295**	**16622**
Building and other grades	711	715	720	720
Total paper and board capacity	**15589**	**16288**	**17015**	**17344**

2 FORESTRY AND WOOD PREPARATION

2.1 General

Forestry operations cover extensive areas of Canada, and their environmental impact is quite different from that of pulp and paper mills. Whereas the environmental impact of a pulp or paper mill depends primarily on the effluents, gaseous and solid wastes discharged, forestry operations themselves have a significant environmental impact. Mill discharges can be defined and regulated by relatively precise scientific standards, leaving the mill designers and operators free to use any technology and equipment they prefer to comply with these standards. Characterisation of the environmental protection aspects of forestry operations is more complex, since it inevitably involves definition of regeneration, planting, cultivation and harvesting techniques and practices. The effects of changes in forest management practices are not usually evident for many years and the full impact may not become apparent for up to 100 years.

Wood preparation at the mill site is described in Reference 6, and a discussion of the current state-of-the-art is included at the end of this section.

2.2 Forest Resources

Canada has the second largest softwood forests in the world, of which about two million acres are harvested annually. Most of this forest is owned by provincial governments, and the timber is harvested by the pulp and paper companies, as well as other users, under various licensing arrangements.

It is anticipated that the world demand for wood will increase by 50 - 100% by the year 2000 but Canada may not be in a very good position to meet this increased demand for forest products. Emerging timber deficits have been identified in eleven areas in Canada by the Canadian Forestry Service (7).

The current status of softwood utilisation is summarised in Table 3. This is generally accepted by foresters as a reasonable estimate of the production of unmanaged natural forests in Canada. At present, much of the forest in Canada is left to regenerate naturally after harvesting, and a small proportion is cleared and scarified to promote natural regeneration. Table 3 demonstrates that the current rate of harvesting softwoods in the Maritimes far exceeds the rate of production of timber, and similar data apply to many of the more intensively developed forest areas in the rest of Canada. If the demand for wood grows as predicted, it is clear that the Canadian forests will be unable to expand production to supply the market, unless the forest yields are improved substantially.

TABLE 3 PRELIMINARY ESTIMATES OF SOFTWOOD TIMBER AVAILABILITY (7)

	Availability (million m^3)*					
	Annual Allowable Cut	Harvest 1979	Theor. Reserve	Econ. Inaccess.	Other Offsets	Adjusted Reserve
Newfoundland	3.7	2.3	1.4	2.1	-	(0.7)
Nova Scotia	2.8	4.1	(1.3)	-	-	(1.3)
New Brunswick	7.1	7.4	(0.3)	-	-	(0.3)
P.E.I.	0.2	0.2	-	-	-	-
Quebec	37.9	29.7	8.2	7.0	-	1.2
Ontario	27.1	19.3	7.8	6.4	1.4	-
Manitoba	5.4	1.6	3.8	2.9	-	0.9
Saskatchewan	3.9	2.4	1.5	0.9	0.6	-
Alberta	14.6	6.7	7.9	1.8	-	6.1
B.C.	99.4	76.0	23.9	15.9	7.5	-
Territories	3.1	0.2	2.9	2.4	-	0.5
Total	205.2	149.9	55.3	39.4	9.5	6.4

*Bracketed values are deficits

The developing wood shortages make it necessary for mills to use greater quantities of partially rotten wood and small wood, which increases the BOD and suspended solids of woodroom effluents and hinders the application of dry barking.

Some of the forest land in Canada and the Northern U.S. are intensively managed to increase wood productivity. The data in Table 4 indicate the increases attained to date in a typical case. The existing Canadian plantations demonstrate the potential for forest management, but they are too small to contribute significantly to the wood production. There are a few large plantations in New Brunswick, Ontario and British Columbia. Plantation-grown trees are relatively free of rot and are more readily debarked at the mill by dry barking processes than naturally grown wood, leading to improved effluent quality.

A small but increasing proportion of Canadian forests are now being efficiently managed. For example, Ontario is in the process of negotiating forest management agreements with the major users (8).

TABLE 4 TYPICAL FOREST PRODUCTIVITY

	Cubic metres per hectare	Age	Mean Annual Increment (m^3/ha)
Natural stands	179.12	70	2.597
Natural stands + cleaning	223.90	40	5.553
Plantations	313.46	40	7.792

Many of the aspects of forest management have little direct impact on the environment but management practices such as logging and the use of herbicides can affect watercourses and human health. These topics are discussed separately in the following sections.

2.3 Herbicides

There is currently very little use of herbicides in Canadian forests, but developments in forest management indicate that their use is likely to increase. Herbicides are important tools required by forest managers to effectively implement the intensive forest management practices necessary for the achievement of the harvest level targets endorsed by the Canadian Council of Resource and Environment Ministers in 1979. However, they are chemicals similar to pesticides, with the potential for adversely affecting other components of the forest ecosystem than the intended targets. Their availability and use is regulated to ensure that they do not have an adverse impact on environmental quality or on human health.

The regulatory aspects of herbicide and pesticide registration, use, and control in Canada are complex. Over 100 federal, provincial and municipal laws have varying degrees of authority over the safe use or consequences of use of pesticides and herbicides. The following are of major concern to forestry:

The Pest Control Products Act

The principal federal law concerned is the Pest Control Products Act, which is administered by Agriculture Canada. All herbicides used in Canada, whether for agricultural, forestry, commercial or domestic use must be registered under this act. The Act was brought into force in 1939, and revised in 1972. The revised regulations gave much more emphasis to environmental concerns than did the earlier version, and forced a much closer look at the toxicology of pesticides and their potential impact on non-target species, including humans, than had been the case in the past.

A number of other federal acts further regulate the use of pesticides in specific situations in Canada. Three of these are of primary concern to forestry:

The Environmental Contaminants Act

This act is administered jointly by Environment Canada and Health and Welfare Canada. It is concerned with environmental and human health hazards associated with pesticide use not covered by other existing legislation. This act could be used, for example, where the Pest Control Products Act did not have adequate powers to deal with a significant source of environmental pollution.

The Fisheries Act

The legal responsibility for administering this act lies with Fisheries and Oceans Canada. However, Environment Canada and some provincial agencies are involved in its administration. Section 33 prohibits the deposit of deleterious substances of any type into water frequented by fish and can be used to control or limit the use of pesticides.

The Migratory Birds Convention Act

This act, which is administered by Environment Canada, is similar to the Fisheries Act in that it regulates the use of materials, including pesticides, in areas frequented by birds.

In addition to these and other federal laws, most provinces now have complementary provincial laws which satisfy their particular requirement with respect to pesticide use.

Recent data (9) report that 16 520 t of herbicides were used in Canada in 1980. Of this, about 79 t or 0.48% were used in forestry with the remainder used in agriculture. With insecticides, the picture is similar; forestry used only about 4% of the amount of chemical insecticides used in agriculture. Due to the relative sizes of the agricultural and forestry markets for pesticides, and the greater stability of the agricultural market, the pesticide industry concentrates its development on materials that show good promise for agricultural use.

Herbicides are developed by the manufacturers who are also responsible for generating the data necessary for registration of the chemical before it can be marketed.

Prior to registration of a herbicide the formulation of the active ingredient and the physical and chemical properties must be defined. Extensive studies are performed to determine acute and chronic toxicities to a range of standard laboratory species (rats, mice, ducks, quail, fish, etc.) via a variety of exposure routes which are used to assess the herbicide's potential toxicity to humans and other non-target species.

These studies usually take about three to four years to complete and cost several millions of dollars. If the resulting data continue to indicate that the material is not likely to cause significant human health or environmental problems, and is likely to be cost-effective in comparison to other products on the market, the material is then subjected to field tests to:

a) investigate its impact on non-target, naturally occurring species in the environment in which it will be used;
b) determine its persistence and fate in various components of the agricultural environment; and
c) determine risks for occupational and bystander exposure.

This level of testing requires from three to five years to generate the additional technical data required for registration with the Pesticides Division of Agriculture Canada. Other branches within Agriculture Canada, Health and Welfare Canada, Environment Canada, and Fisheries and Oceans Canada co-operate in reaching a final decision of acceptance or rejection of registration.

2.4 Logging Practices

Most of the provincial authorities restrict or prohibit logging close to watercourses, control road building practices, and define procedures to be followed to minimise soil erosion and damage to fishing and spawning grounds. These vary widely from province to province, and in some cases are site-specific.

2.4.1 Full Tree Logging. Full-tree logging is becoming more common because it is compatible with increased mechanisation. Using conventional logging methods, trees are felled and then de-limbed on the spot, leaving the needles on the site. With full-tree logging, the tree is felled and then hauled away in its entirety, to be de-limbed by a central machine. The branches and needles accumulate around the de-limbing machine in relatively small concentrated areas. Since most of the essential nutrients taken up by the tree from the soil accumulate up in the needles, the consequences of full tree logging could be environmentally significant. If the needles are not left to decompose around the tree stumps, so that they are widely dispersed over the logged area, the drain of nutrients from the site is substantially increased. On a rich site, this may be of very little consequence, but in Canada many boreal forest sites are very low in the most essential tree nutrients (nitrogen, phosphorus, potassium, magnesium, calcium, and sulphur) and they can ill afford the increased depletion caused by full tree logging. These nutrient-deficient sites could, of course, be fertilized after logging, but this would involve additional expenditure.

2.4.2 High Flotation Tires for Logging Machines. Logging machines can incorporate features intended to reduce environmental damage due to logging. For example, recently developed skidders using 1.5 m wide, low-pressure flotation tires travel over the root mat on soft ground, reducing fuel consumption and the tendency to become bogged down. Besides productivity and cost advantages, the flotation tires also reduce:

- wood breakage,
- soil compaction (improving regeneration and future growth rates), and
- soil erosion.

Ongoing tests are aimed at determining life, economy and areas of application for different types of tires.

2.5 Wood Preparation

2.5.1 General. After delivery to the mill, the wood is stored prior to use. For virtually all production processes, it is essential to remove the bark, and for all processes, except stone groundwood, the wood must be chipped prior to pulping.

The debarking and chipping processes are described in reference 10. The remainder of this section discusses the environmental and energy conservation aspects of the alternative processes and the current trend towards the use of dry debarking techniques.

The cost of treating the effluents from traditional wet debarking systems to comply with environmental regulations has led many mills to convert to dry debarking. While dry debarking does not completely eliminate the woodroom effluent, it reduces the suspended solids, toxicity and BOD in effluents by about 80% to 98%. Most of the new mills constructed since 1975 in North America have selected the dry process.

Wet debarking systems generally produce cleaner wood than the dry systems, particularly in Canadian winter conditions, and this is the principal advantage of the wet process. All mills prefer to minimise the bark content of wood supplied to the pulp mill, but there is no absolute standard, since the amount of bark that can be tolerated varies with the pulping process at the mill, the facilities for cleaning pulp and the quality requirements of the product. The performance of debarking machinery is not easily regulated, but to the extent that it can be adjusted, higher standards of bark removal can be achieved at the expense of increased wood loss and lower production rates.

2.5.2 Debarking Quality. The effectiveness of debarking is normally expressed as the percentage weight of bark remaining on the wood. The determination of residual bark involves manually separating visible bark from samples of chips and weighing each fraction. The procedure is rather tedious and subject to sampling error, since wood fed to a pulp mill is rarely homogeneous, and the practical size of sample is extremely small.

Sulphite pulping has little effect on bark and, therefore, allows much of it to pass on to the papermaking area, where it is expensive and difficult to remove effectively with conventional centrifugal cleaners and screens. In the case of dissolving sulphite grades, the bark content of the wood must be very low, about 0.2%, since some of the components can seriously affect the pulp quality. Newsprint grade sulphite pulp is rather more tolerant, and objectives for bark content are typically in the 0.3% to 0.5% range.

In the case of mechanical pulping, a bark content of up to 0.5% is often considered acceptable. Where the mill bleaches the mechanical pulp, somewhat more bark can be tolerated, but the additional bleaching cost can be significant. Refer also to Section 6.

In groundwood pulping, bark that remains on the wood appears as specks of dirt in the final product, and can, to a large extent, be removed by the more efficient centrifugal cleaners being installed in modern mills. An existing mill which converts a wet debarking operation to dry would often have to simultaneously upgrade its cleaning system.

The presence of bark in chips used in a thermomechanical pulp (TMP) process does not show up as dirt specks like those that appear in the product from sulphite pulp, stone groundwood or refiner mechanical pulp, but rather as a reduction in pulp brightness. The extent of the brightness loss depends upon whether the bark is green or seasoned and on the presteaming temperature used in the TMP process (see Figure 1). A bark content of 1% can result in a brightness loss of up to 4 points.

The loss in brightness of TMP due to the bark content cannot be overcome by hydrosulphite treatment, but peroxide bleaching appears to have a brightening effect on the residual bark.

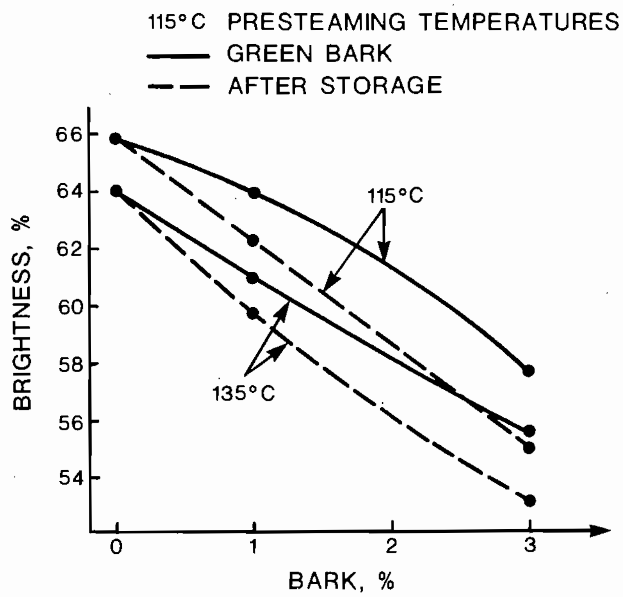
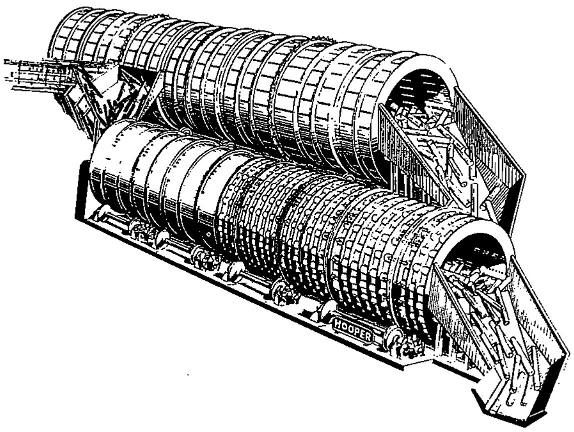


FIGURE 1 EFFECT OF BARK CONTENT ON BRIGHTNESS OF UNBLEACHED THERMOMECHANICAL PULP (11)

Most bleached kraft mills specify that the bark content of their furnish should not exceed 1%. Some operate successfully with several percent bark in the wood feed, but this leads to higher consumption of cooking chemicals. Where the mill production is not limited by the capacity of the chemical recovery system, this may be acceptable. However, in limited recovery mills, the additional load on the recovery system can lead to production losses or increased BOD discharges, thus destroying the environmental advantages of dry barking.

Unbleached kraft mills and neutral sulphite semichemical (NSSC) mills can tolerate relatively large amounts of bark in the wood from the point of view of product quality, although the above comments on the effect on the recovery system load are applicable.

2.5.3 Debarking Techniques. On the British Columbia coast, dry debarking of larger logs is normally accomplished by mechanical ring debarkers and wet barking by high pressure hydraulic jets. In the rest of Canada, and on the west coast for small logs, drum debarkers as shown in Figure 2 are generally used. There is little difference between the drum used for wet or dry debarking, but the capacity of any given drum is generally reduced by up to 50% if it is converted from wet to dry debarking. In some cases, this



The drum in the foreround is suitable for wet or dry debarking, and the background one for dry debarking only.

FIGURE 2 DRUM BARKERS (Hooper)

would require a mill converting to dry barking to install additional drums at a capital cost in the order of $1 million each, including auxiliaries. However, largely due to the trend for mills to purchase increasing quantities of sawmill chips, many mills already have spare barking capacity, and can therefore overcome the capacity limitation relatively easily. Debarking techniques and their environmental significance are discussed at length in reference 10.

Most of the bark removed from logs in pulp and paper mills is used as hog fuel, and it is therefore desirable that it be as dry as possible. Surprisingly, the moisture content of hog fuel from dry woodrooms is only a few percent lower than that from wet debarking operations which have efficient bark presses. However, due to the cost and difficulty of maintaining them, many bark presses are inefficient for much of their operating lives so that the annual average solids content of hog fuel produced from dry woodrooms is probably only about 10% higher than that from wet systems.

The final moisture content of the recovered bark is affected by the method of transport and storage of the logs, since bark that is thoroughly soaked by lengthy water transport and storage tends to retain some of the water, even after bark pressing and dry barking operations.

There is no absolute limit on the moisture content for bark which is to be burned, but the net heat produced is reduced as the moisture content increases. Auxiliary fossil fuel must be burned with the bark to maintain combustion when the bark is very wet. The limiting dryness at which this occurs depends on furnace design, but is typically about 40% OD (oven dry). Although some furnace designs can burn wet bark successfully, fluidized bed systems being very effective in this respect, it is always thermally inefficient to burn very wet material, due to the energy loss to the atmosphere with the evaporated water.

In addition to the obvious energy economy achieved by burning dry hog fuel, there are some environmental advantages, such as more complete combustion in the furnace, less fly ash, and correspondingly lower particulate emissions. In addition, reducing the water content of the fuel reduces the boiler stack gas flow, which usually improves the efficiency of the particulate emission control device.

2.5.4 Debarking Effluents. Traditionally, many mills debarked most of the wood in summer to minimise the difficulty of handling frozen wood and to co-ordinate with river-driven supplies. Increasing numbers of mills now have wood delivered by truck and debark it all year round. Some mills operate in an intermediate mode with lower debarking rates in winter. The main reasons for the move away from seasonal debarking have been to reduce inventory costs and to stabilise employment.

In most cases, it is necessary to wash the logs after dry debarking, but the effluent generated by this operation has much lower BOD and suspended solids content than that from a wet barking operation. In many Canadian mills heat must be used in the winter to thaw frozen bark, and the most practical method of doing this is to use a warm effluent such as bleach plant caustic extract, newsprint machine white water or equipment cooling water. The effluent from thawing contains suspended solids, has some BOD, and is slightly toxic.

Table 5 provides typical comparative values for the different debarking processes and Table 6 for the improvement in effluent quality achieved by a conversion from wet to dry debarking. More extensive data is included in reference 10.

In many cases the effluent flow from dry debarking installations is as high as that from a wet system of the same capacity, but is much less contaminated. The flow from both systems depends more on the degree of recycle practised in the woodroom than on any other factor.

TABLE 5 COMPARISON OF BARKING PROCESSES

Parameter		Units	Wet Drum	Dry Drum	Hydraulic Jet	Mech. Ring	PAPRIFER Chip Debarking
Effluent Flow		m^3/t	3-20	0-5	5-15	0-2	0
Suspended Solids		kg/t	15-50	0-10(6)	10-30	0-3	0
BOD		kg/t	5-10	0-3 (6)	1-4	0-1	0
Toxicity		LC_{50}	< 10%	(8)	< 10%	(8)	0
Energy Consumption (3)		kWh/t	20	21	21	3	60
Dryness of Bark (7)		%OD	40-55	50-55	40-55	50-55	40-55
Reported Operating Cost (3)		$/t	2.15	2.15	1.15	0.60	-
Residual	-Softwood summer	%wt	0.5-1	0.5-1	0.1-0.4	0.2-0.5	2
Bark	-Hardwood summer	%wt	0.5-1	1-2	N/A	-	5
	-Softwood winter	%wt	0.5-1	1-2	N/A	0.5	2
	-Hardwood winter	%wt	0.5-1	1-4	N/A	-	5

Notes:
1) These data are typical for full scale installations, assuming that barker is suitable for the local wood supply.
2) Effluent data excludes BOD and suspended solids from other sources (e.g., organics introduced by use of bleach plant filtrate in woodroom).
3) 1977 costs from reference 10.
4) "t" refers to oven dry tonnes of wood.
5) N/A = Not generally used in these conditions.
6) Upper limits are due to use of flume to handle logs.
7) Lower limit reflects difficulty of maintaining high efficiency in bark presses.
8) No data available; toxicity is probably low.

TABLE 6 TYPICAL NEWSPRINT MILL WOODROOM EFFLUENT DATA FOR WET AND DRY DEBARKING

Effluent Parameter	Units	Wet	Dry	Reduction
Flow	m^3/d	7 800	3 700	50%
Suspended Solids	kg/d	12 700	3 200	75%
BOD	kg/d	2 100	310	87%
pH		5.8	5.3	-
Toxicity		toxic	toxic	-

Note: Data based on 500 t/d newsprint production

The quantity of heat that has to be introduced into the system to thaw the logs sufficiently is an important constraint on recycling log wash water in Canadian winter conditions. It is necessary to prevent the formation of ice within the woodroom, so sufficient heat must be input in the water to compensate for the fact that the logs enter at temperatures well below freezing, perhaps encrusted with snow and ice. In addition, if the debarking capacity is limited, the water system temperature must be maintained well above 0°C to thaw the outer layers of the log quickly enough to soften the bark while in the barking drum. A simple heat balance demonstrates that a flow of at least 1 m^3/t wood is required to maintain a reasonable temperature in the water system if 40°C effluent from another department is to be used to thaw the logs. In practice several m^3/t may be required. It is possible to heat the water in the woodroom system by direct steam addition, which was formerly common practice, but the energy cost can be high. A steam requirement of 10 t/h in a 500 t/d pulp mill would not be unusual, costing about half of a million dollars per year, if waste heat were not used to supply de-icing heat to the woodroom. To some extent, a trade-off occurs between debarking capacity and amount of heat supplied for de-icing since incomplete removal of ice reduces debarking equipment efficiency.

The quantity of suspended solids contained in the untreated woodroom effluent depends on the wood species, the extent of internal recycle and whether the wood has been land driven or water driven, since the latter can remove up to 50% of the bark.

The BOD and toxicity of debarking effluents varies widely, and there is little correlation between these effluent parameters and species or operating conditions, except that the less time the bark spends in contact with the water in the system, the less contaminated the effluents are. The difference between the dry and wet operations in this respect is apparent in the data in Tables 5 and 6, where the "dry" processes would use the water primarily for washing showers.

Typically, converting a wet process woodroom to dry barking reduces the suspended solids content of the untreated effluent from 10-50 kg/t wood to a few kg/t, and reduces the BOD by about 8 kg/t. The toxicity of the effluent from a woodroom using the dry process is typically less than 20% of that from a wet woodroom.

In those cases where the logs are neither thawed nor washed, the effluent from a dry barking system can be zero, but this implies a summer only operation and/or a relatively high bark tolerance level, such as in a linerboard or NSSC mill.

The relative impact of the barking process on total mill effluent depends to some extent on the type of mill as well as on the effluent treatment system. The effluent from wet debarking systems can be improved to comply with typical current regulations by conventional effluent treatment techniques as discussed in Section 9.

2.6 Debarking of Whole-Tree Chips

To date, whole-tree chips have been fed to the digesters along with all the associated bark, foliage, and grit. However, the Pulp and Paper and the Forest Engineering Research Institutes of Canada have jointly developed the Paprifer process for the removal of bark from chips (12). The process consists of separating the bark from the chips in a highly agitated vessel filled with water, similar to a waste paper pulper. The debarked chips are separated from the water/bark mixture and sent to the pulp mill.

The bark removed is dewatered to about 50% moisture and used as hog fuel. Although the process is water based, and therefore would technically be classified as wet barking, there is no discharge to sewer. The only discharges are the pressed hog fuel and about 0.8 m^3 water per tonne wood which is absorbed by the chips and enters the digester. The organic material which is extracted from the bark in traditional wet processes, and causes the BOD of the effluent, will be contained in this water, and therefore will ultimately be incinerated in the recovery boiler. The pressate from the bark dewatering equipment is returned to the debarking system. Comparative data is presented in Table 5.

The use of chips from the Paprifer process in kraft mills suffers the same disadvantages as the direct use of whole-tree chips, but to a much lesser extent. The advantages of whole-tree chip use are also applicable, and the Paprifer process offers the possibility of increasing whole-tree chip use substantially, where the latter is limited by the total quantity of bark, foliage and grit that the mill process can accept due to recovery or product quality constraints. As well as removing bark, the process removes rotten wood from the chips, which will improve pulp quality in some cases.

The Paprifer process has not yet been applied commercially, but it has been operated extensively on pilot scale. The practical limit of the process is about 2% residual bark, so it is applicable primarily for kraft mills.

3 PULPING SYSTEMS

The principal pulp types are discussed separately. From the environmental viewpoint, the most significant change in the last decade has been the trend towards higher yields in newsprint manufacture, with corresponding reductions in discharges of BOD, suspended solids and toxic materials. There has been a major shift from stone groundwood pulping towards refiner and thermomechanical pulping (TMP) processes in the mechanical sector. Changes in kraft pulping have consisted of evolutionary development; no new processes have been introduced on a commercial scale.

3.1 Mechanical Pulping

3.1.1 Stone Groundwood Pulping. The first commercial grinders were built by Voith in 1852, and were capable of being loaded up to 30 kW. Today there are grinders which use artificial pulpstones 1.8 m in diameter and 1.8 m wide driven by 7500 kW motors.

During the 1970's with the development of TMP, there was a feeling that stone groundwood was dead. This, however, has changed and there is some renewed interest in stone groundwood. It is believed that this interest is the result of the development of the ultra-high-yield pulps, which are making it possible to reduce or eliminate the use of chemical pulp in newsprint furnish. This has a positive effect on the pollution load and enables the use of stone groundwood to produce an acceptable grade of newsprint.

Stone groundwood does have some favourable characteristics, i.e., low energy costs and the high fines content which is desirable for printing characteristics. However, in new installations the trend is very definitely away from grinders and towards refiners.

3.1.2 Refiner Pulping. The first attempt to use disc refiners for the production of mechanical pulps suitable for paper production was made in the 1950's. This demonstrated that it was possible to produce a pulp which was stronger than stone groundwood. The process became known as RMP or refiner mechanical pulping. The best results were obtained using two stages of refining. The first stage reduced the chips to a coarse fibre and the second stage reduced the coarse fibre to individual fibres. It was necessary in the beginning to limit the pulp consistency in the refiner to about 6% so that there would be sufficient water present to cool the refiner. The flashing of steam at any higher consistencies inhibited operation since it was not possible to feed chips against the steam pressure with the design of the refiners then in use.

By 1969, there were 44 RMP plants around the world with a design capacity of 4300 tonnes per day and larger refiners were available, e.g., 120-cm diameter discs with installed power capacity of 3700 kW. The plants had one, two or three stages of refining.

Acceptance of RMP was relatively slow and there appeared to be two main reasons for this:

a) The pulp was less dense than stone groundwood and this resulted in a bulkier sheet of paper which created problems in the pressrooms.

b) The pulp contained more shives, or fibre bundles, than stone groundwood. These shives can produce a flaw in a sheet of paper which results in the sheet of paper breaking either on the paper machine or in the printing press.

Work on these problems resulted in the development of the TMP or thermo-mechanical pulping process. It involves the presteaming of chips for a short period, typically about three minutes, at 110-130°C and 150-210 kPa and then performing the first stage of refining under pressure, as described in more detail in reference 13.

This was not a new process. It was first developed by Defibrator in 1932 for the production of hardboard and roofing felts (14). It involved the refining of wood chips at approximately 700 kPa and 170°C using a very low power input of less than 1 MJ/kg. At that time, there was no thought of using it for paper grades because of its low brightness.

The use of the lower refining temperature and pressure resulted in the production of long thin fibres. The resultant pulp was substantially stronger than either stone groundwood or RMP and it had a lower bulk and a lower shive content than RMP. Table 7 compares these three pulps made from black spruce and Table 8 compares stone groundwood and TMP made from jack pine.

The data in both tables show the superior characteristics of TMP. The strength properties obtained have two main beneficial effects, i.e.,

a) With spruce chips, the possibility is provided for either reducing or completely eliminating the chemical fibre component in a newsprint furnish, thereby reducing the BOD and the suspended solids in the mill effluent as discussed in Section 7.

b) With jack pine chips, it upgrades the pulp quality obtained from an inferior wood species to a level where it is superior to spruce stone groundwood and it also has the potential for reducing, to a lesser degree, the amount of chemical fibre used in a newsprint furnish.

Figure 3 shows a typical TMP flowsheet with two stages of refining, the first pressurized and the second at atmospheric pressure. A TMP system can have either one first-stage refiner feeding one second-stage refiner or two first-stage refiners feeding one

TABLE 7 COMPARISON OF STONE GROUNDWOOD, REFINER MECHANICAL, AND THERMOMECHANICAL PULPS (Black Spruce)

	Stone Groundwood	RMP	TMP
Freeness (Canadian Standard Freeness)	99	98	99
Bulk (cm^3/g)	2.24	2.58	2.19
Burst index ($kPa{\cdot}m^2/g$)	1.4	1.6	3.0
Tear index ($mN{\cdot}m^2/g$)	4.4	9.4	9.0
Breaking length (meters)	3 000	3 500	5 400
Stretch (%)	1.6	2.0	2.6
Fibre Classification (Bauer McNett)*			
% Retained on 28 mesh	3.6	5.2	16.4
% Retained on 48 mesh	15.6	20.2	19.0
% Retained on 100 mesh	13.8	13.0	8.8
% Retained on 200 mesh	13.6	8.0	6.8
% Passing 200 mesh	31.2	28.1	30.3
Somerville Shives (%)	-	0.65	0.09

*Bauer McNett method of fibre classification segregates the pulp sample by a series of standard screens, thus providing a convenient, but arbitrary, means of describing the size of fibres and the size distribution in the sample.

second-stage refiner. There are also systems operating with just a single stage of pressurized refining.

The size of the refiners and the installed power have been increasing steadily. The diameter of the flat disc machines is in the range of 137-152 cm with an installed power of 7-10 MW. There is also a conical disc version which permits an increase in motor size up to 75 MW.

At the end of December 1982, 17 TMP systems were operating in Canada with a total design capacity of 7430 admt/d and three additional systems with a capacity of 1520 admt/d were being built. The total number of TMP systems in the world was 164 with a design capacity of 43 433 admt/d (15).

Generally speaking, the production of mechanical pulps has been limited to the use of softwoods preferably spruce, balsam and hemlock and, to a lesser extent, jack pine (due to a lower pulp quality). Hardwoods have not been used because their short fibre

TABLE 8 COMPARISON OF STONE GROUNDWOOD AND THERMOMECHANICAL PULPS (Jack Pine)

	Stone Groundwood	TMP
Freeness (Canadian Standard Freeness)	122	144
Bulk (cm^3/g)	2.70	2.57
Burst index ($kPa\cdot m^2/g$)	0.5	1.7
Tear index ($mN\cdot m^2/g$)	3.7	11.3
Breaking length (metres)	1 700	3 940
Stretch (%)	0.9	2.1
Fibre Classification (Bauer McNett)		
% Retained by 14 mesh	0.6	9.4
% Retained by 28 mesh	6.4	19.8
% Retained by 48 mesh	20.2	21.2
% Retained by 100 mesh	20.4	10.1
% Retained by 200 mesh	18.8	6.6
% Passing 200 mesh	33.6	32.9
Somerville Shives (%)	0.12*	0.04**

* screened pulp
** unscreened pulp

length results in very low strength pulps which are not satisfactory for newsprint production. However, data are available which show that small percentages of hardwood chips, i.e., up to approximately 20%, can be added to spruce chips as a raw material supply for a TMP system with no serious adverse effect on the pulp characteristics, paper machine operation or paper quality. Table 9 shows the effects of adding poplar, birch and maple chips to a blend of spruce and balsam for chips. This is another way to utilize inferior raw material for the production of an acceptable mechanical pulp.

If a mill is faced with the utilization of a higher percentage of aspen or white birch chips, then serious consideration should be given to the use of the chemical mechanical pulping (CMP) described in Section 3.2.2.

TMP has a pulp yield of approximately 94% and the published data on BOD discharge varies from about 15 kg/t to 35 kg/t. The wide range is at least partially due to variations in process conditions but also due to differing ways of assigning BOD loads to

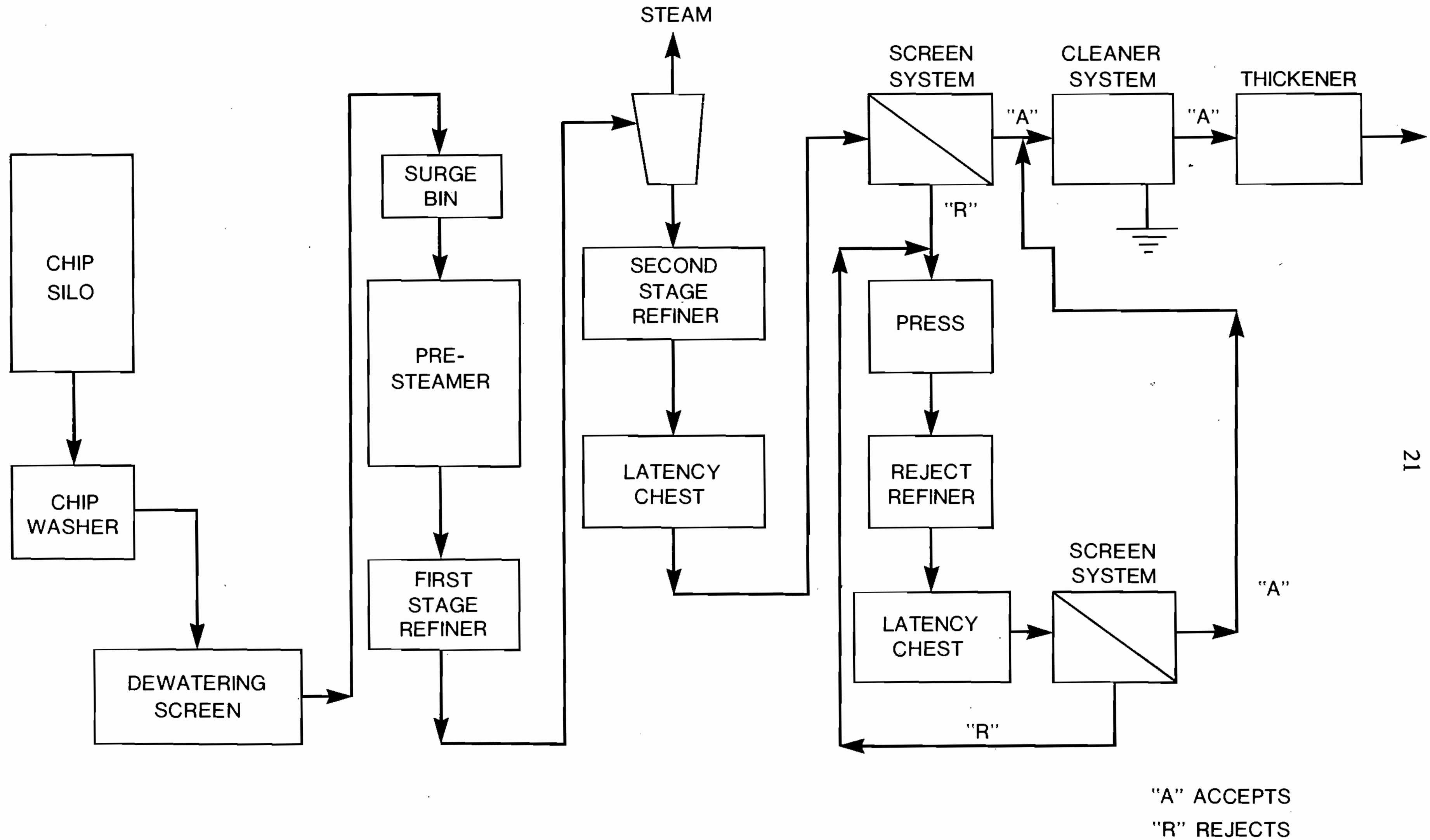


FIGURE 3 TYPICAL THERMOMECHANICAL PULPING FLOWSHEET

TABLE 9 HARDWOOD UTILIZATION IN THERMOMECHANICAL PULPING (Poplar, Birch, Maple)

Wood Species	Trial 1		2		3	
Spruce/Balsam Fir	100	84	100	79	100	83
Poplar	-	16	-	-	-	-
Birch	-	-	-	21	-	-
Maple	-	-	-	-	-	17
Freeness, CSF	162	128	127	123	146	125
Burst Index	2.4	2.5	2.6	2.3	2.5	2.2
Tear Index	10.6	10.2	9.9	9.4	8.3	8.7
Breaking Length (m)	4640	4520	4530	4040	4360	4210
Bulk (cm^3/g)	2.50	2.63	2.57	2.76	2.69	2.63
Brightness G.E.	53	55	51.6	52.7	51.9	52.4
Somerville shives (%)	0.56	0.41	0.32	0.33	0.59	0.29
Fibre Classification (Bauer McNett)						
% Retained on 14 mesh	10.0	4.8	7.0	5.3	6.4	4.1
% Retained on 28 mesh	21.4	21.1	24.5	21.1	23.9	19.7
% Retained on 48 mesh	22.8	22.8	23.4	21.4	21.8	21.1
% Retained on 100 mesh	12.1	15.7	15.3	13.2	13.0	16.8
% Passing 100 mesh	33.7	35.6	23.8	39.0	34.9	38.3

pulping and paper machine operations in any one mill. This has caused some confusion in the literature.

TMP requires 30-50% more energy than stone groundwood to reach a given freeness. However, approximately 2.3 tonnes of steam are generated for every tonne of fibre produced. If this steam is recovered, a significant credit against the high energy consumption can be realized. There are two main types of systems.

In the first, the recovered steam is used to heat a water-glycol solution and then this recovered heat is used to heat incoming fresh air, fresh water and whitewater. The main objection is that this system is only utilized to its fullest extent during the cold winter months.

The other system uses a heat exchanger to produce clean steam from the dirty, contaminated steam and it is used in the paper machine driers. This is the more efficient system and, in order to obtain the maximum benefit, the following points must be considered:

i) Since the heat transfer coefficient of steam is very dependent upon the air content in the steam, it is essential that the air contamination be kept to an absolute minimum.

ii) For maximum heat recovery, both refining stages should be pressurized. This is referred to as a tandem system and the pulp quality is not adversely affected.

iii) It has been shown that it is possible to increase the pressure in the refiner casing from the normal 100-150 kPa to 250-300 kPa for more efficient heat recovery without significant adverse effect on the pulp characteristics, providing that the presteaming time and pressure are reduced to 2 minutes and 60-100 kPa.

This recovered steam is passed through a simple heat exchanger and, in some cases, the clean steam produced is used directly in the paper machine driers at 220-230 kPa. In other cases the clean steam is passed through a compressor to increase the pressure to the desired level.

The energy recovered can be sufficient to reduce the net energy costs of TMP to at least equivalent to those for stone groundwood. The heat recovery systems will increase the BOD of the mill effluent by a small amount, probably under 2 kg/t.

A new development, which has not yet been installed in Canada, is referred to as PRMP. This process differs from TMP in that the presteaming is done at atmospheric pressure and only the refining is done under pressure. Early data have indicated a savings in refining energy compared to TMP and suggest that PRMP is a viable alternative as a refining system.

The BOD and toxicity of thermomechanical pulping effluents is 50-100% greater than that of stone groundwood effluents. However, since the use of TMP to replace stone groundwood in newsprint furnish allows the elimination of some or all of the sulphite pulp furnish, the trend towards increased TMP production has led to substantial improvements in newsprint mill effluent quality, as discussed in Section 7. The current trend towards the replacement of stone groundwood and sulphite pulp with TMP also tends to reduce suspended solids discharges, partly because the retention of TMP fibre on savealls and pulp thickeners is better than with stone groundwood, and partly because

TMP mills generally incorporate modern equipment such as pressure screens, disc thickeners and effective instrumentation.

3.1.3 Pressurized Groundwood. Pressurized groundwood (PGW) is a relatively new development. It is similar to the stone groundwood process but it involves grinding the logs under pressure. The power requirements and BOD discharges are lower than those for TMP and are comparable to the levels for stone groundwood.

The pulp quality is superior to stone groundwood but inferior to TMP. Table 10 compares regular stone groundwood and pressurized groundwood produced from a 50/50 blend of balsam fir and spruce at a mill in the United States. One system is operating in the United States and five are operating in Europe.

TABLE 10 COMPARISON OF STONE GROUNDWOOD AND PRESSURIZED GROUNDWOOD PULPS (spruce/balsam)

	SGW	PGW
Freeness, CSF	55	59
Breaking Length (m)	3 110	3 560
Tear Index	3.5	5.4
Burst Index	1.4	1.7
Brightness (°ISO)	61.3	60.7
Energy (GJ/kg)	6.19	6.15

3.2 Sulphite Pulp

3.2.1 Pulping Developments. There has been a slight but steady decline in production of sulphite pulp since the mid 1970's. Most of the low yield sulphite mills that are integrated with newsprint mills have been converted to higher yields (from 60% to 85%), some using the newly developed processing mentioned in Section 3.2.2 below. The traditional low yield operations, typically about 50%, changed little but the remaining mills installed better process control systems and most installed chemical recovery systems, primarily in response to environmental pressures.

The use of alkaline sulphite pulping with an anthraquinone catalyst has been proposed, but no commercial installations were planned at the time of writing (16,17,18,19,20).

3.2.2 Ultra High Yield Sulphite Pulp. The demand for higher strength newsprint and increased concern about stream pollution led to the development by several Canadian companies of a variety of ultra high yield pulping processes that involve a chemical treatment before, during or after refining. The objective of all of these pressures is the replacement of traditional chemical pulp fibre in a newsprint furnish, such that the continued use of stone groundwood is feasible. Advantages and disadvantages are associated with each combination and the selection for any one mill will depend upon its requirements and preference.

Some of the characteristics of these pulps are compared in Table 11 (21) and the salient features of the processes are discussed below. Except for the Opco process, they have all been used successfully in full scale operations, and the operating techniques are now well developed, although further experience will no doubt lead to modifications in the processes since they are all still quite new. The Opco process has been proven in commercial trials and a 250 t/d system is scheduled to start operating in Quebec by the end of 1983.

TABLE 11 CHARACTERISTICS OF ULTRA HIGH YIELD SULPHITE SPRUCE PULPS (21)

	Consolidated Bathurst	CIP	Price Abitibi	Opco	Typical TMP
Na_2SO_3, on wood (%)	6	4-7	4	7-12	0
pH	4.5	9.5	5	4.5-9.5	7
Reaction temp. (°C)	147	150	100	135-170	135
Reaction time (h)	4	0.5	0.5	0.5	0.05
Yield on wood (%)	80-85	88	94	90	95
Refiner energy (MWh/t)	0.6	1.8	2.2	1.8	2.7
Freeness (CSF)	600	300	100	187	125
Burst Index (kPa•m^3/g)	3.8	3.4	3.4	3.3	2.6
Tear Index (mN•m^2/g)	11.4	8.1	7.3	8.0	8.8
Effluent BOD_5 (kg/t)	100	80	20	50	20

The BOD and yield data reported for these pulping processes tends to vary rather widely due to the difficulty of accurate yield measurement and differing practices in assigning BOD discharges to the pulping operation and the paper mill.

The Consolidated-Bathurst system is a continuous ultra-high-yield bisulphite pulping process with pulp yields in the range of 85% (22).

The CIP process - SCMP - includes a continuous high-yield sodium sulphite cook which can be carried out in either the liquid phase or the vapour phase (23,24,25). There are three operating systems in Canada.

The Price-Abitibi process involves the spraying of a sodium sulphite solution on fractionated chips, steam heating the treated material at about 100°C for 15-30 minutes and then refining (26).

The Opco process involves a sodium sulphite treatment of TMP, either between the first and second refining stages or after the second stage (27).

Other work has shown that a sodium sulphite treatment prior to TMP has significant value for improving pulp brightness, strength characteristics and refiner operation (28).

Some of the chemical treatments are also making it possible to utilize these ultra high yield pulps in higher grades of paper, sanitary products, etc. Their full potential is not known at present but the possibilities are very significant. In general, they are replacing some of the low yield pulps, leading to a reduction in effluent BOD and a more efficient use of raw material.

The processes described above are applicable with softwood utilization. Hardwood utilization requires different process conditions, depending upon the desired end utilization. Poplar and white birch produce very low strength mechanical pulps and the application of TMP results in only a very minor improvement in pulp quality. However, a chemical pretreatment of these chips results in a significant improvement in the pulp characteristics to a point where they can be used in a proper furnish. This process is referred to as CMP and it involves a chemical preimpregnation of chips with a solution containing sodium hydroxide and sodium sulphite. The impregnation is carried out at a temperature of 80-90°C either at atmospheric pressure or at a pressure of 300-350 kPa. Refining is then done at atmospheric pressure in two refining stages. The use of pressurized refining, like TMP, has no significant effect on the strength characteristics of the resultant pulp but there is a tendency towards a lower shive content.

Table 12 shows the effect of the chemical impregnation on poplar and white birch chips, compared to no chemical treatment. The chemical treatment improves the pulp characteristics and, at the same time, reduces the power required to reach a given freeness. The chip process has been used successfully in the U.S.A. since the mid 1960's and the first CMP plant in Canada, using poplar chips, has started operation.

TABLE 12 CHARACTERISTICS OF HARDWOOD CHEMIMECHANICAL PULPS (29)

	Poplar			White Birch	
Pulp Type	SGW[a]	TMP	CMP[b]	RMP	CMP[c]
NaOH, on wood (%)	-	-	1.7	-	1.6
Na_2SO_3, on wood (%)	-	-	1.9	-	2.2
Energy (kWh/t)	-	1660	1110	1780	1100
Freeness (CSF)	80	86	91	139	81
Bulk (cm^3/g)	2.35	2.25	2.12	3.28	2.52
Burst Index (kPa•m^3/g)	0.8	1.1	1.6	0.1	1.7
Tear Index (mN•m^2/g)	3.7	4.3	6.0	2.2	6.3
Breaking Length (m)	2600	3000	4400	1000	3800
Stretch (%)	1.3	1.3	1.6	-	-
Brightness G.E.	61.2	61.2	59.0	53.0	52.0
Opacity (%)	98.9	96.3	92.9	96.0	86.0

[a]SGW is stone groundwood.
[b]15 minutes impregnation at 77°C and 350 kPa.
[c]15 minutes impregnation at 84°C and 300 kPa.

The pulp yield is approximately 92% and the BOD discharge is in the range of 30-50 kg/t. The sodium hydroxide is the driving force for the improvement in strength properties and the reduction in energy requirements, while the sodium sulphite is used primarily to maintain the pulp brightness (29). The optimum chemical adsorption for newsprint production is approximately 2% sodium hydroxide and 2% sodium sulphite. Higher chemical applications will produce higher strength values but at the expense of lower opacity or higher show through.

Poplar CMP, provided it is produced from fresh, clean and sound poplar-chips, responds very well to peroxide bleaching. It can be bleached to a higher brightness than spruce TMP with the same chemical application.

If higher strength hardwood pulps are required, for example, as a replacement for a hardwood kraft pulp, they can be obtained by cooking hardwood chips with sodium sulphite to a pulp yield of 80-85%.

3.3 Kraft Pulping

Kraft pulp has continued to be the predominant type of chemical pulp manufactured in Canada, with several new mills being constructed, and several of the older mills being modernised and/or expanded. Development has consisted primarily of the refinement and widespread application of processes and equipment developed in the 1960's, whereas there have been major changes in the manufacture of mechanical and sulphite pulps. Many kraft mills now install stripping systems for both digester and evaporator contaminated condensates, as described in Section 4, and there has been a general trend toward increased brown stock washing efficiencies.

3.3.1 Digesters. Virtually all new pulping installations use continuous digesters with integral pulp washing. Kamyr has been the principal supplier, hence the frequent use of their name to describe continuous digesters as well as their tradename "Hi-heat Washing" for the process of washing in the digester, which is described in Section 3.3.3.

The gases from a continuous digester are emitted at a constant rate, which facilitates their collection and incineration, and the quantity of contaminated condensates produced by continuous digesters is lower than by batch digesters. Continuous digesters use less steam than batch digesters, and hence reduce the amount of fossil fuel required.

The digester is the heart of the pulping process but it has relatively little direct impact on the environment. Although the continuous process is more amenable to operation with minimal black liquor losses than batch, the quality of design engineering and day-to-day operation has much more effect on the effluent and atmospheric emission quality than the choice between continuous and batch digesters.

3.3.2 Batch Digester Heat Recovery. Several mills have installed new or more efficient systems to condense the blow steam from batch digesters and recover the heat value as hot water. These use conventional technology but are usually more generously dimensioned than in the past. At least one mill is using the heat recovered to evaporate weak black liquor. Such systems have little direct environmental effect, but an effective means of condensing all blow steam is a prerequisite for the installation of an incineration system for non-condensable, total reduced sulphur (TRS) gases.

3.3.3 Diffusion Washing in Continuous Digesters. Since about 1970, it has been standard practice to incorporate diffusion washing systems, known as "Hi-heat Washing", in Kamyr digesters, with the more recent installations being designed with longer retention times to increase washing efficiency.

Figure 4 shows a Kamyr digester equipped with an internal washing zone. Chips move down into the wash zone from the cooking zone. Wash liquor enters the washing zone from the blow zone at the bottom of the digester and flows up counter-currently to the downward moving chips. The liquor is initially withdrawn from a set of peripheral screens at the bottom of the wash zone, heated by steam in a heat exchanger and reintroduced into the centre of the chip column through a central pipe hung from near the top of the digester. This circulation is intended to provide even distribution of the wash liquor and also improves the washing efficiency since the higher temperature increases the diffusion rate of chemicals out of the cooked chips.

Spent cooking liquor and upflowing wash liquor are withdrawn from two sets of extraction screens at the interface between the cooking zone and the wash zone. Sometimes part of the liquor from the lower screen is recirculated as a quench circulation to give a sharper, more uniform cutoff to the cooking zone.

Typically, wash zones are designed for 1, 1-1/2 or 4 hours retention time, and the normal wash zone temperature is about 125-140°C.

3.3.4 Anthraquinone. In the late 1970s, a number of publications reported that the addition of small quantities of anthraquinone would increase the rate of the classic kraft pulping reaction and increase the yield, without any degradation of pulp properties. Much of the early work was by Dr. Holton of Canadian Industries Ltd. (30), but research by others and a number of full scale commercial operations have confirmed his findings (16). Anthraquinone functions as a catalyst in the delignification reaction, and permits a combination of the following improvements to be realised:

- increase in pulping yield by a few percent;
- reduction of chemical requirements by 1 to 2 percentage points;
- increase in pulp production rate;
- lower cooking temperature (hence reduced energy consumption).

Trade-offs between these variables are similar to those in traditional non-anthraquinone kraft pulping, so that mills can utilise the best combination for their needs.

Any increase in yield or reduction in chemical requirements will also reduce the load on the recovery furnace, which allows the recovery and incineration of organic material which may otherwise be discharged to sewer. An increase in pulp production would tend to increase the effluent BOD and toxicity, if the brownstock washing or recovery departments were unable to process the increased amount of black liquor solids produced.

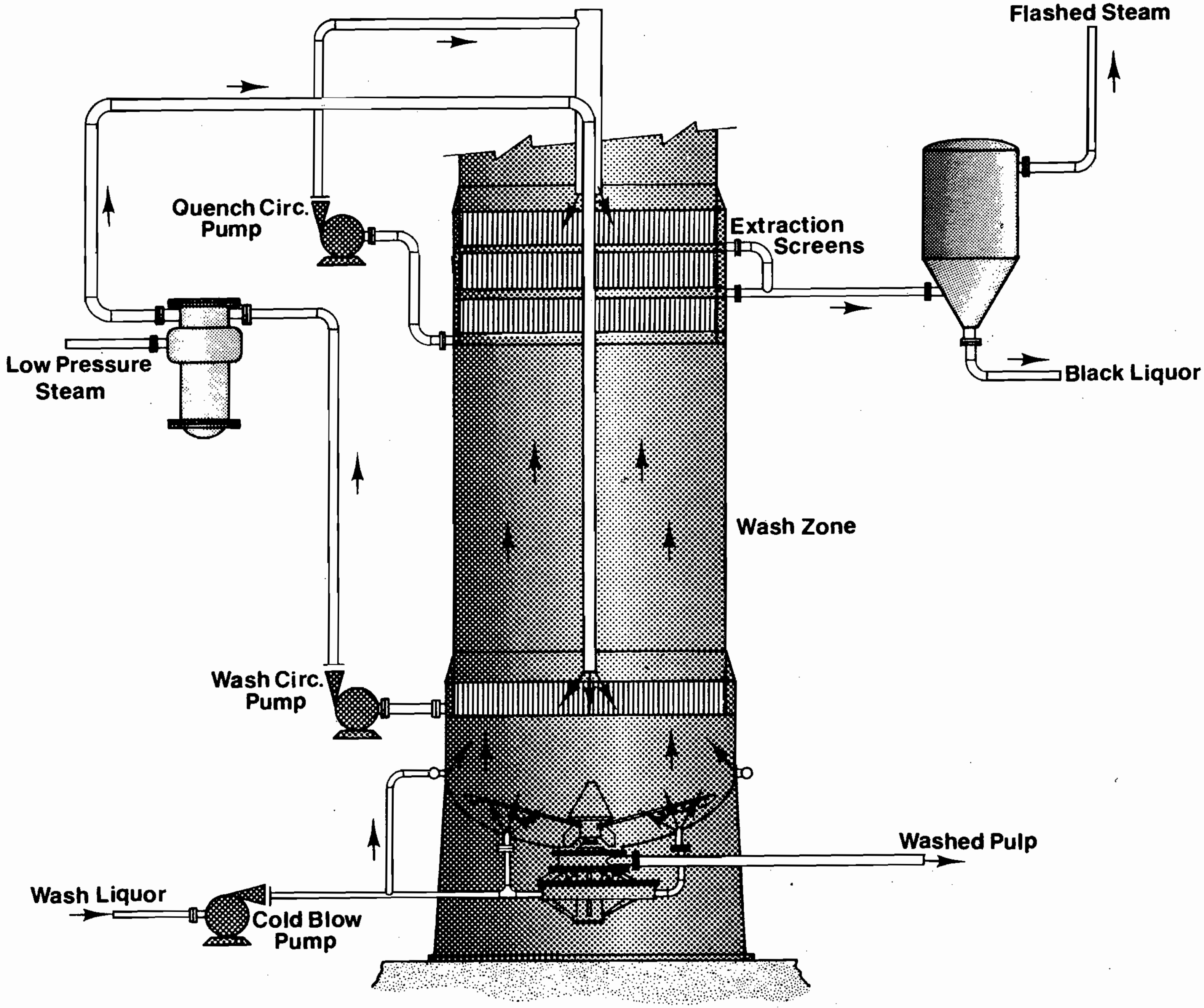


FIGURE 4 DIGESTER HI-HEAT WASHING (Kamyr)

More radical modifications to the kraft pulping process, based on the properties of anthraquinone, have been proposed, but have not yet progressed to commercial application. These include the elimination of sulphur in the process, which would eliminate the kraft mill odour problem and probably reduce effluent toxicity.

A number of researchers have investigated the possibility of any undesirable environmental effects from the use of anthraquinone, and none have been reported. Anthraquinone has been used widely in the textile industry as an intermediate in dyestuff manufacture for a number of years, in quantities exceeding current pulp industry uses, with no known reports of environmental problems. Its use in pulping has been approved by Health and Welfare Canada and by the U.S. Environmental Protection Agency and Food and Drug Administration.

The current use of anthraquinone to achieve modest improvements in pulp mill operations seems likely to continue and probably increase in the near future. However, any predictions on the possibility of one of the anthraquinone assisted pulping processes being used to replace kraft pulp would be purely speculative.

3.4 Neutral Sulphite Semi-Chemical Pulping

The only recent development in neutral sulphite semi-chemical (NSSC) pulping that is of environmental significance is the use of non-sulphur cooking liquors. This allows the use of a relatively simple fluidized bed furnace for incineration of the waste liquor to produce sodium carbonate and eliminate the BOD from this source. The sodium carbonate is used for the regeneration of cooking liquor, avoiding the disposal problem which exists when conventional NSSC waste liquor is incinerated.

Most NSSC mills in Canada have adopted in-plant recycle as the principal effluent control measure, and the most recently built one has a fluidized bed liquor incinerator.

4 CHEMICAL RECOVERY

4.1 General

Chemical recovery systems comprise the black liquor evaporators, recovery furnace, recausticising system and lime kiln (or calciner), including the necessary auxiliaries and directly associated environmental protection equipment. The chemical recovery system converts the spent pulping liquors into useful pulping chemicals and steam. Chemical recovery is practiced in all kraft mills and in a small proportion of the other types of chemical pulp mills in Canada. Since over 90% of the chemical recovery systems in the Canadian pulp and paper industry are in kraft mills, this section concentrates on them, with a short discussion on the state-of-the-art of other recovery processes.

There has been a general trend to increase the capacity of the recovery departments relative to mill pulp production capacity, partly for economic reasons and partly as a result of environmental pressures. The basic technology, and the environmental protection practices, have been described in reference 6, and it is assumed that the reader is familiar with them.

4.2 Evaporators

All kraft recovery furnaces in Canada use a multiple-effect evaporator to concentrate the liquor prior to feeding the recovery furnace. The more modern are designed to minimise liquor carry over into the condensates, and virtually all modern systems use a surface condenser, rather than the traditional barometric condenser, to condense the last effect vapour. This reduces the effluent volume and facilitates the collection of contaminated condensates when it is desired to segregate them for stripping or other use. The surface condenser also recovers heat in the form of warm water, which can be effectively utilised if properly integrated into the mill design. Some recent systems use a two-stage condenser, with temperatures controlled so that the contaminants are concentrated in one stream, reducing the volume for stripping, if applicable.

Since the modern recovery furnace must be fed with black liquor at about 65% concentration rather than the traditional 50%, most of the evaporators installed since 1969 have incorporated a concentrator. This is effectively a forced circulation evaporator with special provisions to deal with the fouling and very high viscosities that occur with black liquor at over 50% concentration.

Several innovations have been introduced in the last five years to reduce the energy consumed by liquor evaporation, including the use of waste heat instead of steam as the energy source, multi-flash evaporators for continuous digester flash tank vents and falling film evaporators instead of the traditional long tube vertical (LTV) design. These innovations have no direct impact on discharges to environment. However, measures that lower evaporation costs allow the use of higher dilution factors in pulp washing, thus reducing the discharge of residual black liquor solids to sewer.

In a few cases, condensate stripping systems have been integrated in multiple-effect evaporator systems. Essentially, they make use of intermediate steam and heat exchange surfaces in the evaporator, and therefore offer some energy and capital cost economies. However, it is common for a mill evaporator system to be shut down for a few hours while the digester is in operation, so that condensate storage is required or other special provisions have to be made, perhaps negating the advantages.

4.3 Recovery Furnaces

4.3.1 Furnace Design. Traditionally, North American recovery furnaces incorporated direct contact evaporators in the exhaust ducting to raise the black liquor concentration from about 50% dry solids to about 66% by contact with the flue gas. This results in significant total reduced sulphur (TRS) emissions, unless the black liquor is effectively oxidized to reduce its sodium sulphide concentration below 0.15 g/L. This type of recovery furnace is frequently referred as to "conventional", since it was the standard design from about 1940 until 1969. This is becoming rather misleading since about half of the black liquor in Canada is now processed in the more modern low-odour furnace design discussed below, and almost all recovery furnaces sold since 1970 have been of this type.

To circumvent the problem of TRS emissions from the direct contact evaporator, the low-odour design was developed in the late 1960's. It does not use a direct contact evaporator, and therefore requires that the liquor supply be at a concentration of about 65%. These furnaces have relatively large economisers to recover the heat that would traditionally have been recovered in the direct contact evaporator by heating the incoming boiler feed water. Although this design eliminates the generation of TRS emissions from the direct contact evaporator, it is still possible for the furnace itself to generate TRS gases if it is overloaded or improperly operated. Recovery systems that avoid a direct contact evaporator generally have higher thermal efficiencies than the traditional direct contact evaporator type, and a slightly higher capital cost. These furnaces are generally known as the extended economiser, or low-odour furnaces.

Both the low-odour and the traditional recovery furnaces have demonstrated their capability for compliance with current regulations concerning TRS emissions in Canada and elsewhere, provided that the furnace is not overloaded and the instrumentation and operating practices are all adequate.

Many of the older recovery furnaces are undersized and furnace conditions cannot be controlled sufficiently well to avoid TRS emissions of several hundred parts per million, even with efficient black liquor oxidation.

The maximum practical ratings for recovery furnaces have increased from the equivalent of a few hundred tonnes per day pulp, to about 1500 t/d over the past 20 years. While this has no direct impact on the environment, it facilitates the installation of effective automatic control systems, including computer control, which can manipulate the operating parameters to minimise particulate and TRS emissions.

4.3.2 Particulate Emission Control. A significant proportion of the sodium salts in the black liquor are fed to the furnace exit with the flue gas, principally as sodium sulphate but also as sodium carbonate and minor quantities of other sodium salts. Recovery furnaces therefore require efficient emission control devices to comply with current regulations, and to recover these chemicals. It is economically attractive to recover about 95% of the particulate, due to its chemical value, but substantially higher efficiencies are required to comply with regulatory requirements.

Virtually all modern recovery furnaces are equipped with electrostatic precipitators, and most of those recently installed can provide compliance with the applicable regulations. Electrostatic precipitators are available with rated efficiencies of 99.7% for the conditions occurring in recovery furnace flue gas. Experience has shown that efficiencies substantially over 99% are difficult, and expensive, to maintain over the long term although many mills with high efficiency precipitators as the sole particulate emission control device emit under 250 mg/Sm^3 (standard cubic metre; see Appendix). The physical size, power consumption and capital cost of precipitators rises rapidly with higher specified efficiencies.

Recently several mills have installed scrubbers in series with a precipitator of moderate or low efficiency, normally to rectify inadequate particulate emission control. The scrubber medium is recycled so that the concentration of sodium salts in the underflow is high enough to permit its recycle to the green liquor or weak black liquor systems. If suitably designed, these scrubbers can recover about 2 GJ/t pulp as hot water, as well as reducing the particulate emissions to under 200 mg/Sm^3. In order to realise the energy recovery, and to avoid energy penalties in the evaporators, it is essential that the scrubber water circuit be properly integrated into the mill hot water and steam system. A common recovery furnace scrubber design is shown in Figure 5 but there are others on the market, and some mills have designed and built their own systems. The scrubbers generally enable compliance with stringent regulatory limits with a greater margin of safety than electrostatic precipitators. The greatest environmental disadvantage of using a scrubber instead of a precipitator is the obvious wet plume produced. This is often misinterpreted as "pollution" by the public, and may lead to visibility limitations if the topography and location are unfavourable. The relatively poor dispersion of the gaseous emissions at the low temperature of scrubbers must be considered in designing odour control systems.

4.3.3 **TRS Emission Control at Source.** The TRS emissions from the furnace itself depend on the operating conditions. The prime requirement is that the oxygen content of the flue gas be over 2%, which in turn implies that the furnace must not be overloaded. It is now generally agreed that the furnace's nameplate rating, normally expressed in tonnes of dry black liquor solids per day, is only an approximation of the its capacity to burn black liquor without high TRS emissions. The ratings are invariably based on a hypothetical black liquor with a heating value of 15.1 GJ/t solids, whereas this value varies in practice. Other factors play a minor part in the furnace's actual capacity, and in the final analysis, the only arbiter from the environmental point of view is the measured furnace emission. Other non-environmental factors may place lesser constraints on furnace capacity (31).

Many of the modern installations have installed instrumentation to monitor TRS levels continuously. This is desirable and helpful to the operator, since tuning of the furnace operation is essential if TRS emissions are to be controlled to low values, and a computer control system requires continuous data if it is to control TRS emissions by manipulating other variables.

Unfortunately, although TRS monitoring instruments have been on the market for over ten years, they are still not reliable and require disproportionate amounts of maintenance time. To circumvent this problem, some systems are successfully controlled by inferring TRS concentrations from other data, particularly carbon monoxide levels (32).

The more recently installed furnaces can be operated to limit TRS emissions to below 20 ppm most of the time they are operating, with daily average levels well below 10 ppm. Older units usually lack the necessary precision in control of air flows and

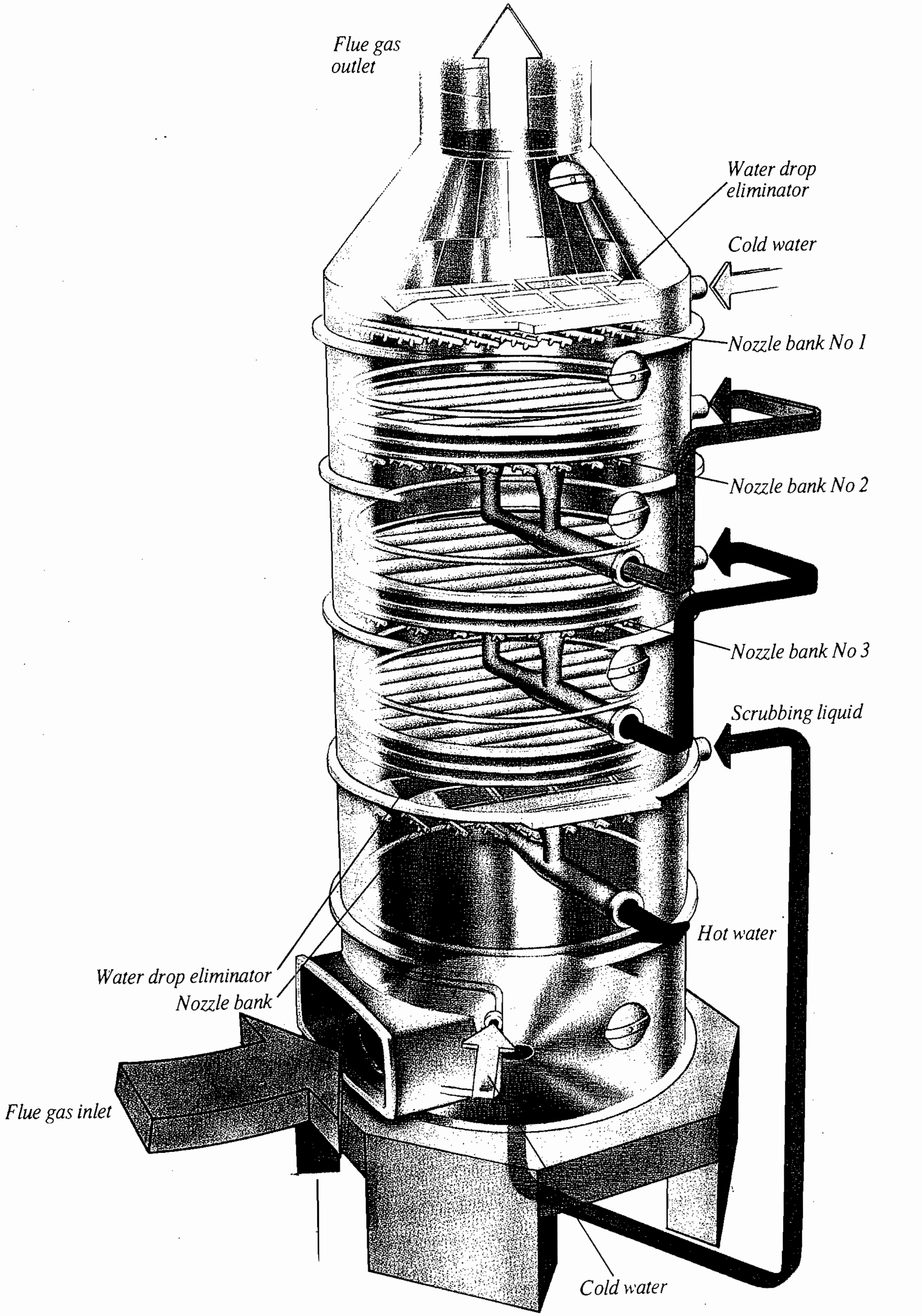


FIGURE 5 PARTICULATE REMOVAL SCRUBBER FOR RECOVERY FURNACE (Flakt Canada)

internal velocities to attain these levels, but many can be controlled to below 100 ppm, if they are not overloaded.

The emissions from the direct contact evaporator, if any, are dependent on the sodium sulphide content of the black liquor, and are added to the furnace emissions to form the stack emission. The sodium sulphide concentration should be under 0.15 g/L if the TRS emission levels are to be controlled below 20 ppm. This requires that the black liquor be very efficiently oxidized.

4.3.4 **TRS Emission Control by Scrubbers.** The scrubbers discussed in Section 4.3.2 for the control of particulate emissions also remove several percent of the TRS from the stack gases. Where it is desired to remove a significant proportion of the TRS from the stack gas, the Paprican scrubbing process developed by the Pulp and Paper Research Institute of Canada is frequently used. This is based on sodium hydroxide, with a small addition of activated carbon, as the scrubbing medium (33,34,35). The equipment used varies among the suppliers that have been licenced to use the process, and one example recently installed in Canada is shown in Figure 6. Teller, the other principal supplier, uses the same process concept but a different scrubber arrangement as shown in Figure 7; a Canadian installation is discussed in reference 36.

This process can recover about 2 GJ/t pulp in the form of hot water, as well as some sodium salts, and reduce the TRS emissions. It is the only proven process for control of TRS emissions from an overloaded recovery furnace, and is most frequently used in such circumstances. The removal efficiency depends on the stack conditions and the design, but can reach 99%. The practical limit for its application is about 1500 ppm TRS in the inlet gas, but this depends on the local conditions and the final emission characteristics required. In the appropriate circumstances, the use of such scrubbers renders black liquor oxidation unnecessary. As in the case of the simpler particulate removal scrubber described in Section 4.3.2 above, the value of the heat recovered depends on how the scrubber is integrated within the mill hot water and steam system, which in turn depends on the quality of systems engineering and the design of the remainder of the mill.

4.3.5 **Fluidized Bed Recovery Furnaces.** Virtually all kraft recovery furnaces installed since 1940 have been the conventional type where the liquor is burned at about 65% consistency in a water walled vessel with a smelt bed in the bottom. It is characteristic of this type of furnace that it is normally impractical to increase the capacity beyond the design maximum without completely rebuilding and extending the

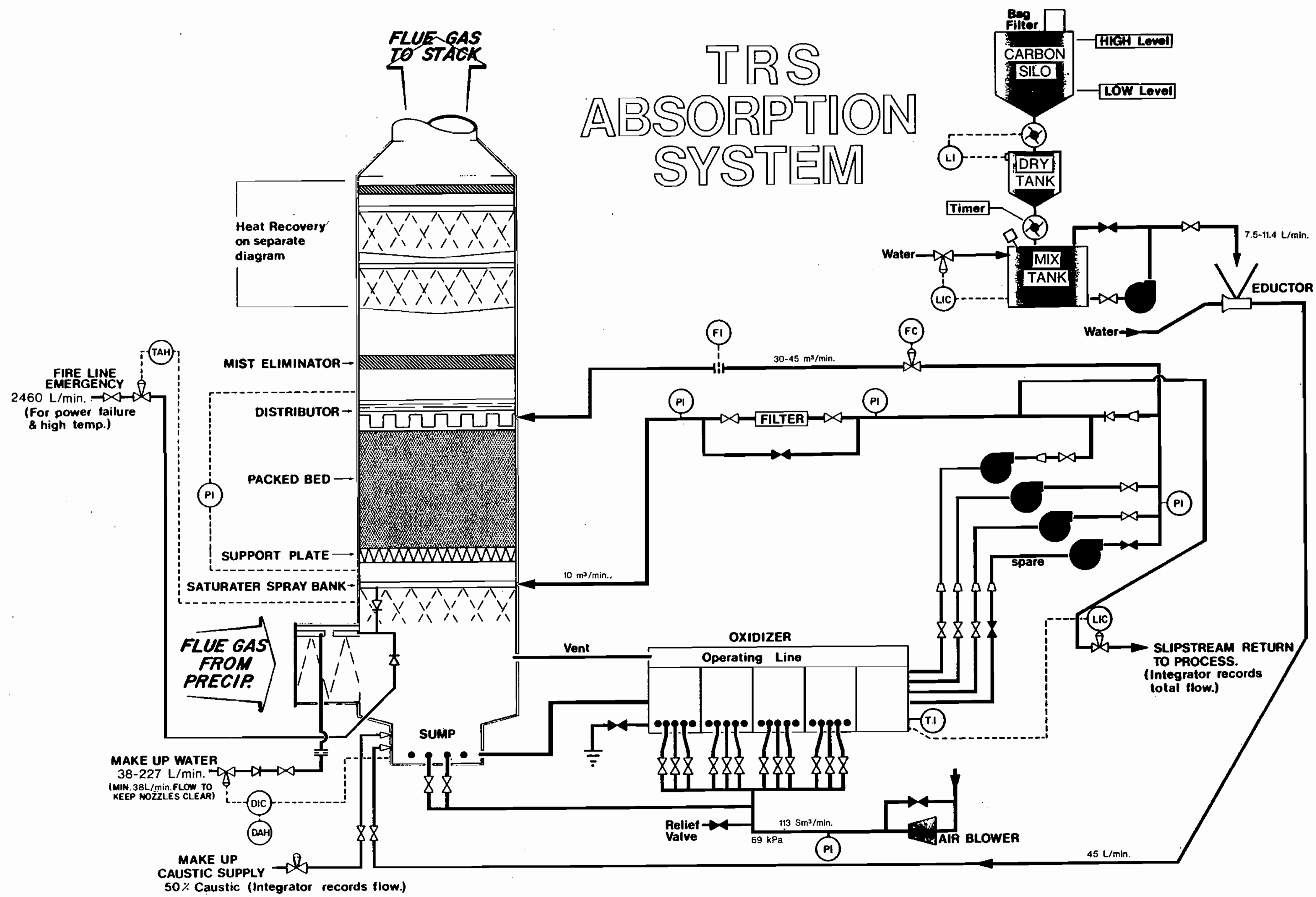


FIGURE 6 TRS AND PARTICULATE REMOVAL SCRUBBER FOR RECOVERY FURNACE (Flakt Canada Ltd.)

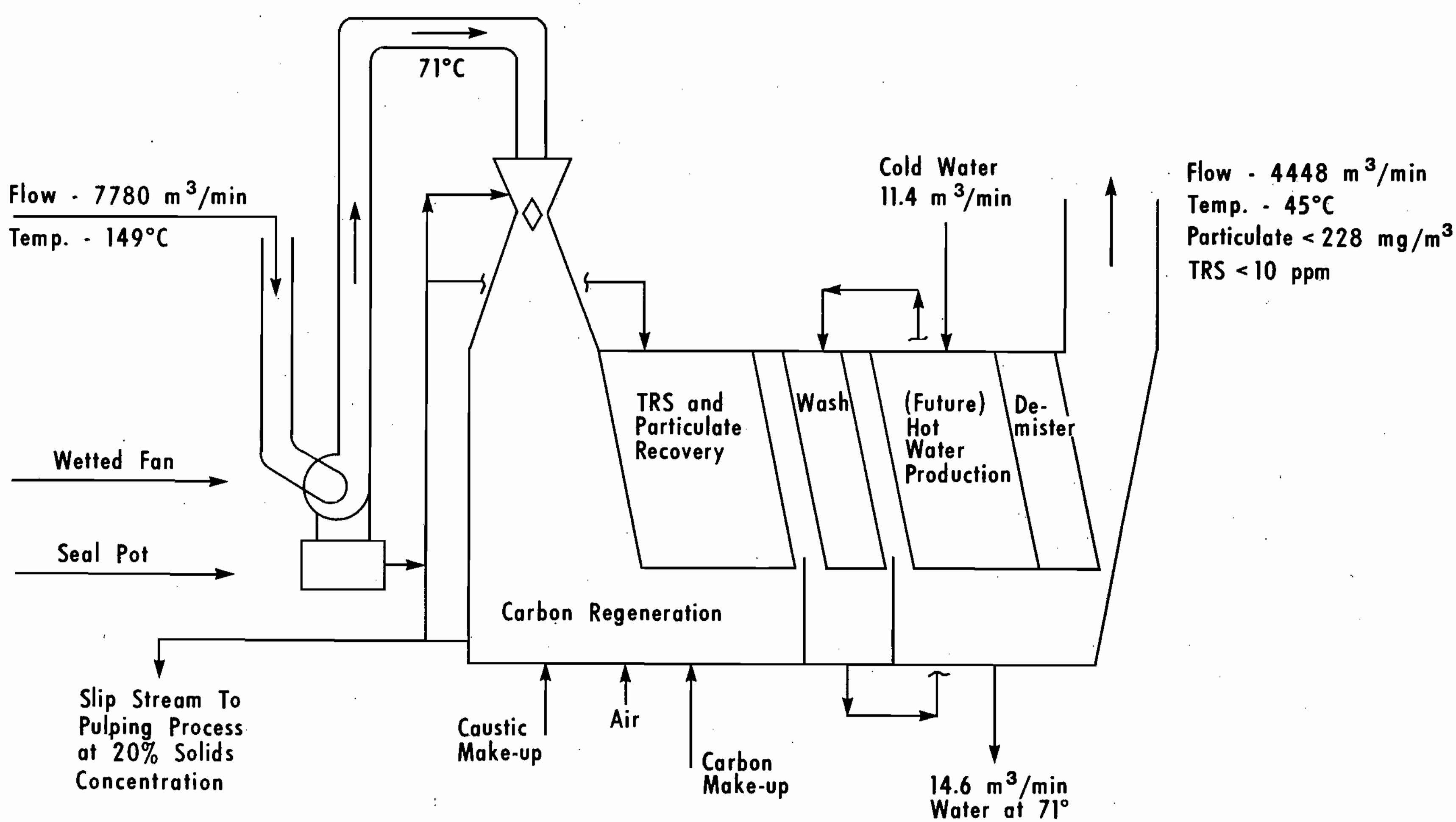


FIGURE 7 TELLER IMPLEMENTATION OF PAPRICAN PROCESS FOR TRS REMOVAL (36)

furnace. This presents many mills with a serious impediment to marginal increases in production or efficiency of recovery of black liquor solids due to improved washing efficiency or the introduction of oxygen bleaching.

The technically simple solution is to install a new recovery furnace, and this is the most common approach, despite the high capital cost. The Domtar mill at Cornwall, Ontario, developed an alternative technique based on the use of a fluidized bed incinerator. A proportion of the black liquor from the brown stock washers is evaporated to about 35% dryness and burned in a Copeland fluidized bed reactor. The organic material is destroyed and some of the heat liberated is used to dry the incoming liquor.

The bed product, a mixture of sodium carbonate and sodium sulphate, is conveyed to the conventional recovery furnace where it reacts with the smelt to produce green liquor. The key to the success of this process is the decrease in thermal load on the recovery furnace.

4.4 Condensate Stripping

The contaminated condensates from the multiple-effect evaporators and digesters are frequently stripped to remove TRS and BOD. The recent trend in this field has been toward air stripping or waste gas stripping to avoid the excessive energy consumption of many of the early steam stripping systems. Some of the older systems required one tonne steam per tonne pulp for effective operation, which represents about a 15% increase in purchased energy costs for a typical bleached kraft mill. Developmental efforts in steam stripping have concentrated on reducing the energy consumption of this process, since many of the systems installed in the 1970s have proven to be excessively expensive to operate.

Improved segregation of condensates has reduced the volumes that must be stripped to as low as 1.8 m^3/t pulp in mills with continuous digesters. This has been achieved by installing segregated two-stage surface condensers and very detailed engineering analysis of the remainder of the digester and evaporator design features that contribute to the production of contaminated condensates.

Systems have been installed which take advantage of the fact that in most mills the lowest pressure steam header is at a pressure of about 300 kPa, whereas the evaporator requires steam at about 200 kPa, by inserting the stripper in the evaporator steam supply line. This can reduce the steam requirement for stripping to a fraction of a tonne steam per tonne pulp.

The theoretical heating value of the gases produced by a steam stripper corresponds to about half a gigajoule per tonne pulp, so it is potentially feasible to develop a condensate stripping system that recovers more energy than it consumes. This performance has been claimed for some systems but commercial scale evidence is not yet available.

Instead of attempting to reduce steam consumption, several installations have adopted the approach of air stripping the contaminated condensates to reduce the TRS content and then allowing the waste heat in the smelt dissolving tank or the the lime kiln scrubber to strip the methanol out and discharge it to atmosphere. No mills have taken maximum advantage of the possibilities of this approach to date, and many of the mills are unaware that BOD is being stripped in this manner.

Reference 37 discusses the use of waste gases for stripping contaminated condensates and also includes extensive data on the established stripping techniques.

4.5 Black Liquor Oxidation

As mentioned in Section 4.3, it is necessary to treat the black liquor to oxidise the sodium sulphide in it. Various designs were installed in the 1950s and 1960s, some of which are still operational. Since the mid 1970s it has been generally accepted that the best approach is to oxidise the strong black liquor by injection of compressed air near the bottom of a vessel containing the liquor at about 50% consistency. A typical modern design is shown in Figure 8.

Weak black liquor oxidation has proven to be less effective because some sodium sulphide is reformed in the evaporators by reduction, and because foaming has been an insurmountable problem in many systems. However, several weak liquor systems are still operating which attain some benefits in the reduction of TRS emissions.

All black liquor oxidation systems reduce the heating value of the black liquor, and generally require several hundred kilowatts of electricity to drive the blowers, pumps, etc. The reduction in heating value is an advantage in mills with marginally overloaded recovery furnaces, since it reduces the thermal load on the furnaces.

4.6 Recausticising and Recalcining of Lime

The role of the recausticising system is to convert the smelt from the recovery furnace into white liquor for the digesters, while recovering the greatest amount of sodium possible from the lime mud and producing a mud that can be reburned efficiently. There should be no effluent from a well-designed and operated recausticising system.

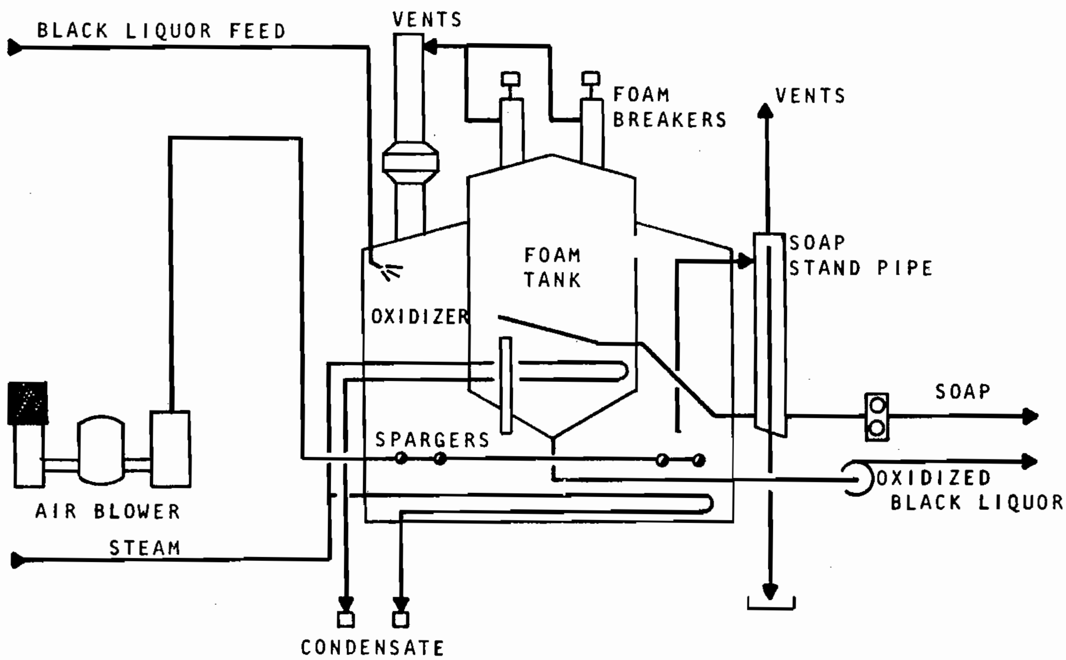


FIGURE 8 STRONG BLACK LIQUOR OXIDATION SYSTEM (MoDo Chemetics)

The modern recausticising system consists of green liquor clarification, dreg washing, slaking, causticising, white water clarification, lime mud washing and lime mud filtration. Significant recent trends are the use of unit clarifiers and the use of vacuum filters for dregs washing. Unit clarifier is the accepted name for single-level clarifiers with liquor storage above the clarification compartments for clarifying green and white liquor and for lime mud washing. These trends represent steady evolutionary development and the principal effect on mill effluent is that the green liquor dregs are discharged as a relatively dry cake which can readily be landfilled, reducing mill effluent suspended solids by about 0.5 kg/tonne pulp.

The most environmentally significant trend in recausticising plant design in the last ten years has been the growing practice of installing sufficient standby capacity, either as separate equipment or by the use of more generous design criteria, to avoid the need to dump lime mud to sewer when there is an operating problem in the system. Computer control of the recausticising and calcining process has been introduced, and has been reported successful in stabilising the operation, which in turn reduces effluent discharges (38).

Several mills have installed a stand-by clarifier which can perform the function of any one of the clarifiers, mud washers or major liquor storage tanks, allowing them to be overhauled without production disruptions or excessive discharges to sewer.

An increasing number of mills operate the recausticising department without discharging suspended solids to sewer. The practice of eliminating recausticising department effluent, except for cooling water, also reduces mill BOD discharges, although there are no organic chemicals in this department. The sodium sulphide present in all process liquids exerts an oxygen demand of about 1 kg/kg Na_2S in a BOD test or biological treatment system.

It is becoming standard practice to burn the malodorous non-condensable gases from the evaporator and the digester in the lime kiln, since it is more reliable and safer than the use of a separate incinerator. A typical modern burning arrangement is shown in Figure 9.

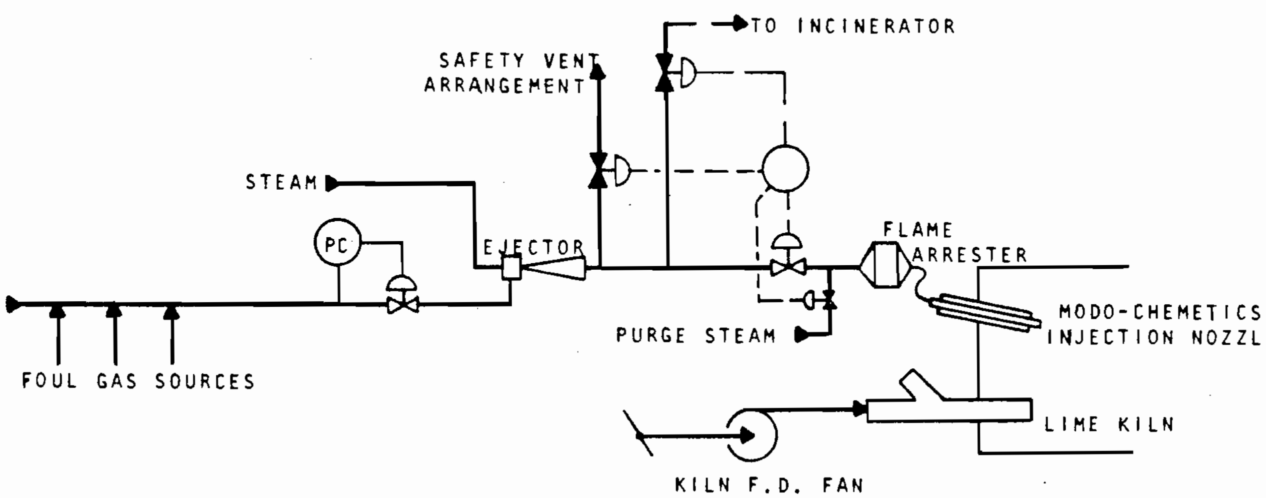


FIGURE 9 BURNING NON-CONDENSABLE GAS IN KILN (MoDo Chemetics)

In most mills, the lime mud is recalcined in a conventional lime kiln to produce the lime (calcium oxide) necessary for slaking. Some mills now use fluidized bed calciners for the calcining operation. The prime reason for this is to reduce fuel consumption, but the reported emission data on calciners indicates that their TRS emission is negligible, whereas the kiln is normally a minor but significant TRS source where the lime is reburned in a kiln (31). However, many mills can comply with TRS emission control regulations for lime kilns by limiting the sodium content of the lime mud and avoiding the use of unstripped contaminated condensates in the kiln scrubber.

A typical lime reburning system with a fluidized bed calciner is shown in Figure 10. The system takes wet lime mud filter cake and dries it in the flash drying system shown on the left hand side of the figure. The dry powder is then blown into the gas or oil fired fluidized bed calciner where it reacts at a temperature of about 900°C. The fine particles of CaO agglomerate to pellets ranging from 6 to 65 mesh. A bed level controller automatically discharges the product to a the cooling bed below, which preheats the incoming air by direct contact, and then the calcined lime is discharged to its storage bin.

The flash drying system utilises primary and secondary cyclone collectors followed by a venturi scrubber operating at a pressure drop of about 450 mm of water, depending on the local emission regulations. Particulate emissions data reported is normally under 200 mg/Sm^3 and TRS emissions under 5 ppm.

Instead of using venturi scrubbers to control the particulate emissions from lime kilns and fluidized bed calciners, it is feasible to use electrostatic precipitators. These offer the advantages of recovering a dry material and discharging a dry, virtually invisible plume. The capital cost is higher than for a scrubber, but the energy consumption is reportedly lower. The opportunity to recover some of the heat from the exhaust gases in the scrubber liquor is lost, although the value of this is dependent on whether it can be utilised effectively in the mill system or not. Whereas a scrubber can be used to reduce TRS emissions from a lime kiln, the electrostatic precipitator removes particulates only. Electrostatic precipitators have the capability of reducing emissions below the levels practicable for scrubbers.

4.7 Sulphite Mill Recovery Systems

Four of the largest sulphite mills in Canada have installed chemical recovery systems in the past few years which have reduced BOD discharges by over 60% (6,39). These mills produce low-yield dissolving or paper grade pulps. None of the mills producing high-yield newsprint grade sulphite pulps have found a satisfactory recovery process, although they have achieved some BOD reductions by increasing their pulping yields. Many sulphite mills have been shut down due to the lack of a viable recovery process.

Most of the sulphite recovery furnaces are constructed similarly to kraft recovery furnaces, but at least one mill in Canada has installed a fluidized bed furnace to incinerate sulphite waste liquor. This mill recovers by-product organic chemicals from

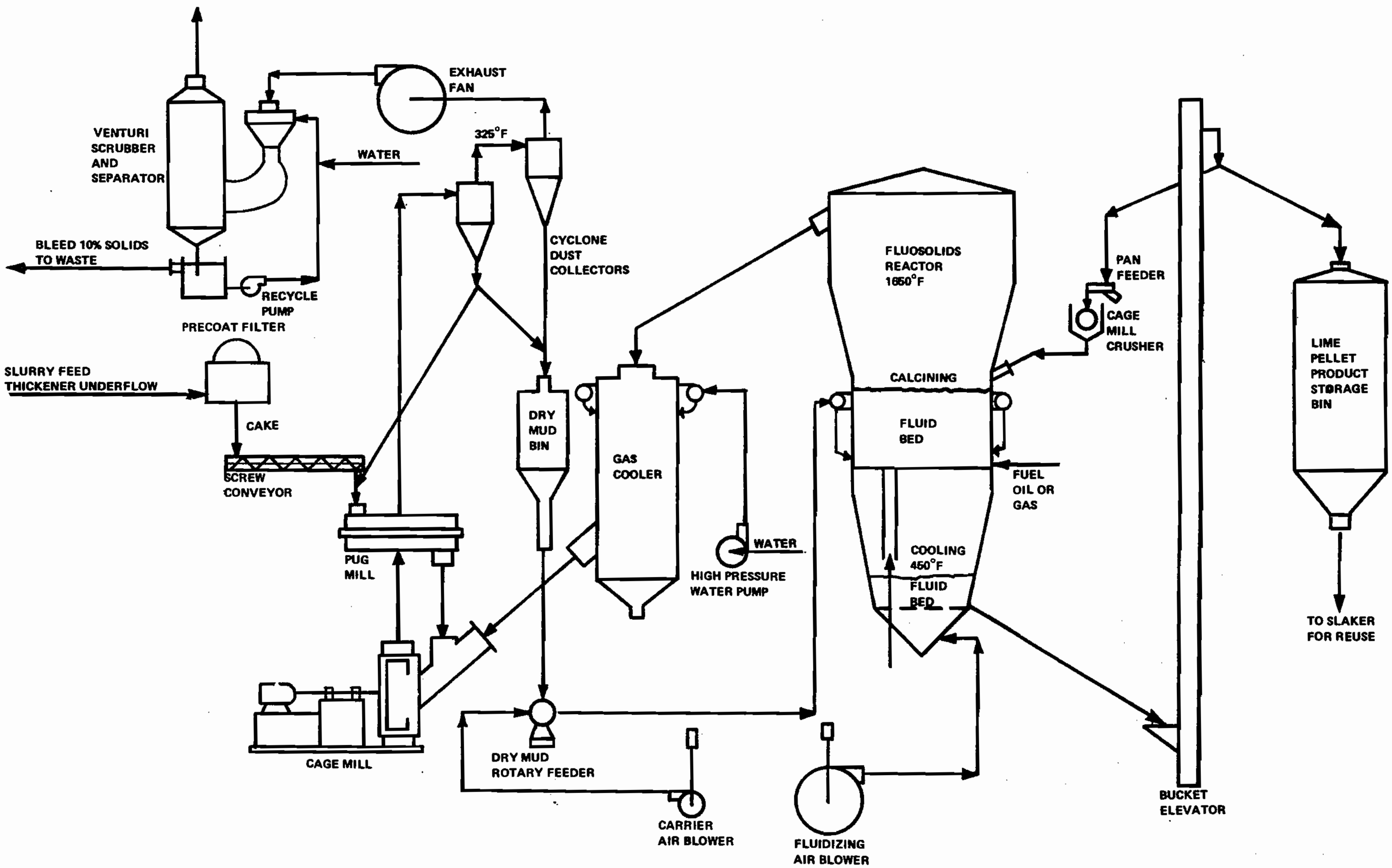


FIGURE 10 FLUIDIZED BED CALCINER FLOWSHEET (Dorr Oliver Inc.)

the liquor, which results in a final waste which has a relatively high inorganic content, and is difficult to incinerate. Although the BOD of the waste liquor is decreased substantially by the recovery of the by-products, it was necessary for the mill to further reduce the discharge of organic wastes, and the fluidized bed reactor was considered preferable to the conventional recovery furnace.

4.8 Neutral Sulphite Semi-Chemical Recovery

Several NSSC mills have installed liquor incineration systems, but these result in the production of a sodium sulphite by-product for which there is a declining market. The recent trend is to eliminate the sulphur from the process, so that the furnace by-product is sodium carbonate, which can be recycled for cooking chemical preparation. Despite the absence of sulphur, the process is often still known as NSSC.

4.9 Accidental Losses

Since chemical pulp mill recovery systems handle large recirculating flows of black liquor and other pulping by-products that have high BOD and are toxic to fish, accidental losses have traditionally been significant discharges. The more recently designed mills have generally installed sophisticated spill collection systems in which most of the tanks overflow to other parts of the process, and the few points of final overflow are routed to collection reservoirs so that much of the material that would have been discharged ten years ago is now recovered. The techniques used have been described in reference 6, and some discussion on the use of computer control to minimise accidental losses is included in Section 10.

5 WASHING AND SCREENING

5.1 General

Washing and screening systems are described in reference 6, and it is assumed that the reader is familiar with the basic technology and terminology.

In mechanical pulping, washing is not practiced, although some active research may be approaching commercial realisation (40). This may allow the recovery and incineration of a substantial proportion of the BOD and toxic material from the TMP process. Screening mechanical pulp is discussed in Section 5.2.

Substantial developments have taken place in equipment design and practices in kraft pulp washing and screening, as discussed in Section 5.3. While the same equipment would be applicable to sulphite pulp mills with recovery systems, it would have less environmental significance.

5.2 Screening Mechanical Pulp

Essentially all new mechanical pulp screening systems use closed, pressurised screens. This has no direct effect on effluent discharges while the screen room is operating normally, but it is much easier to design and operate a screening system with minimal overflows and spills with closed pressure screens than with the older open rotary screens. The more modern screening systems generally operate at higher consistencies, thus reducing the circulating flows and the magnitude and frequency of stock spills.

Most screening systems now incorporate systems for the recovery, refining and recycle of screen rejects, eliminating a former source of effluent suspended solids and/or solid waste that had to be landfilled. The concept of these systems is quite simple. The rejects, which consist mostly of bundles of incompletely defibred wood, are dewatered and passed through a refiner, and the pulp produced is recycled to the screen input. In designing such systems suitable allowances, in the form of storage or standby equipment, must be made for scheduled downtime for refiner plate changes and for breakdowns. This is particularly important in systems that must recover the bull screen rejects since these are bulky and irregular, causing relatively frequent equipment blockages.

5.3 Kraft Washing and Screening

5.3.1 **Process Concepts.** The efficiency of the unbleached pulp washing system is one of the keys to the operation of a kraft pulp mill with minimal water pollution. The lignin and related material separated from the fibres during cooking must be recovered from the pulp stream by the washing system and routed to the recovery department, or they will be discharged to sewer in the screening system or subsequent operations. The lignin is toxic to fish and is difficult to remove by biological treatment, so that high losses from the washing area tend to have a disproportionately large impact on effluent quality. Refer to Figure 11 for a flowsheet of a typical older screening system and Figure 12 for a typical modern one.

There has been a general trend toward increasing the efficiency of existing brownstock washer systems by installing additional stages and improving instrumentation. Most new systems are designed to operate with a loss of under 7 kg/t pulp unbound soda, expressed as sodium sulphate. Consideration of the washing process indicates that the BOD and the toxic chemical content for the effluent from brownstock washing and screening systems is directly proportional to the unbound soda loss (41).

The continuous diffusion washer described in Section 5.3.2 has been selected for almost all new brown stock washing systems in Canada since 1973, and some have been installed in series with existing drum washers to increase the liquor recovery efficiencies. The total capacity of brown stock diffusion washers installed in Canada up to the end of 1982 was 9200 t/d which represents about 30% of the total kraft pulping capacity.

In theory, washing efficiencies obtained with the traditional vacuum drum washers can be as high as with the diffusion washers, resulting in equally low effluent BOD and toxicity. However, more spills and foam overflows generally occur in drum washing systems due to the high recirculating liquor flows and large quantities of air entrained with the pulp in the washer droplegs. These difficulties can be overcome by installing sufficient foam handling and spill tank capacity, but this is expensive. Since most mills that have chosen drum washers have done so to minimise capital cost, a completely adequate foam handling system is rare in a kraft mill drum washing plant.

The flat belt washer was introduced in the late 1970s and is described in Section 5.3.4. It may offer equal performance to the diffusion washer, but little full scale operating information is available to date.

A systems approach to the design of the complete pulping, washing, screening and liquor recovery cycle is essential if the optimum design of the washing and screening area is to be attained. The necessary theoretical process knowledge was available by about 1965, but the amount of work and the time necessary for the calculation of the many possible alternatives limited the use of this knowledge in most new mill design projects. Since the late 1970s, cost-effective and efficient computer methods have been

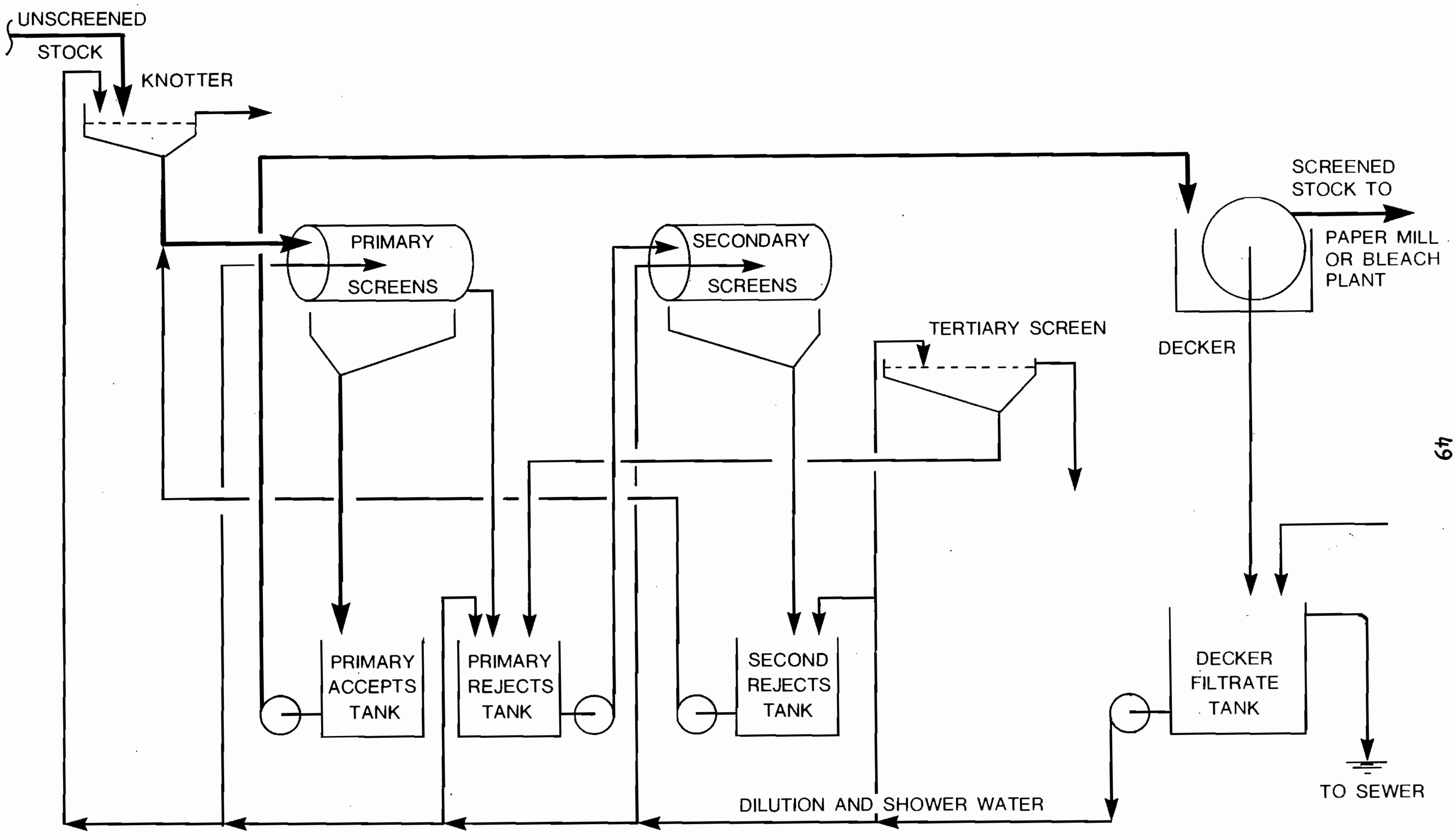
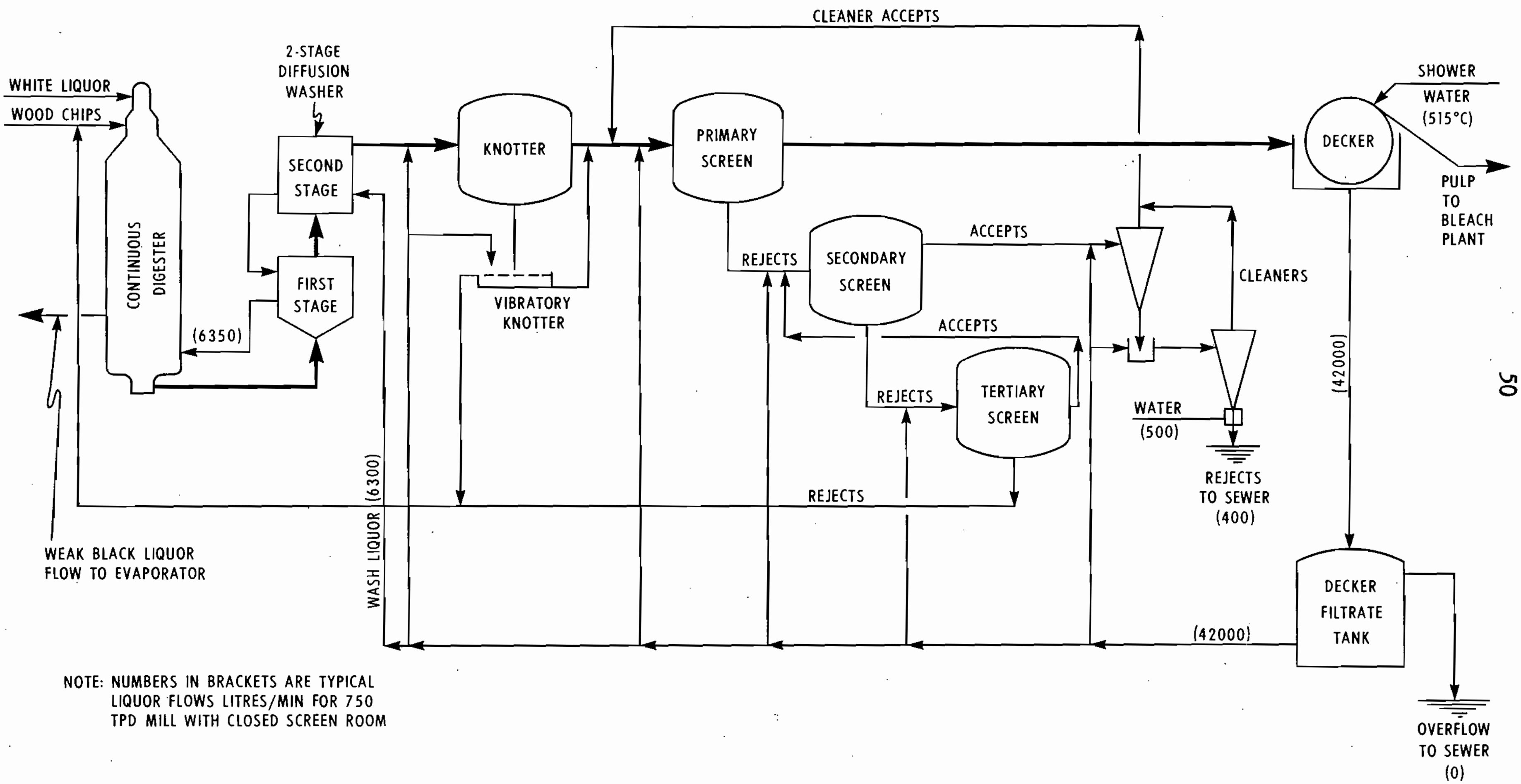


FIGURE 11 PULP WASHING AND SCREENING (Open system)



NOTE: NUMBERS IN BRACKETS ARE TYPICAL LIQUOR FLOWS LITRES/MIN FOR 750 TPD MILL WITH CLOSED SCREEN ROOM

FIGURE 12 PULP WASHING AND SCREENING (Closed System) available, and are being used increasingly for the design of new mills and optimisation studies for existing installations.

Mill design flowsheets commonly show the only exits of liquid from the washing and screening process as being with the washed pulp and the weak black liquor that goes to the evaporaters. However, the operation of a kraft screen room system without any excess water flowing to the sewer from the screening system is impractical unless all aspects of the design of the system and the equipment selection are appropriate. The principal variables are the soda loss of the last washer upstream of the screens, the wood species, and type of washing and screening equipment. The maximum acceptable unbound soda loss is 3 to 12 kg/t pulp depending on the species and equipment. The most resinous softwoods require the most efficient washing and hardwoods the least. Diffusion washers cause less air entrainment in the stock than drum type washers, so a higher soda loss can be tolerated. A higher soda loss prior to screening is tolerable with pressure screens than with centrifugal screens. With resinous woods, it is usually impracticable to operate a open rotary screening system without a continuous overflow to sewer from the decker.

Where the washing and screening system can be operated on a closed cycle, the screen room and decker become integral parts of the washing system and the effluent BOD from this area will typically be reduced by at least 60% compared to effluent from a system where substantial overflow to sewer from the decker seal tank occurs. Most existing mills with oxygen bleaching systems operate in a closed cycle, but relatively few others do.

Figure 12 is a simplified representation of a modern kraft pulping washing and screening system typical of recent installations in Canada, utilising diffusion washers and closed pressure screens and knotters. Note that the flow of decker filtrate (frequently described as unbleached white water in the literature) is large relative to the incoming shower water flow.

The key difference between open and closed screening systems is that the open screen room would have a substantial overflow from the decker filtrate tank, typically 5 - 15 m^3/t pulp. Most of the residual organic material not recovered in the pulp washers flows to sewer in this stream and is one of the major sources of BOD and toxicity in the mill effluent.

In an actual screening system several items of equipment are placed in parallel in most unit operations, and the practicalities of pumping system design and process control mandate tanks at several points.

Most existing pressure screening systems are similar in design to the traditional open screen systems to the extent that each stage discharges into a tank or chest where the necessary dilution water is added prior to pumping to the next stage. Some recent installations have eliminated most of the intermediate tanks by connecting the knotters and screens directly together, generally as shown in Figure 12. This reduces the frequency of overflows, simplifies the operation, and reduces the pumping power required.

Modern systems minimise foam generation by avoiding free falling liquid streams to the extent feasible and by avoiding the open screens and vacuum washers that lead to air entrainment. Overflows are generally connected to other tanks as appropriate, with the ultimate overflow at a controlled point, usually the decker filtrate tank.

It is generally desirable to operate the system so that there is no overflow of decker filtrate. However, a careful analysis of the complete black liquor system is required to determine the optimum method of operation of the available equipment. In a bleached kraft mill it may be more environmentally advantageous to discharge some of the screen room decker filtrate than to have the residual black liquor reach the bleach plant and be discharged in chlorinated form.

In the example in Figure 12, centrifugal cleaners are installed to remove sand and similar heavy material. This requires a discharge of liquid from the system, but the discharge of BOD and sodium salts is reduced by use of elutriation water at the secondary cleaner discharge. This allows the heavy debris collected in the cleaner to exit but only a relatively small proportion of the liquid with it is from the decker filtrate cycle.

5.3.2 Diffusion Washing Equipment. The diffuser assembly is a series of concentric double-sided screen rings approximately 500 mm apart. Each ring of the diffuser is made of two perforated plates spaced and joined approximately 50 mm apart. The screen plates are welded together top and bottom to form a hollow shell with a drainage channel at the lower end. The screen assembly, made up of several rings of screen plates, is interconnected and supported by radial drainage arms as shown in Figures 13 and 14.

High consistency pulp enters the conical bottom of the unit and passes slowly upwards through the diffuser(s). There may be one to three in series, installed vertically above one another.

The washing medium is introduced into the pulp through rotating distribution nozzles. The nozzles rotate at approximately 7.5 rpm. Passing between the screen rings, the discharge from the nozzles leaves a path of washing medium in the pulp. The wash

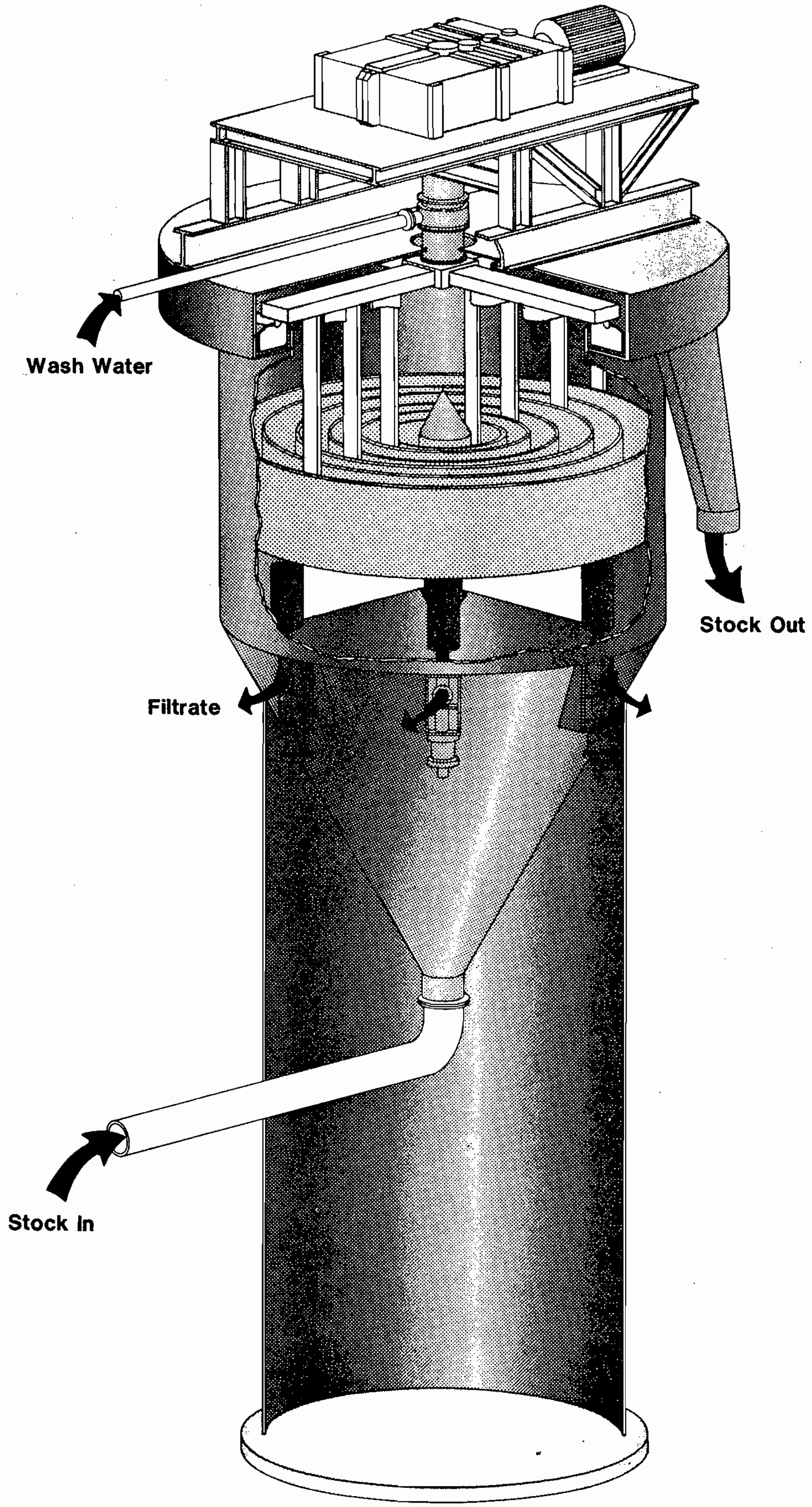


FIGURE 13 SINGLE-STAGE DIFFUSION WASHER (Kamyr)

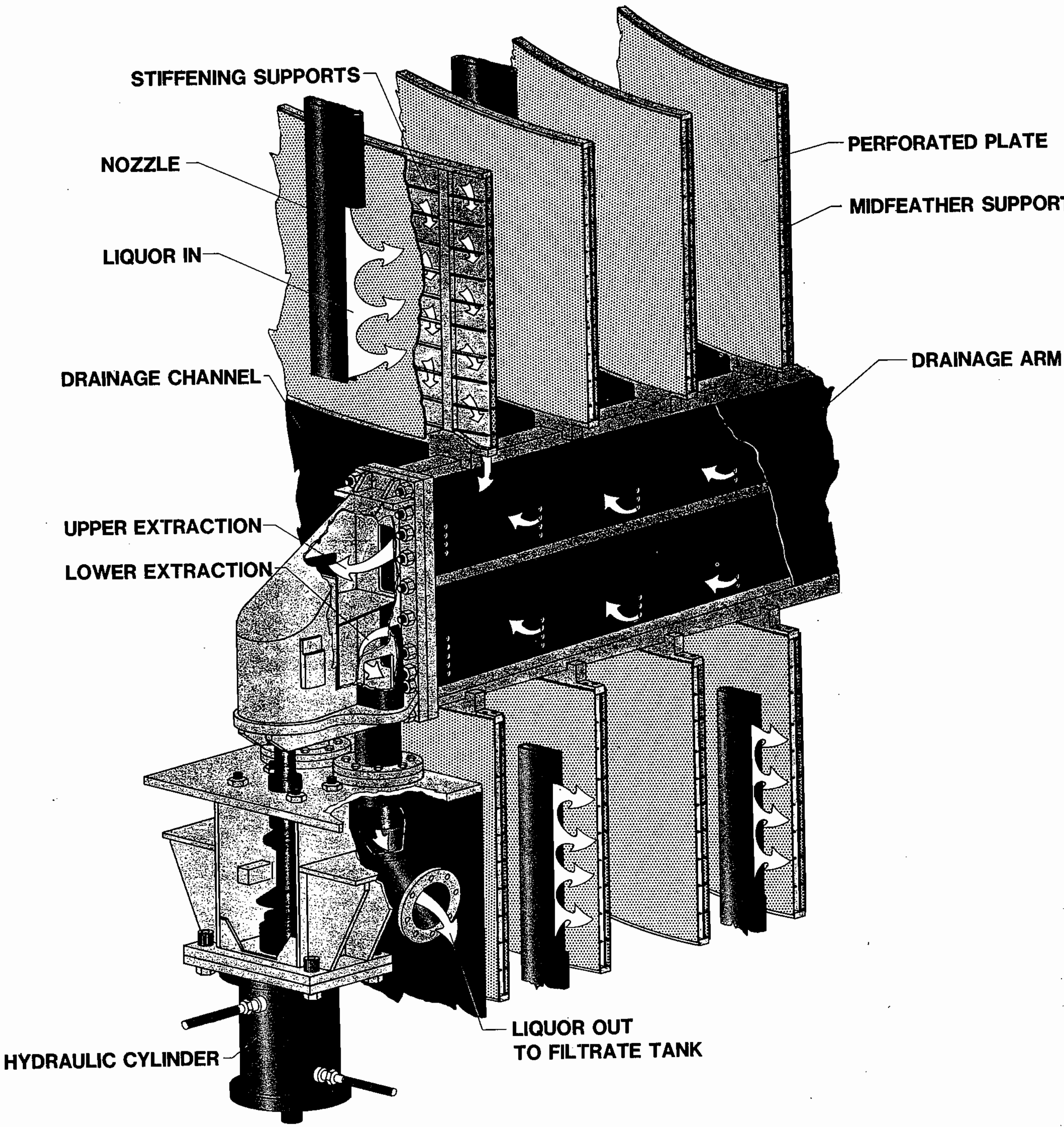


FIGURE 14 INTERNAL MECHANISM OF TWO-STAGE DIFFUSION WASHER (Kamyr)

liquor then rapidly displaces the liquor in the pulp both outwardly and inwardly to the nearest screen ring.

Displaced liquor, collected through the screen rings, flows into the drainage channel, then into the radial drainage arms and from there it is directed into the collecting headers outside the tower shell. It then flows into a small filtrate tank to be pumped to the preceeding washing stage. The washed pulp is discharged at the top of the diffuser tank by means of a scraper which moves the pulp horizontally to a pulp collection launder ring.

During the operation the whole diffuser screen assembly is moving up and down in the pulp. Automatically operated hydraulic cylinders lift the screen assembly at a speed which slightly exceeds the upward velocity of the pulp through the tower. At the end of the lift, the screen assembly is moved rapidly downwards. This latter movement between the screen unit and the pulp keeps the plate perforations wiped free of fibres. This cycle is continually repeated, with an upstroke duration of approximately one minute, and less than one second for the downstroke.

A feature of diffusion washing is that the pulp remains at about 10% consistency throughout the washing process, eliminating the high flows of recycled filtrate which are required in the traditional drum washing system, decreasing pumping power and substantially reducing the volume of potential overflows.

The multi-stage diffusion washer system is also used in a few cases to wash batch digester produced pulp. Stock from the batch digester blow tank is pumped to the inlet of the diffuser tower. The pulp is thickened to approximately 8 to 9% consistency with the first diffuser. The subsequent washing stages operate as previously described.

5.3.3 Pressure Diffusion Washer. The recently introduced pressure diffusion washer is a variation of the conventional diffusion washers described above. The washing performance is similar to the diffusion washer, but the quoted prices are lower and installation is simpler, so that the pressure diffusion washer appears to have the potential to allow mills to improve washing efficiencies at lower cost that in the past (42).

The washer is shown in Figure 15. From ground elevation to the top of the hydraulic system the approximate dimension of a 500 tonne unit is 1.5 m diameter and 11 m high. It is quite small relative to traditional designs, and lends itself to shop fabrication, which reduces total installed costs.

The washing equipment is contained within a pressure vessel, which is designed to withstand full digester pressure, although it normally operates at lower pressures. The

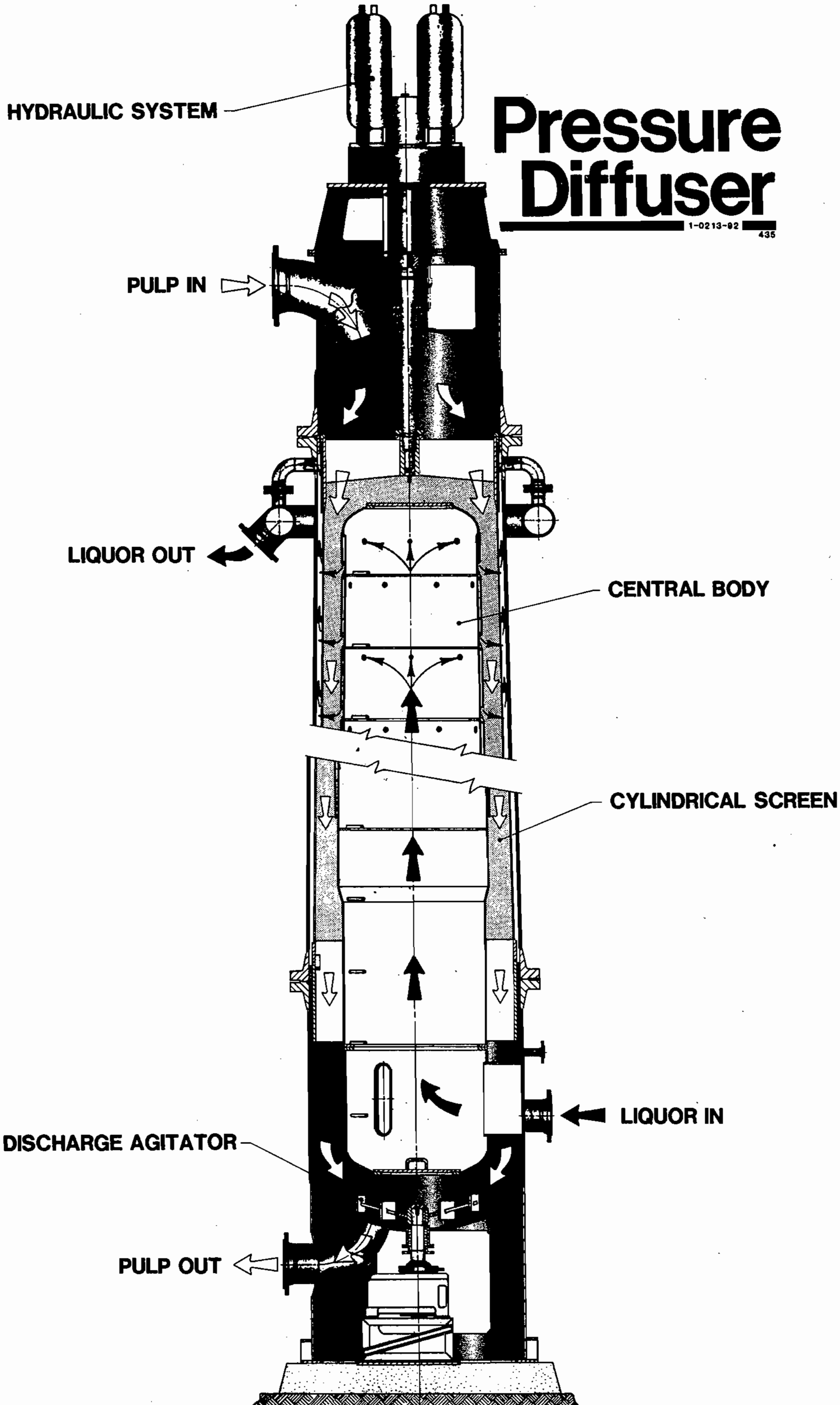


FIGURE 15 PRESSURE DIFFUSION WASHER

pulp, at a consistency of 10 to 12%, enters the top of the pressure diffuser and moves downward as a mat between the stationary central body, and the moving perforated cylindrical screen and is removed at the bottom of the vessel.

The central body is supported at the bottom by three supports, one of which is utilised to introduce the wash medium. This wash medium, at a pressure of about 100 kPa higher than the operating pressure of the machine, flows from the central body, through the pulp mat, through the moving cylindrical screen, and is extracted continuously from the pressure diffuser through an extraction header.

The cylindrical, slightly tapered stainless steel screen moves downwards together with the pulp flow. A single hydraulic cylinder supplies the power to move the screen downward at a speed consistent with the pulp flow and then rapidly upwards. The fast upstroke of the tapered screen clears the opening to prevent plugging.

The pressure diffuser allows control of the pulp stream temperature by indirect heating or cooling of the wash medium, if required.

5.3.4 Pressure Drum Washers. Many pressurised drum pulp washers have been installed since the early 1950's in various kinds of pulp mills, mostly in Europe. Use of pressure instead of vacuum has made multi-stage washing on a single drum possible, and the totally closed design allows washing in a hot environment, improving filtration properties of the pulp and reducing the volume of liquor to be evaporated. Typical six-stage, two- or three-drum pressure washing lines are reported to have a total Norden "E" factor of 9-12 complete cycles of pulp mixing with wash water and dewatering to the original consistency.

The total vent gas volume is very much lower than for vacuum drum washers, facilitating collection and incineration for odour control.

5.3.5 Flat Belt Washer. Ontario Paper Company and Georgia Pacific Company have independently developed flat belt washers for pulp washing. They have been used in several mills to date, reportedly successfully. They appear to offer advantages with respect to minimal foam generation and low volumes of malodourous gases requiring incineration that are comparable to those mentioned previously for the diffusion washers.

Flat belt washers are designed as a Fourdrinier-type, multi-stage, counter-current, enclosed machines. Figure 16 shows a five-stage washer. For illustration purposes, each separate washing stage is shown with one suction box but several are ordinarily used in practice.

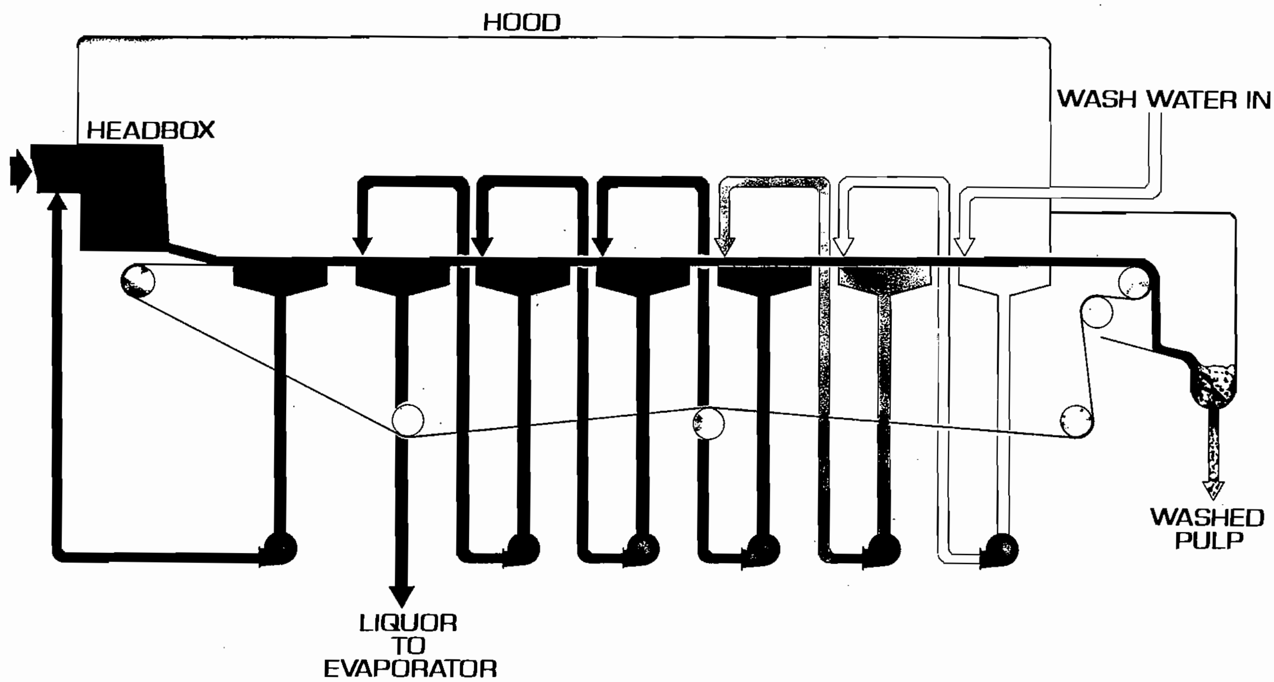


FIGURE 16 FLAT BELT WASHER SCHEMATIC (Black Clawson)

Pulp is pumped into the gravity feed headbox for distribution between the deckles, onto the forming fabric. The consistency of the stock entering the headbox is more dependent upon the equipment that precedes the washer than on any requirement of the washer itself. Thus, either screened or unscreened pulp can be washed at the washer inlet consistencies of approximately 1.0% - 4.0%.

An endless fabric transports the pulp from the headbox to the discharge end of the machine. Suction boxes which collect the liquid displaced through the pulp are located immediately under the wire, from the headbox to the discharge end. The area between the headbox and the first shower dewaters the pulp from inlet consistency up to displacement consistency, which is about 10 - 12%.

Once the pulp mat is formed it is not rediluted to inlet consistency again, as would be the case in traditional drum washers. The pulp mat passes under the series of showers where the filtrate from the succeeding washing stage flows onto the mat.

The filtrate pumps are controlled to maintain the liquor level in the suction box a few centimetres below the pulp mat, so that there is little opportunity for free falling black liquor to entrain air.

A pressure of about 50 kPa is maintained by the recycle of air and water vapour by a blower, eliminating the need for the vacuum drop leg found in traditional drum washers.

Flat belt washers are discussed in more detail in references 43, 44 and 45.

5.4 Sulphite Pulp Washing and Screening

The principles and practical limitations of washing and screening sulphite pulp are very similar to the foregoing discussions on kraft washing. However, in the case of sulphite mills without chemical recovery systems or by-product manufacture, there is no advantage in attempting to wash efficiently with minimal amounts of water. The normal practice in such cases is to wash on simple equipment with relatively large amounts of water. Most mills manufacturing spent sulphite liquor by-products have an excess of liquor solids available, so the normal practice is to extract the strongest liquor from the digester or blow pit, and then wash the pulp as if there were no recovery.

In the case of sulphite mills which desire to recover a high proportion of the spent liquor solids, equipment similar to that described above for kraft is used. However, the washing efficiencies are lower for sulphite, partly due to the high cost of the stainless steel washers and equipment required, which limits the number of stages. Even when the sulphite mill washing system efficiency is relatively low, it is not a major contributor to the total mill effluent BOD, since the evaporator condensates are much more significant than kraft condensates. Some of the sulphite mills with chemical recovery systems also manufacture dissolving grades of pulp, so that the bleach plant BOD is also very high. Dissolving grade mills also have to discharge raycells and resinous material from the screen area, further adding to the BOD, and making a closed-cycle screening operation of the type discussed above for kraft impractical.

To summarise, the opportunities for in-plant BOD and toxicity control in sulphite mill washing and screening departments are very limited compared to kraft mills.

5.5 Washing and Screening Neutral Sulphite Semichemical Pulp

NSSC pulp is normally washed by pressing out the liquor with high pressure screw presses and screened in a closed-cycle screening system. The obstacles discussed above concerning recycle, foam, etc. are generally easily overcome in NSSC pulp.

6 BLEACHING OF PULP

6.1 General

Chemical pulps are usually bleached immediately after the washing stages described in Section 5 in a continuous bleach plant installed adjacent to the pulp mill. About 70% of the kraft pulp and 20% of the sulphite pulp produced in Canada is bleached. The conventional bleaching process is the source of about half the BOD, most of the colour and much of the toxicity in the effluent from a typical bleached kraft mill, but are relatively less significant factors in paper grade sulphite mill effluents. Bleaching dissolving grades of sulphite pulp generates relatively large BOD discharges. The bleach plant effluent normally contains very little suspended solids and it is often routed directly to secondary effluent treatment facilities, by-passing the primary treatment system.

Mechanical pulp is now bleached more frequently than in the past, but this has significantly less environmental significance than bleaching chemical pulp, and is discussed separately in Section 6.5. The following discussion refers primarily to bleaching kraft market pulp, which is by far the predominant application of bleaching in the Canadian pulp and paper industry. The basic technology of the various bleaching processes are described in reference 6 and it is assumed that the reader is familiar with them. Detailed information is provided in reference 46.

Oxygen bleaching, or delignification, has been used in place of chlorine in the first bleaching stage in many mills, mostly in Europe and the U.S., and it is debatable whether it should be considered bleaching or pulping. All variations of oxygen delignification are discussed in this section.

The following abbreviations are widely used in discussing bleaching sequences, and have been adopted in this report.

C Chlorination stage, where pulp is treated with gaseous chlorine, primarily to oxidize and chlorinate the residual lignin so that it can later be dissolved out in hot alkali.

E Caustic Extraction; dissolution of reaction products with sodium hydroxide.

O Treatment of pulp with elemental oxygen, in alkaline conditions.

D Reaction with chlorine dioxide, applied as an aqueous solution.

C_d Chlorination with small, usually 10%, replacement with equivalent chlorine dioxide.

D_c Sequential addition of chlorine dioxide and chlorine in the same bleaching stage; implies greater than 10% chlorine dioxide substitution.

H Reaction with sodium or calcium hypochlorite.

P Reaction with hydrogen peroxide.

Subscripts 1,2, etc. are frequently used to indicate first, second, etc. (e.g., E_1, E_2). The subscript "g", refers to gaseous applications.

6.2 Chlorine-Based Bleaching Sequences

Most of the chemical pulp bleached in Canada is processed by CEDED, CEHDED or similar sequences. This process became established in the 1950s and has been the subject of extensive research into the sources of environmental contaminants and potential mitigative measures.

The efficiency of the pulp washing stages that preceed the bleach plant often have as much impact on the bleach plant effluent characteristics as the bleaching process itself. Essentially, all residual lignin that is not removed from the pulp by the washing system will be discharged with the bleach plant effluent, usually in a chlorinated form which is normally even less environmentally desirable than the lignin itself. Effective brownstock washing is a prerequisite to action in the bleach plant itself to minimise effluent discharges, and any analysis of data concerning such effluents must take into account the lignin content of the unbleached pulp.

6.2.1 Effluent Flow. Although there are no regulations limiting the volume of flow of effluent from bleach plants, it is generally environmentally desirable to minimise the flows, as a significant part of the cost of treating the effluent is directly proportional to its flow. The BOD removal efficiency of conventional effluent treatment plants is normally somewhat higher when treating the more concentrated discharge that results from low effluent flows. However, since the toxicity of a pulp mill effluent is effectively defined in terms of the concentration of the toxic elements in it, reducing effluent flow usually increases the measured toxicity, although the mass flow of toxic chemicals to the environment may not change.

All the water used in the bleaching process has to be heated to the operating temperature (30 to 75°C, depending on the stage), so that any decrease in water use normally reduces bleach plant steam consumption. Since bleach plant effluents are not normally used elsewhere in the mill, any decrease in water input to the bleaching process is normally accompanied by a corresponding decrease in effluent flow.

In the 1960s, bleach plant effluent flow was typically about 100 m^3/tonne pulp, but this has been decreased in many operating mills by various process modifications; some mills use as little as 25 m^3/t. The reductions in effluent flows have been accomplished primarily by countercurrent washing, which is the recycle of filtrate from one washing stage to one of the preceding stages. The concept is very simple, but there are a number of constraints on the extent to which filtrate re-use can be implemented, particularly in older mills, although solutions have been developed to many of the problems.

Corrosion is the most general problem in older installations, since recycle raises the temperatures and most of the chemical concentrations. The pH may also be lowered, which tends to accelerate corrosion, but judicious selection of the filtrate recycle design can mitigate this to a large extent. Very high molybdenum stainless steels, titanium, or plastics have been used in many recently installed bleach plants for virtually all wetted parts to minimise maintenance and to allow higher chloride concentrations. The metallurgy in some older plants has been upgraded, but capital costs can be relatively high. Chloride concentrations up to about 6000 mg/L are considered acceptable in some mills, which theoretically corresponds to effluent flows lower than 20 m^3/t, indicating that chloride concentration, in itself, is not yet an absolute limit on effluent recycle in bleach plants. Where titanium has been used for chlorination washers and other critical parts, it has been successful in reducing mill maintenance costs, and chloride concentration is eliminated as a constraint on filtrate recycle, although the capital cost is substantial. References 47 and 48, which discuss the closed-cycle kraft mill, include further information on corrosion problems and solutions in systems with very low effluent flow.

The temperature in the chlorination stage has traditionally been a major constraint on filtrate recycle. Since the following stages must operate at temperatures around 70°C, recycled filtrate from them would be at a similar temperature. The temperature of the pulp entering the chlorination stage would be over 50°C in many cases, so it was common practice to use cold water as stock dilution to limit the chlorination temperature to about 30°C to avoid fibre degradation. However, the successful introduction of new equipment and developments in process knowledge make dilution no longer necessary and many mills now operate successfully with temperatures up to about 70°C in the chlorination stage. The principal innovations that have made this change possible are improved mixing equipment to diffuse the gaseous chlorine rapidly through the pulp slurry and the use of optical instruments to estimate the degree of chlorination, facilitating effective feedback control of the chlorine addition rate. Improved instrumentation which regulates the mass flow and consistency of the pulp entering the chlorination stage is also helpful in attaining the precise control of the the degree of chlorination necessary for successful operation at high temperatures.

As well as decreasing effluent flow, the operation of the chlorination stage at high temperature decreases the amount of steam required to heat the pulp in the subsequent extraction stage.

In many bleach plants the instrumentation, seal tank and piping systems are not designed to facilitate effective filtrate recycle, so that operators are forced to maintain continuous overflows from each seal tank to avoid instability in the system. Careful attention to these points in the initial mill design is essential to attain optimum operation, but most existing mills can readily be upgraded to approach the optimum in this respect.

The foregoing discussion on lowering bleach plant effluent flows refers to conventional drum washer systems, and is applicable to the modification of existing plants as well as the design of new ones. Displacement bleaching, discussed in Section 6.3, is a completely different approach, which allows lower effluent flows.

6.2.2 BOD. The BOD of bleach plant effluent depends primarily on how much of the unbleached pulp must be dissolved to attain the desired brightness. For typical softwood plants bleaching to a brightness of about 90 Elrepho for market pulp grades, about 7% of the original pulp is extracted and discharged to sewer. This loss of pulp, expressed as a percentage of oven dry pulp, is generally known as shrinkage. The shrinkage with hardwood pulps is normally a few percent lower.

If the pulp entering the bleach plant is not effectively washed, the residual black liquor will be removed by the bleaching equipment, substantially increasing the BOD apparently originating in the bleach plant. The lignin in the residual black liquor will react with the chlorine, consuming substantial quantities of it, increasing bleaching chemical cost and increasing the concentration of chlorinated lignins in the effluent. The latter has an undesirable effect on effluent toxicity, as discussed in Section 6.2.3.

Assuming that the pulp is adequately washed, a range of possible trade-offs remain between the degree of delignification attained in cooking and that in bleaching, and mills that cook the pulp to lower kappa numbers (signifying lower residual lignin content) will have lower bleach plant BOD discharges. However, in practice the range of possible variation in kappa number is limited, so that bleach plant effluent BOD is normally in the range of 15 to 25 kg/t pulp, and in any one mill the decrease in bleach plant effluent BOD attainable by manipulation of the unbleached kappa number is limited to a few kg BOD/t.

6.2.3 Toxicity. The bleach plant is the principal source of effluent toxicity in most bleached kraft mills, provided that the unbleached pulp washers and the chemical recovery system are performing adequately. Where there are high losses of black liquor solids in the pulping and recovery areas, the bleach plant will be a major, but not predominant, source of the total mill effluent toxicity.

A number of mills have modified the bleaching sequence to substitute chlorine dioxide for some of the chlorine in the chlorination stage, to decrease the effluent toxicity. The degree of substitution practiced varies from a few percent to 70%, with the higher values being used where the maximum attainable decrease in toxicity is required. The use of around 10% chlorine equivalent is commonly referred to as low substitution and it is generally accepted that effluent toxicity, BOD and colour are improved when a small proportion of the chlorine is replaced by chlorine dioxide.

With respect to higher substitution of chlorine, the literature abounds with conflicting data on the efficacy of toxicity removal attained by this process modification. At least one Canadian market kraft mill using high chlorine dioxide substitution has reported compliance with federal toxicity regulations without biological treatment of the effluent. It is generally agreed that there is some improvement, but the degree of toxicity removal reported varies from negligible to substantial. In most cases, there is a chemical cost increase associated with the substitution of chlorine by chlorine dioxide which can vary from a few cents to several dollars per tonne pulp depending on local chemical prices and, more significantly, the overall mill chemical balance. A capital cost is also involved in the installation of sufficient chlorine dioxide generation capacity. However, there are also some advantages in terms of decreased shrinkage and improved pulp quality, in addition to the obvious potential savings in effluent treatment costs.

Interpretation of the data in the literature is complicated by the variety of mill configurations and battery limits evaluated, as well as by the inherent variability of the toxicity test itself. In view of the range of data and the surrounding controversy, values have been omitted from this section and the reader is invited to consult the literature (49,50,51,52,53,54).

The increased hypo bleaching sequence modifications discussed in Section 6.2.4 are also reported to have some beneficial effects on effluent toxicity.

6.2.4 Colour. Assuming that the brown stock washing and black liquor recovery systems are operating properly, with reasonably low losses of black liquor solids, the first E (caustic extraction) stage of the conventional chlorine-based bleach plant is by far the most significant source of colour in the mill effluent, as indicated in Table 13. The data are based on reference 55, and are typical for the Canadian industry. The units used are American Public Health Association (APHA) chloroplatinate units, so the kg/t represents an abstract quantity which is the best way of defining the total quantity of colour material discharged.

TABLE 13 SOURCES OF BLEACH PLANT EFFLUENT COLOUR

Stage	Softwood (kg/t pulp)	Hardwood (kg/t pulp)
C	50	26
E	226	78
D	11	6
E	6	4
D	1	1
Total	294	115

It is clear that the E stage is the most significant, and that any in-plant modifications to reduce the mill effluent colour must modify or eliminate this stream. The few external treatment processes for effluent colour are mostly based on segregation and treatment of this stream.

A number of chlorine-based bleaching sequences have been developed in research laboratories which decrease effluent colour, and to some extent toxicity and BOD (49,53,54,55,56,57,58,59,60). In most cases they involve some penalty in operating cost and/or pulp quality, but they have been judged more cost-effective than external colour removal systems by several U.S. mills. They are based on the use of sodium hypochlorite to replace some or all of the sodium hydroxide in the extraction stage, and usually use a high degree of chlorine dioxide substitution in the first stage of the bleaching process.

Several external effluent treatment techniques have been developed to decrease the colour in bleach kraft mill effluents (55).

6.2.5 Mutagenicity. A number of recent publications have discussed the mutagenic activity of bleach plant effluents (59,61,62,63). It is generally agreed that only the chlorination-stage effluents are mutagenic, as determined by the Ames test, but it is not yet clear whether this has any significant effects on the environment or human health.

It has been suggested by Rapson (63) and others that substitution of the chlorine by chlorine dioxide eliminates mutagenicity, and several workers have shown that raising the effluent pH to about 10 is also effective. Lesser increments in pH are beneficial, but not completely effective.

No references were found to any mutagenetic effects of bleach plant effluent on humans, nor were any found concerning any full-scale treatment measures taken by any mills. Research in the field is continuing and further data will become available during the 1980's.

6.2.6 Chlorinated Organic Compounds. A number of publications have been issued on the content of chlorinated organic compounds in bleach plant effluents, particularly with respect to chlorinated phenols (52,62,64). The lower molecular weight (under 1000) chlorinated organic compounds are reportedly acutely toxic to fish according to the types of functional groups and the degree of chlorine substitution on the aromatic ring. They can also cause tainting of fish flesh and are resistant to conventional biological treatment processes.

Compounds identified thus far account for only a small fraction (less than 2%) of the total organically bound chlorine. Typical quantities of chlorinated organic compounds in bleach plant effluents are 3-8 kg/t pulp. Biological treatment decreases this, but some compounds (such as chlorinated guaiacols) are unaffected.

6.2.7 Sulphur Dioxide Treatment of Chlorination Effluent. The effluent from the bleach plant chlorination stage is one of the principal sources of toxicity to fish in most bleached kraft pulp mills. It has been shown that if residual chlorine is stripped from chlorination stage effluent, the pH is raised to 5.5 and about 0.02% sulphur dioxide is added, the effluent toxicity will be substantially decreased or eliminated. The work performed indicates that the performance of this treatment process varies between mills and wood species, as with most effluent treatment processes, and that it is essential that the unbleached pulp be washed effectively prior to bleaching. This process was used successfully for a short time in the 1960's, and has received renewed attention in research recently (60,65,66).

6.3 Displacement Bleaching

In 1964 Rapson and Anderson of the University of Toronto proposed that pulp be bleached by diffusing chemical solutions through a pulp mat at a consistency of about

10%, instead of using the traditional reaction towers. Their papers and patent were entitled "Dynamic Bleaching", and the term is still used by some authors. Although they were able to demonstrate the technical feasibility of this on a laboratory scale, it was not until the early 1970's that Kamyr developed practical equipment for commercial production. By 1976 the process, now known as displacement bleaching, was operating in three mills and had demonstrated its ability to bleach pulp with very low water consumption, and hence very low effluent flows.

Most of the bleaching process is carried out in a single displacement bleaching tower, decreasing water consumption by eliminating interstage dilution and substantially reducing bleach plant space requirements. About a dozen such plants are operating, but none in Canada.

Displacement bleaching is, in effect, an equipment variation on the conventional process in that it does not produce any decrease in BOD, COD, colour or organic discharge, although it renders the effluent more manageable by reducing the volumes substantially. Effluent volumes as low as 10 m^3/t have been reported, but most dynamic bleach plants discharge about 15 m^3 effluent per tonne of pulp.

In addition to facilitating conventional biological treatment of the effluent, the low flows common in displacement bleach plants are well adapted to the requirements of the Rapson closed-cycle mill concept discussed in Section 9.

A modern CEDED displacement bleach plant is shown in Figure 17. Unbleached pulp from the decker is diluted with chlorination filtrate and is pumped through mixers into the displacement bleaching tower. Gaseous chlorine and chlorine dioxide solution are added to the pulp in the mixers. As the chlorinated pulp moves into and up the tower and passes through the lower set of concentric diffuser screens, chlorination filtrate is extracted and displaced by a caustic solution.

A series of concentric screens at each diffuser level, similar to those in the diffusion washers in Figures 13 and 14, are connected by a structure which carries the filtrate out of the tower to a filtrate tank. Three hydraulic cylinders drive each diffuser and are attached to the outside of the tower. They drive the diffuser upward for about 70 seconds, pause for about 5 seconds while a back-flush system cleans the fibres off the screen plates, and then return rapidly to the original position. This cycle is continuous and automatically repeated. A central vertical shaft turns inside the tower, with hollow horizontal arms attached at each diffuser level carrying nozzles which move between each pair of concentric screens. Fresh chemical solution is pumped into the top of the shaft and then flows into the pulp through the nozzles at the appropriate level.

TYPICAL DISPLACEMENT BLEACHING INSTALLATION WITH FIVE BLEACH STAGES IN ONE TOWER C-E-D-E-D

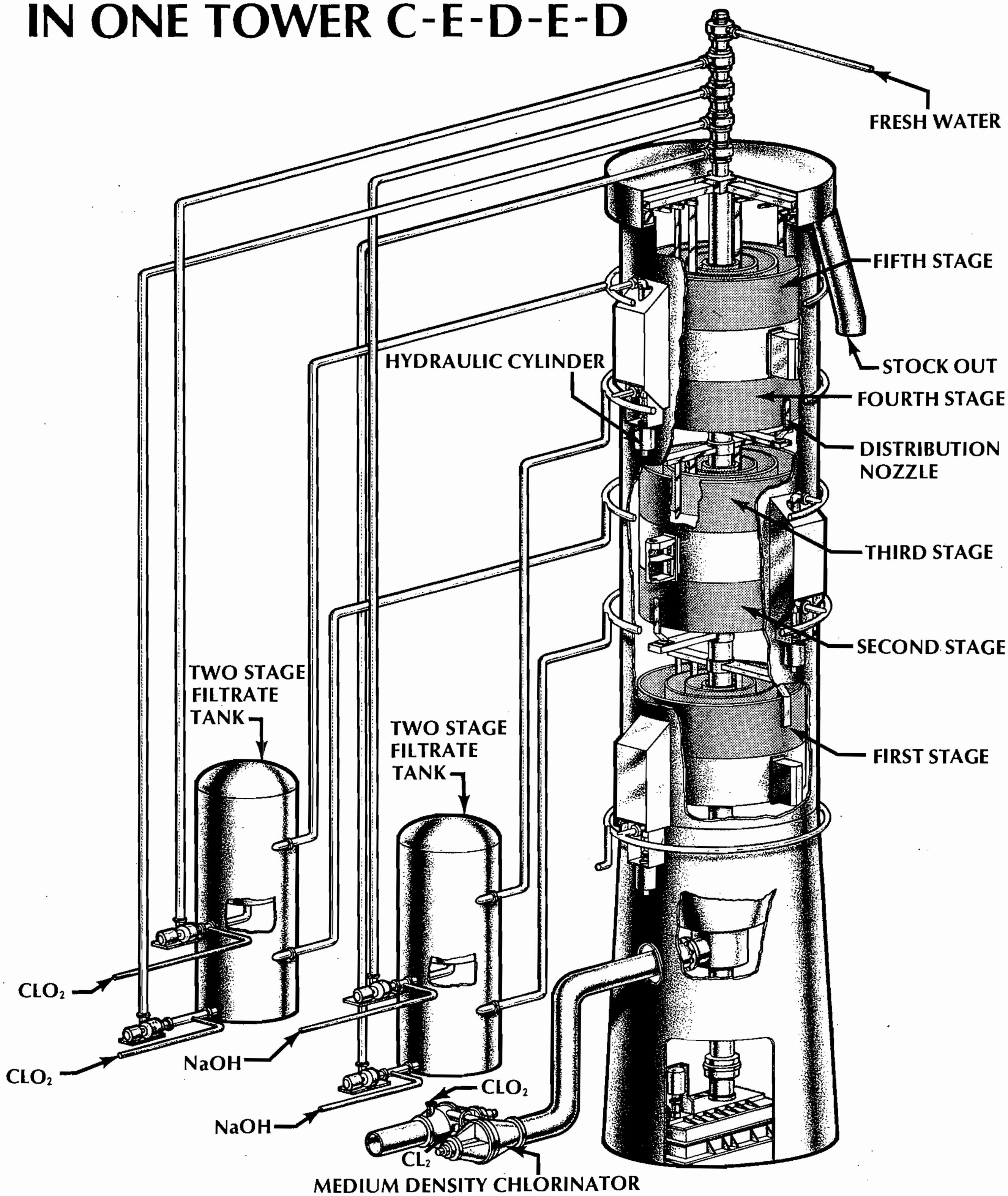


FIGURE 17 DISPLACEMENT BLEACHING SYSTEM (KAMYR)

As the stock passes upward between the screen rings, the solution contained in the stock is displaced by the incoming liquor, through the diffuser screens, to an external header and then flows to the filtrate tank. Rotating nozzles introduce chlorine dioxide solution at rates that maintain about 10% stock consistency. As the caustic impregnated stock moves up through the tower it reaches the second diffuser.

The D_1 bleaching stage starts with chlorine dioxide solution displacing E_1 filtrate in the second diffuser and ends when the solution is extracted at the concentric screen plates at the third diffuser (the second E stage), where sodium hydroxide solution displaces the chlorine dioxide. In the fourth diffuser chlorine dioxide solution displaces the E_2 stage filtrate.

The stock continues its upward flow to the fifth diffuser where the used D_2 solution is displaced by hot wash water which is pumped through the top set of nozzles. Retention time in each stage at design rate is 10 to 15 minutes. E_2 and D_2 extraction screens are combined to form a double diffuser assembly similar to the E_1 and D_1 screens.

Extraction filtrate from each stage is collected in pipes which circle the bleaching tower at each diffuser screen level. The filtrate flows from these circular collection pipes to small individual filtrate tanks.

A scraper unit is attached to the central rotating shaft at the top of the tower to move the bleached pulp into a launder ring where it drops down to a thick stock pump which transfers it to the bleached high density tanks.

Some of the early installations utilised a traditional low consistency reaction tower for chlorination, due to unknown factors concerning the behaviour of gaseous chlorine in the displacement bleach tower. However, the current installations incorporate a medium consistency chlorination stage in the displacement tower along with the other stages. Some of the more recent systems are installed in two towers to provide increased retention time for the last chlorine dioxide stage to bleach to very high brightness levels, particularly for market pulp.

Several of the well known bleaching sequences have been installed in displacement bleach plants, including those using sequential chlorine dioxide/chlorine addition. At least one displacement bleach plant follows an oxygen delignification stage.

Displacement bleaching equipment constructed of titanium and employing fully countercurrent washing is compatible with the closed-cycle mill concept and is discussed in Section 9. The high chemical concentrations which result from the low water consumption would cause severe corrosion if traditional materials of construction were used. The initial corrosion and/or fatigue problems in some of the early plants seem to have been overcome by the use of titanium for most of the wetted parts, in conjunction with an acid-resistant brick-lined tower. This results in relatively high equipment cost, but there are substantial savings in auxiliary equipment and building costs compared with a traditional drum washing system. The initial mechanical problems in displacement bleach plants have been solved as operating experience has increased.

6.4 Oxygen Bleaching

Prior to 1970, virtually all chemical pulp bleach plants were based on the use of chlorine and chlorine compounds. However, since the early 1970's, oxygen has partially replaced chlorine in many new European mills, as well as in a few U.S. mills and one Canadian mill.

The principal reason for the installation of most oxygen bleach systems is to decrease the chloride content of the wastewaters. The oxygen filtrate can be recycled to the chemical recovery system in most cases, thus permitting incineration of the organic compounds that give rise to much of the BOD, toxicity and colour of bleach plant effluents. Since the raw effluent from systems using oxygen is generally more contaminated than chlorination bleaching effluent, significant environmental benefits are realised only if the filtrate from the oxygen stage is recycled to the chemical recovery system. It is not to customary to install a salt removal process where recycle of oxygen filtrate is practiced.

6.4.1 High Consistency Oxygen Delignification. Oxygen delignification refers to the use of oxygen to lower the kappa number of the unbleached pulp prior to its entry to a conventional chlorine-based bleach process. This has been practiced in about 25 mills worldwide, including one mill in Canada that has separate systems for hardwood and softwood. The term oxygen bleaching is frequently used synonymously with oxygen delignification.

In most oxygen delignification systems the washed, unbleached pulp is dewatered to 25 - 30% consistency in a press and fed to a pressurised reactor where gaseous oxygen is introduced. Sodium hydroxide is added to the pulp to control the end pH to about 10, and about 4 kg magnesium salt per tonne of pulp is also added to control the tendency of oxygen to attack the cellulose fibres. The reactor is a pressure vessel with an internal fluffer and/or agitator to disperse the high consistency pulp to ensure even contact with oxygen. The oxygen is fed to the reactor directly, and a small bleed to atmosphere is maintained to purge air, along with small quantities of carbon monoxide and volatile organic compounds. After discharge from the reactor, the pulp is washed, either on a drum washer or a diffusion washer, in a similar manner to that used for the unbleached stock from the digester. The filtrate from this washing stage contains about 50% of the BOD, toxic material and coloured material that would be discharged from a conventional chlorine-based bleach plant. The actual quantities depend on the amount of delignification attained in the oxygen reactor, but typical values are 7 kg BOD/t and 40 kg colour/t pulp.

Some work has indicated that the colour content of an oxygen bleach stage effluent is higher than an equivalent chlorine stage. This is of little environmental significance, provided that the oxygen stage filtrate is all recycled to the recovery furnace.

Some of the filtrate from the oxygen stage washer is reused for pulp dilution in the oxygen stage itself, and the excess must be recycled to the brownstock washing system if the potential environmental advantages of oxygen bleaching are to be realised. This is routine practice in mills using oxygen delignification stages preceeding all chlorine-based bleaching.

Pulp washing to a soda loss of below 12 kg sodium sulphate per tonne pulp is recommended to avoid excessive oxygen consumption and heat generation in the oxygen reactor, and to minimize strength loss. Washing to a lower soda loss value is desirable. (Note that "soda loss" is a misnomer, since the soda remaining in the pulp will eventually be recycled from the oxygen stage washers to the mill's chemical recovery system. However, the term is widely used, for historical reasons.) The pulp screening systems preceeding most oxygen delignification stages operate without any discharge of decker filtrate, and this is essential if the full environmental advantages of oxygen delignification are to be realised. Refer also to Section 5 concerning pulp washing.

The economics of oxygen bleaching depend on local prices for oxygen relative to chlorine and the chemicals for on-site manufacture of chlorine dioxide. The majority of the published data indicates that the operating costs for bleached kraft mills incorporating oxygen delignification stages are lower than for the traditional chlorine-based systems. The capital costs of oxygen delignification systems have historically exceeded those for comparable chlorine-based bleach plant mills by about $12 000 per daily tonne capacity. As experience with the operation of commercial-scale oxygen delignification systems accumulates, simpler and lower cost oxygen delignification systems may become practicable.

Oxygen delignification at high consistency (20% - 30%) is being used to produce a variety of pulp grades, and the total installed capacity is about 10 000 t/d worldwide, although few North American mills have selected this process. When oxygen delignification was introduced in the early 1970s, the effluent permit requirements pertaining to new mill construction in most parts of North America were such that a biological treatment system was necessary comply with the BOD and/or toxicity criteria, so that the environmental advantage of using the oxygen process was limited to a relatively modest marginal reduction in effluent treatment costs. Many Scandanavian mills have been permitted to operate without biological treatment systems, provided that oxygen delignification stages were installed, so it has been more economically attractive for them to do so than for North American mills.

6.4.2 Medium Consistency Oxygen Delignification. Since the first commercial scale high consistency oxygen delignification systems were commissioned in the early 1970s, there has been considerable evolutionary development, as is characteristic of any new technology. Most of this has had little effect on the environmental protection aspects of the process, but the demonstration of the feasibility of performing the delignification at medium consistency, 10% to 15%, is important in that it allows the construction of oxygen delignification systems at capital costs comparable to chlorine-based systems. This process variation is described in reference 67 and, at the time of writing, Kamyr Inc. which has supplied about 50% of the operating high consistency oxygen bleaching systems recommends the medium consistency approach.

6.4.3 Alkali/Oxygen Extraction. The use of relatively small quantities of oxygen in the conventional caustic extraction stage has been shown to have some advantages in reducing the consumption of chlorine dioxide in later bleaching stages. This has little direct impact on effluent quality, but since it decreases the input of chlorine to the system, it would facilitate the application of the Rapson-Reeve closed-cycle bleached kraft process mentioned in Section 9.

In this variation, the gaseous oxygen is mixed with the pulp and sodium hydroxide immediately prior to the caustic extraction (E) stage of a conventional CEDED or D_CEDED (or similar) bleaching process. The gas is introduced near the bottom of the extraction tower, which is typically about 20 m high, where the hydrostatic pressure is about 200 kPa, and the oxygen reacts with pulp almost immediately. The same process can also be used in the extraction stage of OCEDED bleaching sequences.

Several Canadian mills are testing alkali/oxygen extraction, and a few are installing permanent equipment for its application.

6.4.4 Bleaching Following Oxygen Delignification. The most commonly used sequence is OC_dEDED, where about half of the total delignification is accomplished in the oxygen stage, resulting in 50% of the BOD and at least 60% of the colour and toxic material in the effluent being recycled to the recovery furnace. Where the C_d stage utilises high chlorine dioxide substitution (over 20%), the effluent colour and toxicity are reported to be further decreased, as is the total chlorine content of the effluent, facilitating any recycle to the recovery furnace.

Other, simplified, sequences have been proposed, and are attaining limited commercial status, such as OD_cED where the E stage uses alkali/oxygen extraction as described in Section 6.4.3. Such "short" sequences generally have lower capital costs and lower effluent flows than the conventional sequences, but further operating experience is required to demonstrate whether or not they will be commercially successful. Speaking generally, they seem to offer potential for improvement in bleach plant effluent quality, to decrease the need for external effluent treatment, and to facilitate completely closed-cycle bleached kraft mill operation.

6.5 Bleaching of Mechanical Pulps

Most of the bleaching of mechanical pulps is based on modifying the lignin in the pulp to lower its colour, and is commonly referred to as brightening, to distinguish it from bleaching chemical pulp, which uses different processes as discussed above which remove significant amounts of lignin from the pulp.

The brightening of mechanical pulp has become widespread in the past 10 years, particularly for newsprint, for three main reasons:

- Deteriorating wood quality. The average quality of wood used for pulping has declined due to increasing costs and the need to utilise non-ideal wood sources.
- The increasing use of TMP which has a lower brightness than stone groundwood pulp due to the higher temperature used in the process. The extent of the brightness loss depends upon the temperature and pressure used.
- Some newsprint production is being converted to groundwood speciality papers which require a brighter pulp.

Bleaching is carried out using either hydrosulphite or peroxide; the choice depends upon the increase in brightness level desired.

6.5.1 Hydrosulphite Bleaching. Reduction bleaching using hydrosulphite increases brightness by 1 - 8 points, depending upon the chemical charge and the process conditions selected with essentially no loss in pulp yield. Most of the early work was done with zinc hydrosulphite but the unacceptability of discharging heavy metals to watercourses has resulted in almost a complete replacement with sodium hydrosulphite.

The sodium hydrosulphite can be purchased as a dry powder or as a refrigerated aqueous solution, or it can be generated on-site by reacting an aqueous solution of sodium borohydride with sodium bisulphite. The bleaching is performed at low consistency in either a storage chest or an upflow tower.

The important process variables are:

- The pulp brightness will increase with the amount of chemical added but it tends to level off as the hydrosulphite charge approaches 1%, based on oven dry pulp (see Figure 18).
- Pulp consistency is kept between 3 and 4% to eliminate the possibility of air entrainment which decomposes the hydrosulphite.
- The optimium pH range is between 5 and 6.5. The bleaching efficiency diminishes rapidly at pH over 7 and less sharply below optimum range.
- The feasible temperature range is 35 - 80°C, but since the reaction is time-temperature dependent, it is normal practice to bleach in the range of 50 - 70°C.
- Reaction time is usually in the range of 15 - 60 minutes and depends upon the chemical addition and the temperature. Most upflow towers are designed for a retention time of one hour.
- The addition of a chelating agent to the pulp prior to the addition of the hydrosulphite solution is becoming widespread. The purpose is to prevent any metallic contaminants, particularly iron and copper from being absorbed on the pulp because they can cause severe brightness reversion, reducing the effectiveness of the hydrosulphite addition.

The bark content of the wood fed to the pulping system has a significant effect on the response of the pulp to bleaching chemicals as shown in Figure 19.

Corrosion of iron, mild steel and copper components in the mill equipment is a major concern in hydrosulphite bleaching. The mild acid conditions used for bleaching have a minor effect but corrosion can be accelerated by the products of the reaction and decomposition of the hydrosulphite solution.

6.5.2 Peroxide Bleaching. Oxidative brightening by hydrogen peroxide produces a higher and more stable brightness than hydrosulphite brightening but it is more expensive. Brightness increases of up to 20 points or higher can be obtained. There is about 1% shrinkage in the process, generating a few kg BOD/t pulp.

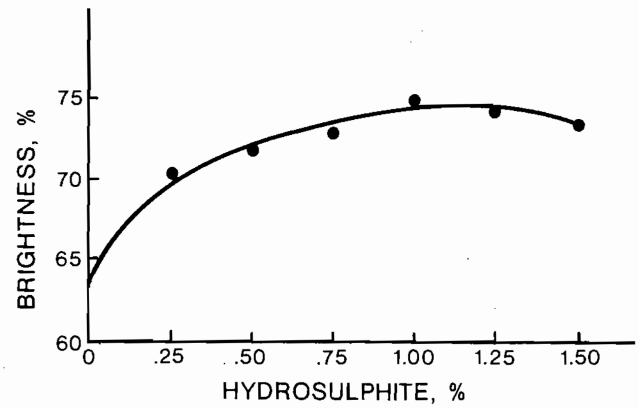


FIGURE 18 RESPONSE OF SPRUCE GROUNDWOOD TO HYDROSULPHITE BLEACHING

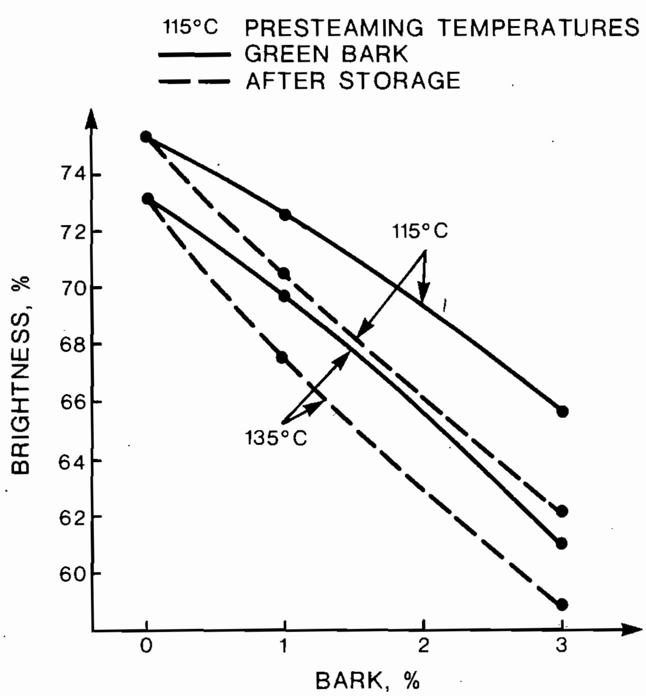


FIGURE 19 EFFECT OF BARK CONTENT ON BRIGHTNESS (Hydrosulphite)

The bleach liquor contains hydrogen peroxide, sodium silicate, sodium hydroxide and magnesium sulphate. The bleaching was formerly performed at a medium consistency of 12 - 14% but there is growing interest and activity in bleaching at consistencies between 20 - 30%.

The important process variables are:

- A chelating agent such as DTPA (diethylenetriaminepentaacetic acid) is normally added to the pulp suspension (2 - 3% consistency) before it is thickened for bleaching. The chelating agent is added to tie up the trace metals which may be present in the pulp because they can cause a decomposition of the peroxide.
- Dilute pulp slurry is thickened to the desired consistency by using either a vacuum thickener or a press.
- The thickened pulp is heated by steam to the desired temperature. 60°C can be used providing stability of the peroxide can be maintained.
- Reaction time is normally two to three hours to obtain the best results but most of the brightening is done within the first hour.
- Peroxide pulp brightness increases with an increasing charge up to a practical limit as shown in Figure 20.
- Magnesium sulphate is added to inhibit peroxide decomposition. Sodium silicate, which also serves as a buffering agent, is maintained at a constant level while the addition of sodium hydroxide varies with the peroxide charge.

The bark content of the wood fed to the pulping system has significant effect on the response of the pulp to bleaching chemicals as shown in Figure 21, but peroxide is more effective than hydrosulphite in brightening pulp containing residual bark. When high brightness is desired, a two-stage process of peroxide followed by hydrosulphite is less expensive than a single-stage peroxide.

High strength, high brightness mechanical pulps can compete successfully with bleached chemical pulp in some applications because the substantially higher pulp yield offsets the high bleaching costs.

6.5.3 Environmental Effects. The effects of bleaching mechanical pulps on mill effluents are minor compared to those of chemical pulp bleaching. BOD discharges due to hydrosulphite bleaching are negligible, and those due to oxidative bleaching are normally under about 3 kg/tonne pulp.

In principle, no suspended solids are discharged from mechanical pulp bleaching operations, but the additional pulp and white water handling equipment required

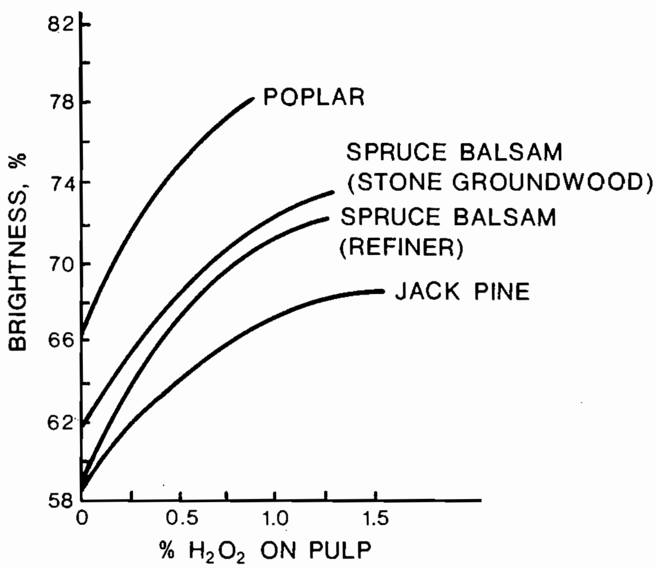


FIGURE 20 INFLUENCE OF SPECIES ON RESPONSE TO PEROXIDE BLEACHING

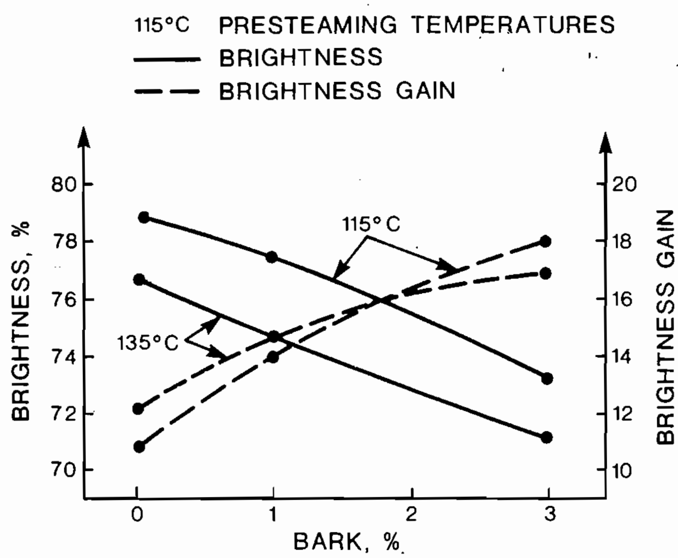


FIGURE 21 EFFECT OF BARK CONTENT ON BRIGHTNESS (Peroxide)

increases the potential for accidental discharges of stock and white water. Many of the recently installed systems include suitable spill collection equipment in the mechanical bleach plant.

7 PAPERMAKING

7.1 General

The basic processes used in papermaking have changed very little in the past 50 years, although the equipment has been developed to produce paper at ever higher speed and, usually, improved quality. The equipment described in (6) is state-of-the-art, and it is assumed that the reader is familiar with the technology discussed therein.

The papermaking area of most mills has a direct impact on mill effluent suspended solids and flow, but usually little effect on BOD or toxicity. Most Canadian paper mills are integrated with pulp mills, and the selection of furnishes and market requirements of the paper mill have a significant impact on the pulp mill effluents, particularly in the case of newsprint mills.

A high proportion of the paper machines installed in the past five years have twin wire wet ends. Many Fourdrinier machines are being converted to twin wire operation, either by complete replacement of the wet end or by the addition of an upper wire. The retention on twin wire machines is generally lower than on the more traditional designs, leading to higher consistencies in the white water circuits, which tends to increase suspended solids discharges. However, due to a combination of environmental and economic pressures, some mills discharge substantially lower flows of excess white water than in the past. This has been achieved by improvements to white water systems.

Most recent installations incorporate provisions to recover the overflows and spills from tanks and process equipment containing stock. Many older mills have installed spill protection measures to reduce suspended solids discharges.

7.2 Newsprint

About 60% of the paper manufactured in Canada is newsprint, and about half the pulp manufactured is destined for newsprint production, so market trends and equipment developments in the newsprint sector have a major effect on pulp and paper mill operations, and hence on effluents.

Since 1973 there has been a market trend towards lower basis weights in order to offset increases in postage rates and the price of the newsprint. The production of a lighter sheet requires a higher and more uniform pulp quality than traditional sheet production. In addition, there is a problem with print show-through or opacity with the lighter weight sheets. This problem is reduced by using a higher proportion of mechanical pulp than in the past. This can be achieved by replacing stone groundwood with TMP, and this is one of the reasons for the increasing use of thermomechanical pulp.

A wide range of pulping processes, and hence, of chemical and mechanical pulps, are now being used to produce newsprint. The traditional standard furnish was either 15 - 25% low-yield sulphite and 75 - 85% stone groundwood, depending upon the wood species used and the demands in the newsprint press rooms. In the 1960s, some mills began using high-yield sulphite (60 - 75% yield) and stone groundwood, and the trend has continued to the point where few mills use low yield sulphite as a newsprint furnish. This reduced the cost of wood but there was a loss in brightness and some losses in pulp quality. The most recent trend is to the use of TMP as a single furnish or as a partial replacement for stone groundwood.

The considerable variation in the composition of a newsprint furnish is illustrated by the data in Table 14. The single furnish TMP gives the highest overall yield of 94%.

Effluent BOD has been considerably reduced by these trends, but toxicity has often increased since the mill effluent flows were usually reduced when modernising and installing the higher yield pulping systems. The examples of BOD discharges for different newsprint furnishes shown in Table 14 are typical of the range currently in use. As indicated in Table 2, the use of TMP in newsprint furnish is likely to increase at least until 1986, which will further reduce the BOD discharges per tonne newsprint produced. The effect on toxicity is less clear, since it is dependent on the effluent flow. The mass of toxic material discharged per tonne newsprint is roughly constant for all variations of high-yield, CMP, CTMP, and mechanical pulp. The effluent flows from the existing TMP mills are significantly lower than from the sulphite mills they have replaced, and consideration of the current design practices indicates that flows will continue to drop, thus raising the concentrations of the effluents.

Modern newsprint paper machine departments discharge virtually no BOD and very little suspended solids, since all excess white water is routed to the mechanical and/or chemical pulp mill. Cleaner rejects, typically about 10 kg per tonne paper, are usually also recycled to the pulp mill, and eventually contribute to its effluent loadings, but they may be discharged to sewer in the paper mill, dewatered and incinerated, or landfilled.

Newsprint paper machine systems are closely integrated with their pulp mills, and should be considered as one system when studying effluent characteristics.

TABLE 14 RANGE OF NEWSPRINT FURNISHES ON VARIOUS PAPER MACHINES

Machine No	Speed (m/min)	Basis Weight (g/m²)	Efficiency (%)	Pulp Type (% of total) SGW	RMP	TMP	SCMP	LYS	HYS	SBK	BOD (kg/t)
1	1048	48.3	82	3	-	80	-	-	-	17	24
2	936	48.7	82	52	-	41	-	-	-	7	17
3	918	48.6	80	-	-	87	-	-	-	13	24
4	913	48.7	79	-	-	100	-	-	-	-	25
5	911	45.1	86	-	-	100	-	-	-	-	25
6	858	46.9	79	-	-	92	-	-	-	8	25
7	844	48.7	81	64	-	-	31	-	-	5	32
8	841	48.6	81	-	80	-	-	20	-	-	72
9	814	48.8	78	76	-	-	-	-	24	-	39
10	742	48.4	75	50	-	26	-	-	24	-	43
11	683	46.2	89	44	-	34	-	22	-	-	79
12	653	48.7	87	68	-	-	-	-	33	-	50
13	584	48.7	81	62	-	-	35	-	-	3	35
14	583	47.1	75	21	-	51	-	-	28	-	51

Notes:
SGW - Stone Groundwood
RMP - Refiner Mechanical Pulp
TMP - Thermomechanical Pulp
SCMP - Sulphonated Chemi-Mechanical Pulp
LYS - Sulphite Pulp (48% nominal yield)
HYS - High-Yield Sulphite Pulp
SBK - Semibleached Kraft Pulp
Efficiency - Paper machine efficiency; the ratio of actual production to the theoretical maximum.

BOD discharges shown assume conventional chemical recovery for kraft pulp but not for the other pulping processes, reflecting current Canadian practice.

7.3 Paper Grades Other than Newsprint

A wide variety of paper grades is manufactured in Canada. Other than newsprint, however, no single grade represents over 10% of paper production.

Many mills producing packaging grades have modified their white water systems by applying the techniques discussed in Section 7.4, reducing the effluent suspended solids substantially. Most of these mills are integrated with pulp mills and have reduced the excess white water flow sufficiently to be able to route all of it to the pulp mill without generating an overflow in the pulp mill system. In some cases, the only contaminated effluent from the mill is the spent cooking liquor which is incinerated in a recovery furnace or used as road binder. In such cases, the closure of the white water system leads to very substantial reductions of effluent BOD and toxicity, as well as of suspended solids. Some of the packaging grade paper mills have also installed conventional effluent treatment facilities, while others comply with the regulations by in-plant measures alone.

The other principal types of paper produced are printing and writing grades. While many of these mills have improved their white water systems and segregated uncontaminated effluents, most of those that comply completely with effluent suspended solids regulations have installed external effluent treatment systems. Where a fine paper mill is integrated with a chemical or mechanical pulp mill, there may be some integration of the white water systems but this is not feasible to the extent common in newsprint mills.

7.4 White Water System Design

The design of the white water system in the paper mill has more impact on suspended solids discharges than the grade of paper being manufactured or the type of paper machine. There have been many publications on the principles of white water system design (68,69,70,71,72,73), but relatively few mills yet take full advantage of all of the methods for reducing effluent suspended solids discharges, energy losses, and fresh water requirements that have been developed.

The many reasons for this include the capital costs, the complexity of the control systems required, the tradition that high water usage leads to high quality paper, and the fact that the white water system does not lend itself to the development of a clearly defined package that an equipment supplier can market and guarantee. At the mill design level, the variety of interrelationships between departments, the complexity of the mass and energy balance calculations required, and the need to design mills in a short time frame to respond to market requirements and obtain regulatory approvals, inhibit the application of the best design techniques in the white water systems. However, there has been steady progress in the application of the better design principles and some mills have reduced white water losses by as much as 75% over the past ten years.

The basic principles of white water system design are to introduce as little water as possible, recycle rich white water from the paper machine forming section to the headbox as directly as possible, and segregate the use and storage so that the leanest white water is overflowed to the sewer. To achieve the optimum design, it is essential to calculate more detailed mass and energy balances than are normally used, and to examine the normal modes of failure or abnormal operation to ensure that the system will function as designed for all likely conditions, and not only for an idealised design condition.

Most paper mills in Canada are integrated with the pulp mills that manufacture all or most of their pulp furnish, and an optimum white water system must be integrated with the pulp mill, particularly in the case of newsprint mills. There has always been some degree of integration, and many mills have improved their white water systems to reduce the costs of effluent treatment, but few mills have reached the optimum levels.

The quality of white water systems, particularly with respect to the environmental aspects, is frequently described in terms of "degree of closure" for which the definitions vary, but all are based on a portion of the white water being recycled. Since there is no common basis for the definition, nor a realistic way of developing one to cover the variety of systems used, the degree of closure is of little value, except perhaps when discussing modifications to one specific system. The effluent discharge per tonne paper is a useful measure of the quality of the white water system in a non-integrated paper mill, although it may be misleading when there are several paper machines with some interconnections between their white water systems. In integrated mills, the white water system is usually common to the paper machines and the pulp mill, further complicating comparisons between mills, but the effluent volume and fibre loss per tonne paper is still the best comparison available.

The equipment used in white water systems, modern or otherwise, is primarily the mill production equipment, since the white water system is essentially a design concept, rather than a set of specific hardware. Equipment incorporated in the better, more modern, white water systems includes savealls, white water screens, and self cleaning showers.

A saveall is any device used to recover fibre from white water. Vacuum drum filters, flotation clarifiers, belt filters, gravity deckers and disc filters have all been used for the purpose, but the best white water systems, for most purposes, require a multiple disc filter (Figure 22).

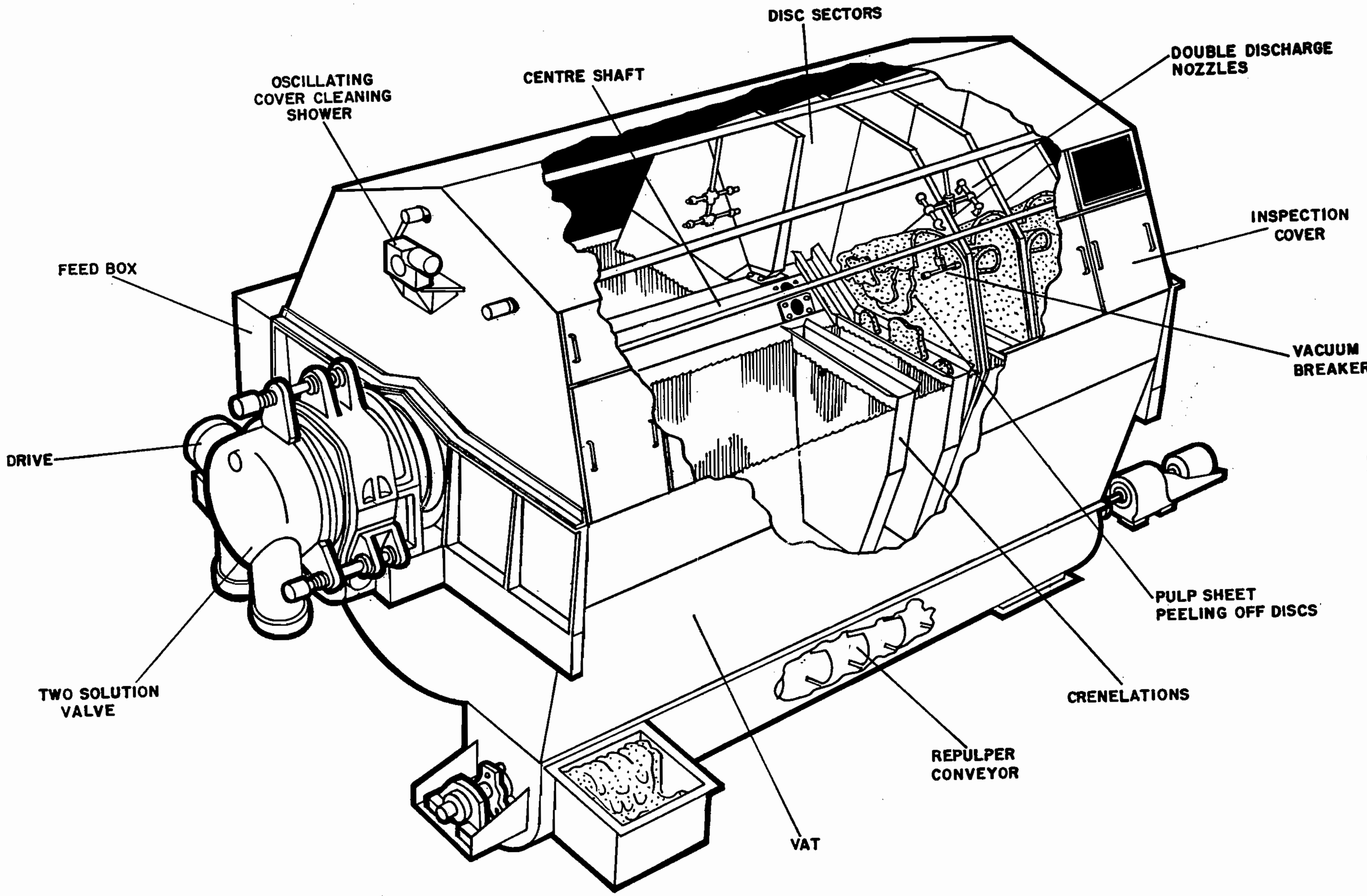


FIGURE 22 DISC FILTER SAVEALL (Dorr Oliver)

Most white water systems installed or modernised in the past ten years have incorporated disc filters as the principal device for separating fibres from the excess white water. They are effectively a specialised type of vacuum filter and use a barometric dropleg to generate a vacuum which extracts water from a dilute stock suspension. They are far superior to the traditional drum filters, deckers, etc., for this application, since they can be designed to segregate the filtrate into two streams, generally known as clear and cloudy. This is accomplished by arranging the water passages inside the discs and the central shaft so that the filtrate from the initial stages of dewatering the feed stock and the formation of the fibre mat on the surface of the filter media is discharged to one drop-leg, known as the cloudy leg, while the filtrate from the second stage of dewatering is routed to the clear leg. This results in very low loss of fibre in the clear leg white water, since it is filtered through a mat of pulp fibres.

It is not practicable to operate a disc filter with only white water as the feedstock, since the concentration of larger fibres would be too low to form an effective mat and the filter media would blind. The normal practice is to raise the feed consistency to a suitable level by the addition of a sweetener stock. This is usually either broke from the system concerned or, preferably, some of the chemical pulp that is to be fed to the paper machine concerned.

The consistency of the filtrate from a disc filter depends primarily on the type of pulp concerned, and the sweetener used. The cloudy filtrate normally has a consistency of several hundred mg/L, but the clear leg filtrate can have a solids content as low as 60 mg/L where kraft pulp can be used as sweetener, or in the order of 150 mg/L where there is only mechanical pulp available. The proportional split of hydraulic flows between clear and cloudy is adjustable by a mechanical device on the disc filter shaft. This is usually adjusted so that the flows of cloudy and clear filtrate are approximately equal. Generally, lowering the proportion of clear filtrate lowers its consistency, but there is always a minimal value for any one installation, which depends on the pulp stock characteristics and the equipment selected.

Effective white water systems are designed so that all of the cloudy filtrate and some of the clear filtrate is reused in the process system, and only the excess clear filtrate is discharged to sewer. It is essential that the saveall is designed as an integral part of the overall white water system, and that due allowance is made in the design for the type of pulp fibre which will actually reach the filter. The stock at the saveall is predominantly fine fibres, and therefore drains much more slowly than the stock at the paper machine itself. Stone groundwood fibres drain more slowly and also result in higher filtrate consistencies than TMP or chemical pulps. In fine paper mills, the use of non-fibrous fillers in the stock tends to degrade saveall performance and must be considered in system design. The operating temperature has some effect on the saveall's capacity, with higher temperatures raising capacity.

The origin of much of the excess white water is the fresh water that has traditionally been added to the process system by the showers required to keep the Fourdrinier wire and rolls clear of fibre accumulations. There is a steady trend to replace much of this fresh water with recycled white water. The key criteria for the reuse of white water in such applications is that it should not plug the shower, so it is common practice to filter the water through a screen with 100 μm openings. The suspended solids content of the reused water is of relatively little importance, but it must be free of larger particles. Water containing over 200 mg/L suspended solids in the form of filler clay has been used successfully for felt cleaning showers, whereas 10 mg/L of fibre in the water will plug many paper machine showers and will often lead to additional problems. Filter screens (usually known simply as filters) have been developed to remove residual fibres from such streams prior to use in showers.

Several types of self-cleaning showers have been developed to facilitate the use of white water instead of fresh water. These are based on the use of nozzles whose size can be increased significantly for very short periods to clear fibre bundles that are blocking the orifice. The increase in size, usually obtained by removing a plug from the opening, is accomplished by direct mechanical or hydraulic action. In some cases the hydraulic force is applied by abruptly changing the pressure in the shower header, in others a separate device removes the nozzle plugs. The shower cleaning action may be initiated by the operators as required, or may be performed automatically at predetermined intervals.

An alternative method of reducing fresh water input to the white water system which has been used in many applications, particularly felt and wire cleaning, is the replacement of older, continuous, low-pressure showers by high-pressure, intermittently operated showers that use relatively low quantities of water.

7.5 Vacuum Pumps

All paper machines rely on the application of various levels of vacuum for dewatering the sheet and the felts, and the most commonly used equipment for creating the vacuum is the liquid ring pump. The seal water from these pumps is from about 3 to 10 m^3/tonne of paper, which is a substantial proportion of the total mill effluent. Due to fibre and/or filler carry over, the water from some of the pumps is contaminated by suspended solids, and cannot be discharged without treatment. It is becoming increasingly common practice to install separators in the vacuum lines upstream of the pumps to recover the solids and ensure that the seal water is clean enough to discharge without treatment. It is also becoming common practice to reuse the seal water to reduce the net volume discharged. A completely closed cycle is impractical, since most of the pumping energy is absorbed by the seal water, raising its temperature. However reduction of the vacuum pump seal water effluent to about 2 m^3/t is achieved by some recycle systems (74).

An increasing number of new mill installations are using dry centrifugal vacuum pumps instead of the traditional liquid ring pumps. These must be preceded by separators to ensure that no liquid reaches the pump. The fibre and filler removed from the paper machine by the vacuum system is recovered as a relatively concentrated stream from the separators, and the only effluent is less than 0.2 m^3/t of clean cooling water. The separators themselves are relatively simple, consisting of a sealed vessel with a liquid outlet at the bottom and a vapour outlet at the top. Since they are under partial vacuum, the liquid must usually be exhausted by a pump and the vessels must be designed for the highest vacuum likely to occur.

The air is discharged from the dry centrifugal pumps at a temperature of about 130°C, and can be used for pocket ventilation or other purposes. The use of dry vacuum systems has been more common in Europe than in North America, but rising energy costs have led to increased application in recent years.

7.6 Effluents Other than White Water

The effluents from the paper machine presses were traditionally not considered to be part of the white water system, and were discharged directly to sewer. However, many mills now recycle the press effluent to the white water system to recover the fibre contained in it, typically about 0.5 kg/tonne paper. In the past there was considerable concern about the dangers of felt hairs being introduced to the stock and causing sheet breaks or contamination. However, this problem has largely disappeared with the replacement of wool by synthetic material for felt manufacture.

Washup water and minor stock leaks are usually discharged to the effluent treatment system, and represent from 0.5 to about 3 kg/t paper, depending on the operating practices.

Most other discharges from the paper machine areas are cooling water that has not been in contact with any process materials, and is uncontaminated. This is often segregated and by-passes any effluent treatment system. The principal objective is to reduce treatment costs, but it is also helpful in raising treatment efficiency in most cases since it raises the concentration and temperature of the effluent being treated.

8 STEAM AND POWER

8.1 General

A general trend toward increased use of hog-fuel has led to the installation of a number of large boilers, typically with a capacity of over 100 000 kg steam/h, which are specially designed for the purpose. Most so-called hog fuel boilers installed before 1975 were effectively oil, gas or coal burning units with some rather unsophisticated facilities added to enable burning of some auxiliary hog fuel. However, energy costs and environmental pressures have led to the development and installation of boilers that are designed primarily as hog fuel boilers, with some fossil fuel capacity. These usually replace a number of smaller, obsolete units and often result in the shutdown of inefficient, smoky, particulate emitting wood waste burners in sawmills in the area of the pulp or paper mill.

There has also been a trend toward the installation of turbogenerators to generate electric power from the high pressure steam before it is used at low pressures for process heat. This encourages the use of higher pressure boilers, and the replacement of many older multiple unit hog fuel burning boilers with one high pressure unit. While there is no inherent reason why a high pressure boiler should emit less particulate material than a low pressure one, the modern designs achieve more complete combustion, so that the particulate emissions are invariably reduced when steam plants are modernised. Any increase in particulate emissions due to the larger quantities of fuel burned when a turbogenerator is added to a power plant are usually more than offset by the benefits of the more modern boiler.

The trend towards greater hog fuel utilisation has reduced the amount of bark being landfilled and the total sulphur dioxide emissions, due to the replacement of sulphur-bearing oil.

8.2 Particulate Emission Control

The most commonly used particulate emission control equipment is still the multiple cyclone. It can generally limit stack emissions to 200 mg/Sm^3, complying with most regulations, when installed on modern boilers burning fuel that is free of sodium chloride or other material causing unusually fine particulate emissions.

Many older hog fuel boilers emit too much char to enable conventional multiple cyclones to provide compliance with current regulations. In some cases two multiple cyclones are used in series. In others, the efficiency is augmented by evacuating about 10% of the gas flow from the cyclone's dust hopper and treating it separately in a scrubber or additional cyclone.

Baghouses are capable of reducing particulate emissions to very low levels and have been used for hog fuel boiler particulate emission control in a few cases, but difficulties with fires due to the carry over of carbon dust and red-hot char particles have severely limited application.

When logs are transported or stored in sea water, as is common practice on the west coast, the bark becomes saturated with sodium chloride. Much of this is discharged with the flue gas from hog fuel boilers which burn the bark. The sodium chloride particles are small, virtually all under 5 μm diameter, and are more difficult to remove from the gas than the normal fly ash from the hog fuel itself. Electrostatic precipitators have proven effective in controlling such emissions, but the capital cost is several times higher than for multiple cyclones.

It is technically feasible to use electrostatic precipitators on all hog fuel boilers, but in most circumstances the higher capital costs are not warranted. When converting former recovery boilers to hog fuel service, it is common practice to retain the former precipitator for particulate emissions control.

Conventional wet scrubbers such as the low-pressure drop venturi, or the impingement type, have been used successfully. While they are effective in reducing emissions, they are not popular since they result in a wet stack gas, which often requires an expensive corrosion-resistant stack, and create a visible plume.

The dry-scrubber has been used in a few applications. This consists of a filter bed of fine gravel which moves slowly downwards within the scrubber chamber while the stack gases flow perpendicular to the gravel flow. The filter medium is continually removed and cleaned by vibratory screens and re-injected at the top of the scrubber. Emissions of under 150 mg/Sm^3 have been reported, but the capital cost is about twice that of a multiple cyclone, and maintenance of the gravel handling equipment can be high. There have been reports of operational difficulties due to frequent blockages when there are substantial quantities of sodium chloride in the hog fuel.

The performances and costs of particulate emission control equipment are compared in Table 15.

8.3 Effluents from Steam and Power Plants

The principal discharges from hog-fuel burning boilers are clean cooling water and ash. In the late 1960s and early 1970s, many mills selected dry ash handling systems

TABLE 15 COSTS AND PERFORMANCE OF PARTICULATE EMISSION CONTROL EQUIPMENT

Type	Installed Capital Cost ($\$/m^3\cdot h$)	Power Consumption ($W/m^3\cdot h$)	Performance (mg/Sm^3)
Multiple Cyclone	1 - 2	0.4 - 1.5	down to 200
Multiple Cyclone (with hopper evacuation)	2 - 3	0.6 - 2.0	under 200
Wet Scrubber	3 - 5	0.6 - 3.0	under 150
Baghouse	3 - 5	0.2 - 0.5	100
Electrostatic Precipitator	5 - 7	0.5 - 1.3	100

in response to pressures to reduce mill effluent suspended solids. However, a number of installations have suffered from fires in the ash handling systems, since hog fuel ash often has a significant carbon content, and the dust can be explosive in certain circumstances. To avoid this, most of the recently installed ash handling systems have been the wet type. The ash slurry is either dewatered and landfilled, or is routed through storage ponds where the ash settles. The excess water is usually recycled, although it may be sufficiently clean to permit direct discharge to the receiving water in some cases. There is generally no intention of cleaning out the ash ponds, and the process is, in effect, a means of hydraulically conveying the ash to landfill.

Provided that the ash storage ponds are suitably located and constructed, this approach is environmentally effective. Generally, hog fuel ash contains substantially lower proportions of heavy metals than coal ash. The volumes of ash generated are also about 10% of the quantity from burning equivalent amounts of coal.

8.4 Hog Fuel Storage

An efficient hog fuel burning system requires several days, or sometimes several weeks, storage close to the boilers. This is most commonly in the form of open piles, so that appropriate precautions are required for the inevitable leachate.

9 TOTAL MILL DISCHARGES

9.1 General

This section discusses the overall effect of recent technological developments in pulp and paper manufacture on mill effluents and atmospheric emissions, and the external treatment systems used by a large segment of the industry to protect the environment and comply with regulatory requirements.

Federal regulations respecting effluents from the pulp and paper industry are defined in reference 4. Some provinces have adopted them and others have comparable regulations. Most of the environmental protection measures taken by pulp and paper mills over the past ten years have been in response to the regulations, and it is clear that they have been responsible for substantial reductions in pollutant discharges.

However, in some cases the effects of the regulations are unclear. The toxicity regulation is effectively a measure of the concentration of material in the effluent that is toxic to fish, and therefore does not require a reduction in the mass flow of toxic material. This regulation tends to discourage the use of processes which discharge low volume, high concentration effluents such as displacement bleaching systems.

The "building block" approach used in the regulations to calculate the allowable discharge for a mill can lead to anomalies where mill operators have to evaluate the installation of "low-pollution" processes in comparison with external effluent treatment. An example is the encouragement offered to mills to use the wet debarking process rather than dry, due to the relatively strict regulatory limit imposed on dry debarking installations, although the dry systems invariably result in lower discharges of BOD and suspended solids.

9.2 Effluent Sources and Treatment

Average raw effluent discharges have steadily declined over the past 20 years due to the construction of new mills and modernisation of older ones. Prior to 1970, process and equipment design was based on production efficiency and was often biased toward minimising capital costs at the expense of operating costs, so that fibre and chemical losses were relatively high. While the characteristics of the effluents from mills built during the 1970s often approach the data shown in Tables 16 and 17 for the state-of-the-art mill, the untreated effluents from many older mills are more like those shown in the first three columns of these tables. Some older mills have incorporated many of the

TABLE 16 KRAFT MILL EFFLUENT BREAKDOWN

	Older Mill			Maximum In-plant Control		
	Flow (m^3/t)	SS (kg/t)	BOD (kg/t)	Flow (m^3/t)	SS (kg/t)	BOD (kg/t)
Wood Preparation (wet)	15	90	16	-	-	-
Wood Preparation (dry)	-	-	-	5	2	1
Pulping (non-process)	10	3	3	5	0.2	0.1
Washing and Screening	15	5	15	3	0.3	0
Contaminated Condensates	10	0	15	-	-	-
Evaporator (non-process)	20	0	5	3	0	1
Recovery Furnace/Power Boiler	15	0	0	5	0	0
Bleaching CEDED	75	1	25	-	-	-
Bleaching OC_dEDED	-	-	-	10	0.2	10
Recausticising (process)	2	10	5	0	0.1	0
Recausticising (non-process)	5	1	0	2	-	0
Pulp Dryer	15	10	1	3	0.2	0.1
Accidental Losses	20	30	30	10	5	5
TOTALS	202	150	115	44	8	17.2

recently developed in-plant environmental protection measures discussed previously, and have reduced untreated effluent discharges substantially below the higher values shown in these two tables. The substantial reductions in accidental losses shown for the state-of-the-art mill reflect the improvements in system design and control that have taken place over the last 20 years, as well as the current practice of installing spill collection and recovery systems in critical areas.

Ideally, there would be no accidental losses in the modern mill, but experience has shown that it is essential to allow for human errors and equipment failures in the concept and design of environmental protection systems. Human errors, and equipment failure due to inadequate maintenance, can be, and often are, minimised by operator training (75).

9.2.1 Kraft Mill Effluent Sources. Although the fundamental process and pulping yields are very similar for all bleached market kraft mills, and do not radically differ for

TABLE 17 NEWSPRINT MILL EFFLUENT BREAKDOWN (All quantities expressed per tonne newsprint)

	Older Mill			Groundwood +85% Yield Sulphite			TMP with Maximum In-plant Control		
	Flow (m^3)	SS (kg)	BOD (kg)	Flow (m^3)	SS (kg)	BOD (kg)	Flow (m^3)	SS (kg)	BOD (kg)
Wood preparation									
(wet)	15	40	8	13	35	7	-	-	-
(dry)	-	-	-	-	-	-	2	1	1
Sulphite pulping	100	1	75	20	1	25	-	-	-
Mechanical pulping	70	30	8	65	27	6	5	5	19
Papermaking	25	15	1	25	15	1	5	1	1
Nonprocess water	50	1	0	40	1	0	10	0	0
Accidental losses	20	10	0	15	7	0	5	2	0
TOTALS	280	97	92	178	86	39	27	9	21

unbleached kraft pulp or linerboard mills the effluent discharges from kraft mills vary widely. The differences are due to technological developments, varying environmental pressures at the time of initial mill design, deliberate decisions on in-plant vs. external measures for effluent quality control, operating skill levels, and historical accident.

Table 16 summarises typical effluent discharges by department for two hypothetical mills selected to cover the range of data typically found in the Canadian pulp and paper industry. The "older" mill shown would have been originally designed before there were any effluent regulations, and would probably have been modified several times to respond to market pressures, resulting in the imbalances between departments which characterise this class of mill and limit the possibilities for effective implementation of in-plant effluent controls. Older mills of this class are often installed in restricted locations, which would be unlikely to be selected as mill sites today. Those constructed in the 1960's are usually on sites that are suitable by modern standards, and facilitate modernisation.

The state-of-the-art kraft mill in Table 16 incorporates all of the proven in-plant technology discussed previously for the reduction of effluent BOD, suspended solids and toxicity, except that it does not utilise the closed-cycle concept, which is discussed separately in section 9.2.5. No actual mills incorporate all of these design features, and it is not necessarily the optimum combination of in-plant measures and external effluent treatment. In any one case it would be necessary to examine the economic aspects of all alternatives, and in many cases it would be more economic to omit some of the more expensive in-plant measures and increase the size of the waste treatment facility. The local regulations and the margin of safety required for the pollution control facilities have a significant impact on the final selection; where the discharges shown would be considered acceptable, this mill configuration could be the optimum without external treatment.

Some of the proven and widely accepted in-plant measures for effluent quality improvement are cost-effective where they avoid the need to expand an existing effluent treatment facility, or avoid the need for external effluent treatment completely, but are not cost-effective when the only economic benefit is a marginal reduction in the capacity of an effluent treatment system that is not yet installed, or perhaps a marginal reduction in the operating cost of a treatment system.

The data shown in Table 16 assume that the older mill would discharge all excess lime mud, screen and cleaner rejects to sewer, whereas the mill using the maximum in-plant control would dewater such material at source and dispose of it to landfill or incinerate it. Where a mill has a primary effluent treatment system, it would normally be more economic to discharge such rejects to sewer and remove them from the effluent in the clarifier.

The effluent from the older mill would be toxic to fish. Despite the spectacular reduction in toxic organic material discharged, including almost complete elimination of chlorinated organics and residual black liquor, the effluent from the state-of-the-art mill would also probably be toxic, since the effluent flow is only about 20% of that of an old mill.

9.2.2 Newsprint Mill Effluent Sources. Table 17 summarises the effluent sources for three general types of newsprint mill. The first is a traditional mill using 25% low-yield sulphite pulp and 75% stone groundwood pulp, which would have been typical prior to 1970. The second is a modern mill which has replaced the low-yield process with one of the ultra high-yield sulphite processes described in Section 3, retained the stone groundwood mill, and modernised the white water system to some degree, but is not attempting to comply with effluent regulations without an external treatment system.

The third is a new mill which uses 100% TMP furnish and is designed to comply with BOD and suspended solids regulations without an effluent treatment system.

9.2.3 Sources of Effluent from Other Types of Pulp and Paper Mills. Data have been presented for kraft pulp mills and for integrated newsprint mills because these two types of mills produce most of the pulp and paper products in Canada. The other types of mills are more diverse, and it is not feasible to summarise effluent loads in the same manner.

Data for specific types of mills and process units have been reported widely in the literature, and most mills now operating have developed sufficient data over the past ten years to be able to break down the sources into the principal components. The reported data must be examined critically to establish the actual source of many pollutants, since there are no generally accepted battery limits for the departments. Particularly in the more complex mills, the recent trend to increased recycle of process discharge streams to reduce effluent discharges leads to confusion in the interpretation of effluent data from individual departments and unit operations.

9.2.4 Effluent Treatment. It is often possible for pulp and paper mills to comply with effluent regulations by installing end-of-the-pipe treatment, without implementing any in-plant measures (6). This was common in the southern U.S. in the early 1970s, but is rare in Canada and Scandanavia. Most mills implement some in-plant measures to reduce the costs of external treatment, and to eliminate or reduce discharges of material that is not readily removed by simple sedimentation or biological treatment.

When a mill has an external effluent treatment system, it is common practice to segregate effluent streams and route some of them past some or all of the treatment system. For example, kraft bleach plant effluent usually by-passes primary treatment systems, and some newsprint mills have adopted in-plant measures for the pulp mill and paper mill, but install a primary treatment system for the effluent from a woodroom using a wet debarking process.

The established effluent treatment processes have been described in reference 6. No full scale new treatment processes have been applied in the past ten years, although some anaerobic treatment systems may be approaching full scale application.

Most mills have selected conventional circular clarifiers for primary treatment, although several use earthen settling ponds. When the site is suitable and the ponds are correctly designed and operated, they have proven to be effective for compliance with effluent regulations and more reliable than mechanical clarifiers.

The aerated lagoon is preferred by most mills that have had to install secondary treatment systems, although some high-rate systems and one oxygen activated sludge system have been installed by mills that lack the necessary space for an aerated lagoon. The low-rate systems have been more reliable and have exhibited better control over effluent toxicity than the high-rate systems.

As is apparent from the range of characteristics of the untreated effluent shown in Tables 16 and 17, the capacity of the effluent treatment system must vary quite widely, even for mills using similar production processes and producing similar quantities of product.

Many mills have installed some facilities for the control of accidental losses, and one has installed a colour removal system for the mill effluent (76).

9.2.5 Rapson-Reeve Closed-Cycle Bleached Kraft Mill. It is apparent from Table 16 that the bleach plant effluent contributes a major portion of bleached kraft mill effluent BOD. It is also the principal source of toxicity in most bleached kraft mill effluents. These effluents cannot be recycled within the process if conventional technology is used, but a concept for a closed-cycle bleached kraft mill has been developed. This is the Rapson-Reeve closed-cycle process (48).

To date, only the Great Lakes Forest Products Co. mill at Thunder Bay, Ontario, has been designed and built to use this process. In view of the fact that it is the first in the world and has been producing and selling market pulp since start-up in 1977, it must be considered successful, although a small amount of contaminated effluent is still discharged.

The basic features of the process could be implemented in several ways, and an oxygen bleach stage could be incorporated if desired to lower the circulating chloride load. Variations of the kraft contaminated condensate treatment systems described in Section 4 could be incorporated into the concept to reduce operating costs, and the displacement bleaching equipment described in Section 6.3 could be utilised to achieve the very low bleach plant effluent volumes required for this process to be successful.

Fully countercurrent washing is required in the bleach plant from the second chlorine dioxide stage to the first extraction stage. The showers for the D/C washer are countercurrent from the first extraction stage (applied last to the pulp mat) and from the first chlorine dioxide stage (applied first to the pulp mat). No external wash water is supplied to any of the pulp washers. This means that external water inputs to the bleach plant are kept to a minimum, and the total volume discharged is kept low enough to be reclaimed into the kraft chemical recovery cycle. No external water is regularly added to seal tanks, except as required for level control. Air doctor pulp takeoffs with low-volume, high-pressure, timer-operated wire cleaning showers are used on the washers rather than hydraulic doctor showers. Second caustic extraction stage filtrate is used to dilute the purchased 50% sodium hydroxide to 13% strength for bleach plant use.

Reclaiming the bleach plant filtrates into the recovery cycle results in introduction of sodium chloride as an inert dead load in the system. The sodium chloride must be removed at the same rate that it is being introduced, and a salt removal process (SRP) is used for this purpose. It is based on evaporation and recrystallisation of the white liquor to separate the salt from the kraft cooking chemicals. The byproduct salt produced is used as the sodium chloride supply to the chlorine dioxide generator.

9.3 Atmospheric Emission Control

The control of atmospheric emissions from individual sources was discussed in Sections 3 to 8, as well as in reference 6. Except for odour control systems in kraft mills, there is no overall collection of atmospheric discharges analogous to that for effluent. Many kraft mills now collect and incinerate the high concentration reduced sulphur gases from the digester and the evaporator, and all mills with condensate stripping systems incinerate the gases.

An increasing number of kraft mills collect the low concentration total reduced sulphur (TRS) gases and incinerate them to reduce the odour due to mill operations. The most recent systems collect all of the following vents, to the extent that they exist in the mill concerned:

- knotter hoods;
- drum type unbleached pulp washer hood;
- drum type unbleached pulp washer seal tanks;
- black liquor storage tanks;
- black liquor filter;
- tall oil system tanks and reactor;
- foam tanks;
- black liquor oxidation system, and
- turpentine storage.

Effective odour control also requires that the recovery furnace and lime kiln or calciner TRS emissions be controlled as discussed in Section 4.

9.4 Solid Waste Disposal

The total volume of solid wastes generated by the pulp and paper industry has tended to decline over the past 20 years, due principally to the increasing proportion of bark that is burned. However, solid waste production has increased at many mills because material that was formerly discharged with the effluents or atmospheric emissions is now collected and must be disposed of in an environmentally acceptable manner.

Primary treatment sludges are sometimes incinerated, but since the principal combustible material in them is fibre, it is often preferable to reduce the fibre losses and recover their value, rather than install the necessary facilities to dewater the sludge sufficiently for disposal by incineration. Other than fibre, most of the suspended solids in pulp and paper mill effluents consist of sand, lime, boiler ash, or filler clays and are non-combustible, so that a suitable landfill site must be developed.

Secondary treatment sludges are primarily organic in nature, and are usually difficult to dewater effectively; incineration often requires the use of auxiliary fuel. Some systems are claimed to operate without auxiliary fuel, because the sludge is burned with hog fuel. However, any introduction of low consistency sludge into a boiler or furnace requires fuel to evaporate the water content.

Various methods of disposing of biological sludges by conversion to fertiliser, or animal feed, have been developed and are utilised to some extent in the U.S. and Europe (77,78,79). However, there is little need for such processes in the Canadian pulp and paper industry because most mills use low rate biological treatment systems which generate little or no sludge.

Many sophisticated tertiary treatment systems have been successfully demonstrated on a laboratory scale, but have failed to find commercial acceptance because of the volumes of low consistency sludge they produced. In designing any effluent treatment system, it is essential to include effective provisions for sludge disposal.

The pulp and paper industry in Canada has generally adopted in-plant measures to avoid the generation of sludges, rather than utilise complex, expensive and sometimes environmentally questionable incineration or land disposal methods. Except for some special problems, such as the biological treatment sludge from a dissolving grade sulphite mill, it is technically feasible to limit sludge generation to under about 10 kg/t pulp production by in-plant measures, and by using low-rate biological treatment systems rather than high-rate processes. Whether or not this is economically realistic depends on local conditions.

10 COMPUTERS AND ENVIRONMENTAL PROTECTION

10.1 General

As in most fields of technology and business, computers are being used increasingly in the pulp and paper industry. A small but significant proportion of computer applications are directly concerned with environmental protection measures and many of the engineering design and process control applications have side effects on the environmental aspects of designing and operating pulp and paper mills.

The use of computers in the industry falls into five broad categories, as follows:

- engineering design and optimisation studies of the production processes;
- process control;
- environmental impact analysis;
- mechanical, civil and electrical design; and
- business, accounting and commercial.

The latter two are of little environmental significance, and are not discussed further. The environmental aspects of the other three categories are discussed below. The discussion on the application of computers for process control is the most detailed, as this is the predominant application and probably the least understood.

10.2 Engineering Design and Optimisation Studies

The pulp and paper industry production processes are characterised by large numbers of recycle streams and complex interrelationships between departments and unit operations. The mathematical techniques necessary for the analysis of the operations have been quite well known for many years, but they have not been utilised to their full potential for the design of new and modified mills to achieve the best compromises between capital cost, operating costs and discharges to the environment. This is partly due to the historical origins of the industry, but primarily due to the excessive labour required to perform the calculations properly. The labour costs and delays involved in preparing complete and detailed mass and energy balances have led to the practice of designing mills by department, instead of as a complete system, and to the use of many short-cut and rule-of-thumb calculating techniques based on past operating experience. While this will always be necessary to some extent in the practice of engineering and business, complete reliance on past experience for design and modification of large production systems has the effect of limiting technological change and becomes less and less effective as the production systems become more complex, and the rate of development of technology increases.

Rapid and efficient calculation techniques are essential for the development of optimum process designs to meet the environmental and economic needs of this decade. To overcome these problems, computer programs have been developed to perform the mass and energy balances for the initial design and for modernisation of even the most complicated pulp and paper mill flowsheets.

To perform the first mass and energy balance calculation for any one mill flowsheet, whether using a computer or manual calculation techniques, requires a substantial amount of work (typically about two man months for a medium size mill), but where suitable computer software is used, further calculations for alternative designs or operating criteria can be performed very rapidly and inexpensively. Since engineers can use these programs to evaluate the effects of many potential changes prior to selecting the optimum design and committing resources to equipment purchase and construction, they are commonly referred to as mathematical models or as process simulation systems.

Although process simulation techniques can reduce design costs, their principal advantage is that they permit the mathematical modelling of complete mill systems, the prediction of effluent and atmospheric emission characteristics with a reasonable degree of accuracy, and other data essential for optimum mill design. This allows many different mill designs to be evaluated and all implications of any alternatives to be considered before entering into commitments for major equipment purchase.

In the case of operating mills, such models allow the investigation of the process, and development of improvements to reduce operating costs and/or effluent and atmospheric discharges in the most effective manner. They are of particular value in complex fields such as overall mill white water systems where several paper machines and, perhaps also several pulp mills, are involved.

Some specialist equipment manufacturers were using computers very effectively for process design in the 1960s, but their interest was limited to their own equipment.

The available software was not sufficiently adaptable for effective application to complete and varied mill systems until the mid 1970s. Several systems are now available and are being used increasingly. Some of the software systems capable of detailed process analysis of complete mills have been developed by consultants, and access is limited to employees. However, other effective process simulation systems for the pulp and paper industry are publically available on timesharing networks. These are used by mills, consultants, and equipment manufacturers for their own calculations, and may be accessed from anywhere in North America by public telephone lines using computer terminal equipment costing only a few thousand dollars. This has led to more widespread and increasing application by research and development organisations as well as by mills, consultants and equipment suppliers, some of which have purchased the software to run on their own computers.

10.3 Process Control Computers

10.3.1 General. The basic building blocks of process control systems can be explained by reference to Figure 23. The purpose of automatic control is to maintain the controlled variable or output of the process at a target value. This requires a sensor to measure the variable (measured value) and a controller which calculates the deviation of the measured value from target and the amount by which the manipulated variable (process input) must be changed to bring the controlled variable to target. The manipulated variable is adjusted by means of an actuator such as an automatic valve.

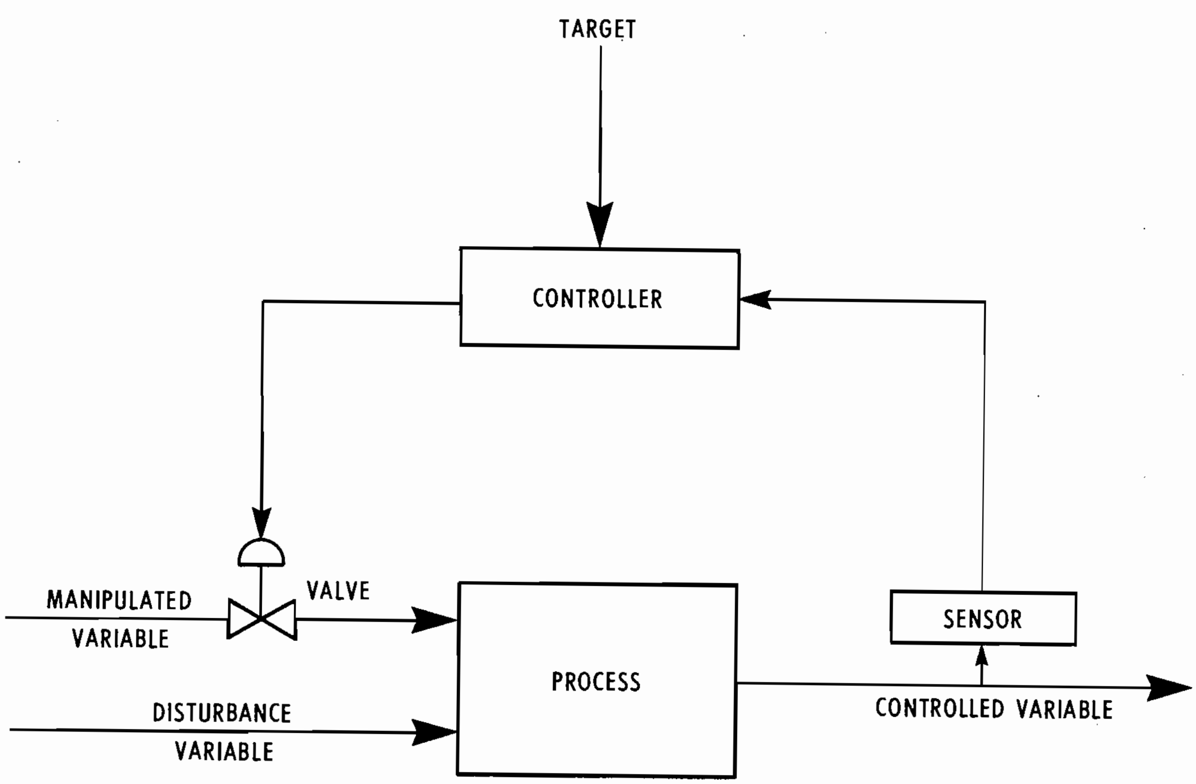


FIGURE 23 BUILDING BLOCKS OF PROCESS CONTROL SYSTEM

Automatic control systems are needed because of the presence of one or more disturbance variables which cause changes in the controlled variable. This type of control is called a feedback control loop and is the most commonly used. Obviously it cannot provide perfect control because it only makes corrections after the controlled variable has deviated from target.

In certain cases it is possible to measure one or more disturbance variables and to adjust the manipulated variable to prevent variations in the controlled variable. This is called feedforward control and is generally more complex than feedback control, and the designer requires a more exact knowledge of the process. Feedforward control is an example of multivariable control. Another type of multivariable control is when the manipulated variable also causes a change in a second output variable (known as an interaction). If both the output variables are to be controlled, then two manipulated variables are required and non-interacting or decoupled control must be provided.

10.3.2 Control of Connected Processes. Pulp and paper mills consist of hundreds of individual processes connected in series and parallel. In general, processes are separated by buffer storage capacity or tanks. The levels of these tanks will rise and fall whenever the throughput of the upstream and downstream processes differ. If a tank overflows, this is a potential source of pollution, and if a tank runs empty it frequently leads to process upsets and perhaps accidental overflows in other, related equipment.

10.3.3 Hierarchical Control. Pulp and paper processes are complex, and the modern process control systems reflect this complexity. Nonetheless, the basic structure of mill control systems seems to be common for all process industries and is hierarchical in nature (80,81). This structure consists of five levels which have the following functions:

A Direct Control

- performs the single-loop feedback and multivariable feedback and feedforward controls on a single process unit;
- receives targets from supervisory control level;
- causes alarms for abnormal condition and takes corrective actions;
- collects information on unit production, material use, energy use and discharges and transmits it to supervisory level.

B Supervisory (Region) Control

- controls process region consisting of several process units each with its own direct control system;

- optimizes operation of unit processes within region i.e., sets target for manipulated variables including enforcement of production schedule by setting throughput rate of each unit;
- collects data for whole regional process from each unit on production, in-process inventory, material use, energy use and discharges;
- maintains communication between lower (direct control) and higher (area) levels.

C Intra-area Coordination

- establishes production schedule for each region within an area, in conformance with mill production schedule;
- minimizes costs (material, energy, discharges) within area;
- prepares area production reports;
- collects and maintains area data files on production, inventory, material and energy use and discharges;
- maintains communications between lower level (region supervision) and higher level (mill operational management).

D Mill Operational Management

- establishes production schedule for all areas, regions and unit in mill;
- reschedules production based on receipts of new orders and unplanned process interruptions;
- determines optimium in-process inventories (such as tank levels);
- keeps track of in-process inventories;
- keeps track of product quality;
- keeps track of material use, energy use and discharges for the mill.

E Mill Management Information

- maintains contact with the world outside of mill production processes including other mill departments (accounting, maintenance, etc.) and outside the mill (sales department, head office, government, etc.)
- supplies routine and status reports on production, costs, quality, discharges, etc.;
- supplies order status.

This hierarchical control parallels the normal hierarchical personnel organisation consisting of operators (unit), foremen and supervisors (region), superintendents (area), production managers (mill operations) and mill management (mill information).

The structural analysis is important because of its bearing on process control of discharges as they originate within the mill prior to effluent treatment.

There are two basically different cases to consider in applying the hierarchical control structure:

- control of the flow and composition of an individual process stream such as flue gas, or excess white water, and
- control of tank levels and equipment to avoid overflows, spills and the need to dump material for repair access.

According to the control structure, both of these cases could be affected by control actions and decisions at all levels in the hierarchy. The improved direct control possible with well-designed modern computer control systems stabilises individual unit operations, minimising variations in flow and composition of discharges. Optimizing control at the supervisory level should include effluent and atmosphere emission discharge rates as constraints.

Scheduling and intra-area coordination at the higher levels minimizes tank overflows and unnecessary discharges due to mismatch of upstream and downstream throughput rates. Alarm action at the lower levels and reporting at the higher levels help focus short and long term corrective action.

10.3.4 Digital vs. Analog Computers. At the direct control level, automatic control is performed by analog and digital computers. Analog systems represent the controller inputs and outputs (measured variable, target, actuator) by pneumatic air pressure or DC current. This has been the prevalent method but is being gradually replaced by digital equipment. In this case, the necessary controller action is calculated numerically and a signal generated to actuate the control valve or other device which manipulates the process. Digital systems always include analog/digital conversions to accommodate sensors and actuators, which are predominately analog.

Analog systems are confined to the lowest levels of direct control. The hardware becomes too complex and inflexible at higher control levels.

10.3.5 Unit Computer Control. The rate of application of digital systems has to a large extent been dependent on the cost of computers. The first breakthrough came in about 1970 with the relatively low cost mini-computer. This permitted the development of a new industry providing turnkey control systems for unit or region control. These packages included all hardware (computers, special sensors, operator stations), the software, (computer programs which control the system), and engineering services.

The initial applications were mostly for paper machine control. No direct benefits in pollution control were claimed. One could, however, postulate both a benefit and disadvantage as follows: the benefit would result from more stable operation of the paper machine. This resulted in fewer paper breaks and operational rejects, both of which cause unpredictable surges in wet and dry broke, which can in turn overflow tanks and cause spills. The other side of the coin results from a fundamental property of control loops. The purpose of the loop is to minimise variations in the controlled variable (such as paper moisture). These variations are caused by the disturbance variable (such as pulp freeness). The control system transfers this variation to the manipulated variable (steam flow). This disturbs the stream pressure and boiler fuel and air control, increasing the potential for emissions. It also upsets other steam dependent units such as black liquor evaporators, which in turn upset the recovery furnace, making emission control more difficult.

Computer control systems for batch and continuous digesters have become common and provide certain environmental benefits. Batch digesters use large quantities of steam during the heating phase. Computer control (intra-area coordination) permits improved scheduling of batches and results in leveling of steam demand. Improved control of digester Kappa number reduces upsets in pulp washing due to the stabilising effect on the quality of the washer feedstock.

Both of the above can reduce and stabilise the loads on the recovery boiler reducing atmospheric emissions and the likelihood of black liquor spills. More importantly, recovery furnaces that operate at a steady load are easier to control and can be relatively easily tuned to minimise emissions.

Bleach plant computer control reduces variations in pulp brightness and the residual chlorine concentration in the bleach plant effluent.

Since 1973, the increase in fuel prices has caused emphasis to be placed on improved control of recovery, fossil fuel and hog fuel fired boilers. In all cases, these involve combustion controls which use flue gas composition sensors and automatically adjust combustion air. This is done primarily to maximise combustion efficiency, but usually reduces particulate emissions from hog fuel boilers compared with manual control.

It has been found that control of carbon monoxide emissions to below 600 ppm in recovery furnaces (Figure 24) eliminates hydrogen sulphide emissions as well as being close to maximum combustion efficiency (32,82,83). This is discussed in Section 10.3.6.

Additional control functions for recovery furnaces include liquor firing control, bedshape control and furnace temperature control. These have an effect on the

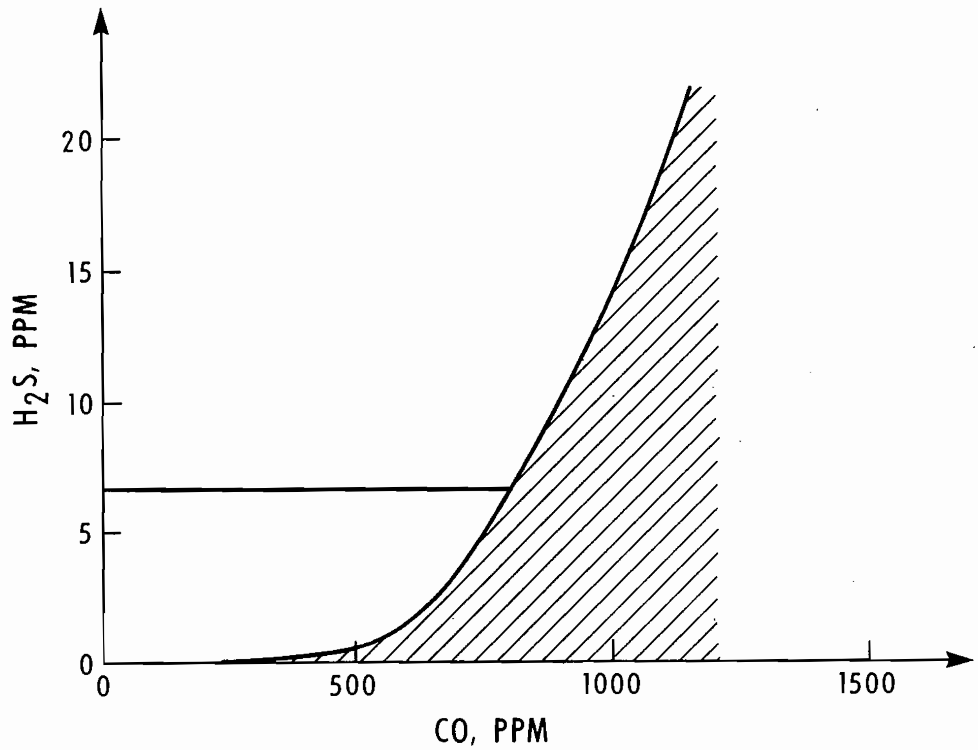


FIGURE 24 RECOVERY FURNACE HYDROGEN SULPHIDE vs. CARBON MONOXIDE EMISSIONS

oxidation/reduction balance and hence the composition of the gaseous combustion product. Recent work (84) has shown the importance of measuring and controlling carbon monoxide and oxygen independently to maximise reduction of Na_2SO_4 to Na_2S, reducing the load on the recovery system.

Particulate emissions generally increase as the firing rate on hog fuel fired boilers increases. The supplier of one package control system states that bark rate is automatically adjusted to keep the stack gas opacity at the limit.

Control of mechanical pulping processes such as TMP, CTMP, and stone groundwood (85) is basically in its infancy in Canada although it is more widely practised in Europe. The primary benefits are reduced variations in pulp quality (freeness) with steadier paper machine operation.

The computer control functions mentioned above are all essentially unit process controls at the direct and supervisory level. In addition, energy management systems are available which operate on several boilers, turbines, etc., at the intra-area level.

About 80% of the Canadian paper machine capacity is now computer controlled. About 15% of the Canadian recovery furnaces, and a small proportion of the power boilers have computer controls. In the chemical pulping and bleaching areas, about 50% of the plants have some form of computer control. There are no computer control systems on stone groundwood and perhaps 10% for TMP or CTMP.

In general, the main emphasis is on multivariable feedback and feedforward control at the direct level plus some supervisory functions such as optimisation. The systems also generate production reports, but usually at the unit level rather than area levels. The computers are generally stand-alone, that is to say they have no communications links with other computers.

Most newsprint mills and several other mills have roll handling computer systems for the finished paper which carry out certain parts of two of the highest levels, mill operational management, and mill management information, as well as the lower levels of control associated with roll finishing handling and shipping. These systems are mostly of Canadian origin. They operate in isolation from the other process computers in these mills and have no environmental effect. However, they are likely to be expanded to manage larger areas of the mill process, including those which affect effluents and atmospheric emissions. A new system designed to integrate the hierarchical control system both horizontally and vertically has been announced, including links to existing process computers, extending operational management control into the mill process.

A second price breakthrough in computer technology was the commercialisation of the micro-computer in the late 1970s. This lowered the cost of individual computers dramatically. In addition, it enabled the development of cost-effective digital communications networks linking together distributed microcomputers. This type of system is being used instead of analog controllers in a significant proportion of mill expansions and re-builds. They are frequently referred to erroneously as "mill-wide" systems because the network permits access to any variable or control loop regardless of its physical location. Generally, however, these systems are limited to the direct control level. The term "mill wide" system should be reserved for systems that also include the higher levels of control to be discussed in Section 10.3.7.

10.3.6 Sensors for Effluent and Emission Control. Automatic control depends on accurate and reliable sensors. No sensors are presently available to measure BOD or toxicity in effluent directly, but volumetric flow can be measured quite readily. The concentration of suspended solids is not directly measurable, but some optical sensors are now available that provide useful estimates of suspended solids concentrations where the solids composition of the effluent is reasonably constant.

Direct computer control of effluent treatment systems is technically feasible, but has not yet been applied in the pulp and paper industry. The most useful field of application would be activated sludge plants, but these are rare in Canada.

Particulate matter in atmospheric emissions can be correlated quite well with opacity sensor readings. TRS is also measureable although the reliability of the instruments has been disappointing (86). As mentioned previously, this problem could be overcome in recovery furnaces by inferring TRS concentrations from carbon monoxide concentrations measured by CO sensors which are potentially much more reliable.

10.3.7 Mill-wide Control Studies. As mentioned in Section 10.3.3, the higher level functions will play an important role in the future of environmental protection. There has been no experience with mill-wide control in Canadian mills, but the concept has been confirmed by a major cooperative project in Scandanavia (83,87). The project was principally concerned with effluent control. The philosophy behind it was that traditional monitoring of mill effluent after treatment, usually based on 24-hour averages, is quite unsuitable for short-term detection of the source of a pollutant, and hence its control. This requires measurement at source. One of the objectives was to overcome the problem of automatic warning alarm systems which cause so many false alarms that their usefulness is destroyed, while still retaining the necessary sensitivity to be effective.

Additional process instruments were installed as follows:

- flow and conductivity sensors to monitor waste streams in the kraft liquor cycle;
- flow and suspended solid sensors to monitor waste streams in the fibre processing departments; and
- level sensors on buffer tanks, liquor tanks, and filter vats.

Because effluent discharge flows are generally very unsteady the system includes comprehensive data analysis programs to analyse all the measurements. The alarm criteria for peak discharges are such that only environmentally significant discharges trigger alarms. The system is designed so that a peak discharge initiating the alarm must:

- contain a minimum amount of contaminant, and
- exceed a dynamic alarm limit set at a particular value above the current steady discharge.

Increases in the pollution load resulting from deliberate actions should not alert the operators. Otherwise, they will quickly become confused and/or ignore the system. Examples of such situations are the routine drainage of tanks or production rate changes. Data, trend graphs and alarms are displayed on a colour video screens.

The cost of this one mill-wide control project, including all the upper level functions and the discharge monitoring system, was about \$1.5 million. Total annual savings of \$700 000 were reported to have resulted. Of these savings, about half were due to reduced losses of fibre and chemicals. It should be noted, however, that more than half of the latter savings were due to process modifications motivated by information generated by the monitoring system, rather than by direct control of losses.

10.4 Environmental Impact Studies

Most regulations intended to reduce odour around pulp mills, except those of Ontario, are based on emission levels, rather than on ground level concentrations. However, the impact of any TRS emission on ground level concentrations is often more dependent on the elevation, temperature and velocity of emission than on the quantity of malodourous gases emitted. In the case of a pulp mill with a typical arrangement of stacks, one kilogram of TRS gas emitted from a low elevation, cool vent can have over a thousand times the effect on ambient concentration of TRS at ground level as the same kilogram emitted from a high hot stack, such as from a recovery furnace.

The state-of-the-art of mathematical modelling for prediction of atmospheric dispersion of stack emissions is sufficiently advanced to allow different stack and vent arrangements to be compared for any mill-site, even in complicated terrain. These models often require fairly large computers, which often limited application in the past, but is not a significant factor today due to the dramatic reduction in computer costs.

The calculation power of computers is also useful in studies of river assimilation capacities, as well as a statistical and data logging in preparation of data bases related to environmental quality. Without computers, much of the technology developed in the last 20 years would be unusable due to the workload involved in calculations.

11 ENERGY IMPLICATIONS OF NEW PROCESSES

11.1 General

Except for aluminum production, the manufacture of pulp and paper requires more energy per dollar sales than any other major industrial product, so energy costs and consumption have a major impact on the industry's viability.

Most of the "add on" atmospheric emission control equipment and external effluent treatment systems that have been installed in response to environmental regulations have increased mills' energy consumption. Estimates vary as to the amount, but are usually about 0.3 GJ/t product for a mill that complies with current regulations (88). This is small but not insignificant when compared with the average consumption of about 14 GJ purchased energy per tonne production.

The energy requirements for primary treatment systems are up to about 0.05 GJ/t product, and depend mostly on the volume of effluent that has to be pumped and the amount of sludge that has to be dewatered.

Secondary treatment energy requirements depend mostly on the BOD removal required, since this is the key parameter defining aeration power. About 0.2 GJ/t kraft pulp or thermomechanical pulp is generally necessary, but the requirements for sulphite pulp mills are much higher and are very dependent on pulping process yield as well as the characteristics of the final product.

In-plant measures for reduction of discharges mostly reduce energy consumption, and can recover up to about 2 GJ/t in some cases. A few in-plant measures, such as the older steam strippers for contaminated condensates, are high energy consumers, up to about 1 GJ/t pulp, but they are being replaced.

The increasing cost of energy has resulted in the implementation of a wide variety of measures to reduce the energy consumption of the pulp and paper manufacturing processes. These have had various environmental impacts, such as reducing emissions of sulphur dioxide, and reducing effluent flows due to increased reuse of water. The reductions in flow often result in modest reductions of BOD and suspended solids discharges, but usually increase the effluent toxicity since the current toxicity guideline is effectively a measure of concentration of material toxic to fish, rather than a measure of mass flow as most other Canadian regulations are.

11.2 Kraft Pulping and Bleaching

Environmental pressures and energy costs have led to extensive recycling of water and spent cooking chemicals, which has reduced the energy requirements for kraft mills in recent years. No industry-wide data have been published, but some mills have indicated savings of 2 GJ/t in bleach plant steam consumption.

Oxygen bleaching, discussed in Section 6, and improved brown stock washing, discussed in Section 5, lead to increased steam production provided that the recovery furnace has sufficient capacity to burn the recovered organic material. This is significant in the design of new mills, but many existing mills would have to install new recovery furnaces to take advantage of such savings. Any increase in steam production from burning black liquor solids generally reduces the quantity of oil or other fossil fuel fired in one of the other mill boilers. However, the effect on total emissions from the recovery furnace or the power boiler is generally negligible.

The high efficiency electrostatic precipitators now required for recovery furnaces consume about 0.1 GJ/t and the lime kiln scrubbers typically require 0.03 GJ/t to comply with current regulations.

11.3 Newsprint

The trend towards increased use of thermomechanical pulping, partly due to environmental pressures to reduce the effluent from the sulphite pulp mills, has increased energy requirements by about 2 GJ/t newsprint, compared to the traditional processes. Much of this energy is recoverable for drying paper (89).

11.4 Power Plant

All pulp and paper mills have boilers to produce steam for process use, and many also generate some or all of the mill's electrical power requirements.

Primarily due to the increasing costs of oil and other fossil fuels, but also because of environmental pressures to reduce the quantities of bark being landfilled, a number of mills have installed new hog fuel boilers. Some mills have modified existing boilers or operating procedures to increase the quantities of hog fuel burned. Since this generally replaces oil or natural gas, there is an increase in particulate emissions. However, most of the new and rebuilt boilers comply with the current particulate emission regulations, and there is no evidence that emissions of this level have any significant environmental impact. When the hog fuel firing rates of older boilers are substantially increased, it is usually necessary to upgrade the particulate emission control equipment to avoid excessive emissions.

Where mills install turbogenerators, their total fuel consumption will increase, typically by several percent, which may also increase particulate and sulphur dioxide emissions. However, in practice, most turbogenerators are installed to take advantage of cogeneration, where oil is often replaced as the fuel for a utility power station, decreasing SO_2 emissions. Most major expansions in mill turbogenerator capacity are associated with the installation of modernised boilers, which usually incorporate efficient emission controls. A turbogenerator installation in a pulp or paper mill rarely has any significant detrimental effect on emissions.

11.5 Sulphur Dioxide Emissions

The steam and power plant is the principal source of sulphur dioxide emissions in most mills, except acid sulphite mills. The emissions from the power plant boilers themselves depend entirely on the total quantity of sulphur in the fuel burned. There is no useful correlation with the type of mill or the production rate. When natural gas is the fossil fuel, the sulphur dioxide emission is essentially zero.

Where residual fuel oil is burned, the consumption could be up to three barrels oil per tonne pulp, if the mill does not use hog fuel. With 3% sulphur oil, this could represent about 27 kg SO_2/t pulp. However, at least one Canadian mill burns only black liquor and hog fuel, and therefore emits no sulphur dioxide from its steam plant. Most mills emit from 5 to 20 kg per tonne pulp; the average emission in 1978 was 10.7 kg/t product.

The total oil consumption by Canadian pulp and paper mills in 1978 was approximately 20.8 million barrels, with an estimated average sulphur content of 2.24%. This is equivalent to a sulphur dioxide emission of about 135 000 t/year, after deducting for oil usage in lime kilns, since they do not generate sulphur dioxide emissions.

The total sulphur dioxide emissions from pulping processes were estimated at 104 500 tonnes in Environment Canada's national emission inventory of 1978, so that the total pulp and paper industry sulphur dioxide emission at that time was approximately 239 500 t, or about 5% of the total sulphur dioxide emissions in Canada from all sources (4 500 000 t).

No definitive data is readily available to calculate the 1983 situation. However, oil consumption has dropped to about 18 million barrels, and several sulphite mills have closed or converted to high yield sodium base processes which emit little sulphur dioxide, so that the total pulp and paper industry sulphur dioxide emissions have probably dropped by about 10 - 15%. The trend toward low odour recovery furnaces and the installation of more sulphite recovery systems has added a small quantity of sulphur dioxide to the total emitted by recovery systems, but most other process developments have tended to reduce emissions of sulphur oxides.

To summarise, the pulp and paper industry contributes a small but not insignificant proportion of the total sulphur oxide emissions in Canada. The quantities emitted are declining, and will probably continue to do so, primarily because of the continuing implementation of energy conservation measures which reduce the industry's consumption of oil.

12 COSTS

12.1 General

The definition of the costs of environmental protection measures for the pulp and paper industry is complicated by the fact that much of the equipment required is integrated with the production systems, particularly when the more modern in-plant technologies are utilised. There is no accepted definition of what would constitute a pulp or paper mill without environmental protection measures, and therefore no yardstick for comparison with the known current costs for mills which have adequate environmental protection measures. The following data indicates the approximate capital and operating costs of facilities for which the principal justification is compliance with environmental regulations.

There is no doubt that additional costs are incurred by the industry when mill modifications or equipment selection is influenced by environmental concerns, but these cannot be clearly identified. Reductions in operating costs have also resulted from the improved understanding of the manufacturing process as an overall system gained from the studies of mill operations and research performed in response to environmental pressures. No attempt has been made to include such intangible costs and savings in the data discussed below.

A number of studies were conducted in the United States in the early 1970s on the costs for environmental protection measures in the pulp and paper industry. Some of them were quite comprehensive, technically sound investigations, but inflation and technological developments have rendered the data obsolete. Much of the data on environmental protection costs published in the late 1970s was simply extrapolated from these earlier studies, so that further extrapolation is more likely to be misleading than useful. No comprehensive studies applicable to 1983 environmental protection costs in Canada have been published, with the exception of reference 90. Published data are available from Statistics Canada and several private sources on the rates of inflation for industrial construction, chemical costs, labour rates, etc. However, changes in regulatory requirements and technology make it impractical to apply these to environmental protection costs for periods exceeding about five years.

The principal factors affecting the capital and operating costs of environmental protection measures are the mill process and the applicable regulations. In addition, the actual costs at any one mill are site-specific and any one of the following factors can lead to variations in local costs by a factor of at least 2:1:

- quality and ingenuity of engineering and project management,
- constraints due to previous technical decisions,
- topography,
- local energy costs, and
- land availability.

12.2 Effluent Treatment Costs

The capital and operating costs for the installation of facilities to bring Canadian mills into compliance with federal regulations were estimated by Beak Consultants in 1977, with data reported as 1976 dollars (90). The data in Table 18 are based on these estimates and were calculated by applying Statistics Canada inflation factors, with some modifications on the basis of the author's recent experience.

TABLE 18 APPROXIMATE WATER POLLUTION CONTROL COSTS (1982 Dollars)

	Capital Costs ($/daily tonne product)	Direct Operating Cost* ($/tonne)
Kraft Mill	24 000	7
Low Yield Sulphite	195 000	5 (credit)
Integrated Newsprint/sulphite	40 000	3
Newsprint (without sulphite)	20 000	5
Other Non-Integrated Paper	9 000	3

*Direct costs include labour, energy, technical support, maintenance and chemicals but exclude depreciation, interest and taxes, etc.

These costs were based on the mid 1970's proven technology, and it is probable that actual costs could be reduced in 1983 by the application of the in-plant technology that has been developed in recent years. No comprehensive studies are available to confirm this, but the author's experience concerning specific mills indicate that this is so.

In-plant measures generally incur roughly the same capital costs as the external treatment systems mentioned above, but the operating costs of in-plant systems are usually substantially lower than those shown. The technology of in-plant environmental protection measures is generally more complex than external measures. Constraints such as the availability of sufficient, technically qualified staff and restrictive union practices have forced many mills to use the more expensive external treatment approach.

In some cases, provincial regulations are significantly more demanding than the federal regulations, particularly where a mill discharges to a small or environmentally sensitive watercourse. The foregoing cost data contain no allowances for the additional costs incurred in such cases.

12.3 Atmospheric Emission Control Costs

The available publications on atmospheric emission control costs for complete mill systems are all based on late 1960s and early 1970s technology and regulations. They are hardly relevant to 1983 technology, regulations and costs, and the data has not been utilised in the preparation of this review, although some references are listed (91,92).

There is no lack of published costs for specific pieces of air pollution control equipment, but the authors are usually also the vendors of the items concerned, and any data cited on the costs for installation and the necessary auxiliary equipment in such publications must be treated with caution. The following data on costs are based on the experience of the author and quotations from equipment suppliers, and must be interpreted in that context. A comprehensive study of requirements and actual field costs would be necessary to estimate costs in any detail.

In the case of a new kraft mill, the capital cost of the air pollution control systems would be in the order of $9 000 per daily tonne of production capacity. The direct operating costs are normally under $1/t, and there may be a small revenue due to chemical and energy recovery.

For soluble base sulphite mills with chemical recovery systems, the additional cost for sulphur dioxide emission control over that required for purely economic reasons would be under $2000 per daily tonne of pulp production.

For other mills, the capital cost of air pollution control facilities would be under 1% of the mill capital cost in most cases.

These figures do not include the costs of atmospheric emission control for steam generating plants. These could vary from negligible for natural gas fired boilers to about 5% of the total capital cost for hog fuel fired boilers.

For coal fired boilers, the costs of particulate emission controls to comply with current regulations would probably be higher. In the event that sulphur dioxide emission control equipment was required, the capital cost would be very much higher. However, there seems to be little likelihood that the Canadian pulp and paper industry will install significant coal firing capacity in the forseeable future.

The most significant operating costs for most of the air pollution control equipment used in the industry are maintenance and capital-related charges (depreciation, interest, insurance, taxes, etc). In some cases the energy consumption is significant, but most of the systems also recover chemicals, which tends to offset the energy costs. It is unusual for air pollution control facilities to increase the direct operating labour requirements, except for some increase in ash trucking costs where applicable. The annual costs for equipment maintenance, technical support, and emission testing are typically a few percent of the capital cost of the installation concerned.

Where air pollution control facilities have to be retro-fitted to an existing plant, the capital costs are usually somewhat higher than those indicated above for new installations. In some cases the costs could be substantially higher, such as when an improved multiple cyclone for a hog fuel boiler requires a new induced draft fan and major structural modifications due to space constraints. It is not possible to provide realistic guidelines for retro-fit costs, since experience has shown that they vary widely.

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Over 5000 articles have been published in pulp and paper industry technical journals in the last 10 years concerning pollution and the environment. Readers with specific need should consult them, preferably via one of the commercial computer data banks such as DIALOG, or INFOMART.

The National Research Council's CAN-OLE literature service has quite complete coverage of Canadian sources, including government publications, but does not include the Abstracts Bulletin of the Institute of Paper Chemistry (ABIPC) which is the best source for most pulp and paper industry oriented searches. The other services mentioned above include ABIPC under the trade name PAPERCHEM.

APPENDIX METRIC CONVERSION

The world is currently moving towards a uniform system of measurement. In 1971, the Canadian government established Metric Commission Canada to investigate, plan and coordinate implementation of the conversion to the metric system in Canada. In recent years the Canadian pulp and paper industry has been steadily converting data reporting to the SI system.

The basis for this move is the International System of Units and most current technical publications use it. "Système International d'Unités" (SI) has been adopted by the General Conference of Weights and Measures and endorsed by the International Organization for Standardization (ISO).

Principal SI Units and Abbreviations

Quantity	Name	Symbol	Other Units
length	metre	m	
mass	kilogram	kg	
time	second	s	
frequency	kertz	Hz	
force	newton	N	
pressure; stress	pascal	Pa	N/m^2
energy; work; heat	joule	J	N•m
power	watt	W	J/s

Although it is not a customary SI unit, the term "Sm^3" is routinely used in air pollution control in Canada. It refers to one cubic metre of dry gas at 25°C and 101.325 kilopascals absolute pressure. Other countries frequently use a slightly different temperature. The following specialised units and abbreviations are routinely used in forestry:

1 cord = 128 ft^3 stacked roundwood = 3.6 m^3 (stacked)

1 cunit = 100 ft^3 solid wood = 2.83 m^3

1 cord/acre = 9 m^3/ha

1 ft^3/acre = 0.07 m^3/ha

General Conversion Factors

The following short list contains only the principal conversion factors relevant to the pulp and paper industry.

acres	x 0.40469	= ha
barrels (US,oil)	x 0.15899	= m^3
Btu	x 1.0551	= kJ
calorie	x 4.1868	= J
ft H_2O (pressure)	x 2.989	= kPa
sq. mile	x 259	= ha
pounds	x 453.59	= g
pound-force	x 4.4482	= N
pound/ft^3	x 16.018	= kg/m^3
pound-force/ sq. inch (psi)	x 6.895	= kPa
tonnes (t)	x 1000	= kg
tons (long)	x 1.016	= t
tons (short)	x 0.90718	= t
kW	x 0.0036	= GJ/h
hp	x 0.0027	= GJ/h
hp-day/short ton	x 0.0714	= GJ/t
Quad	x 1.0551 x 10^9	= GJ
Btu/lb	x 2.326	= J/g
million Btu/short ton	x 1.163	= GJ/t