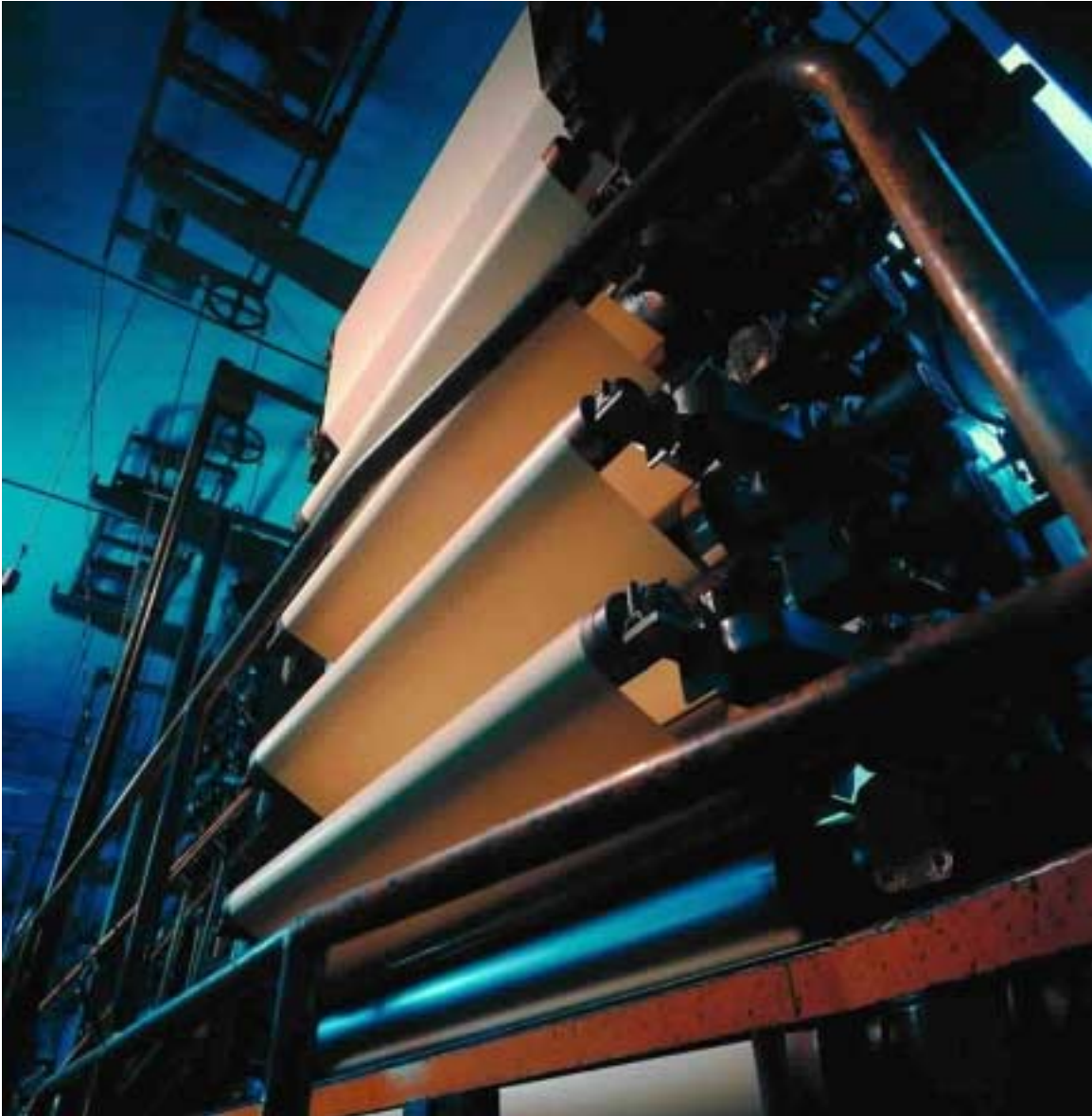


APPENDIX W
PULP AND PAPER





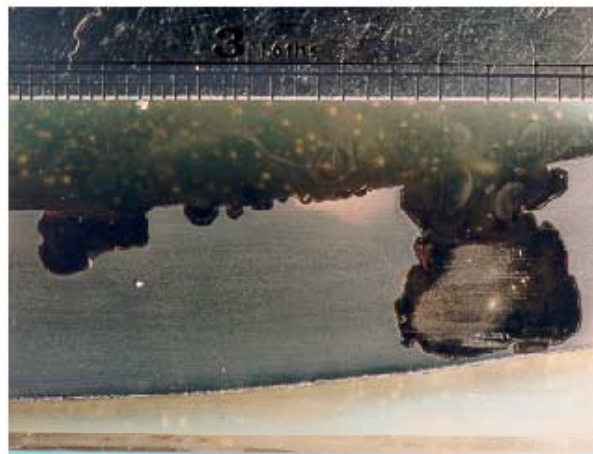
Pulping plant



Suction rolls



Corrosion of vessel wall



Microbiologically influenced corrosion

PULP AND PAPER

MICHEL P. H. BRONGERS¹ AND AARON J. MIERZWA¹

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The \$165 billion pulp, paper, and allied products industry supplies the United States with approximately 300 kg of paper per person per year. More than 300 pulp mills and more than 550 paper mills support its production. A typical pulp mill uses approximately 64 m³ of water per metric ton of pulp, and the combined pulp and paper manufacturers release approximately 100 thousand metric tons of toxic chemicals per year into the air, water, or land.

The total annual corrosion costs for the pulp, paper, and paperboard industry, as determined as a fraction of the maintenance cost, is approximately \$1.97 billion to \$9.88 billion (average \$5.928 billion per year). These estimates are between 1.2 percent and 6.0 percent of the total sales for the entire U.S. pulp and paper industry. The cost of corrosion for the pulp industry was only estimated at approximately \$808.5 million per year.

Paper production consists of a series of processes and can be roughly divided according to the five major manufacturing steps: (1) pulp production, (2) pulp processing and chemical recovery, (3) pulp bleaching, (4) stock preparation, and (5) paper manufacturing. Each manufacturing step has its own corrosion problems related to the size and quality of the wood fibers, the amount of and temperature of the process water, the concentration of the treatment chemicals, and the materials used for machinery construction. Examples of corrosion affecting production are: (1) corrosion products polluting the paper and (2) corrosion of rolls scarring the sheets of paper. Corrosion of components may also result in fractures or leaks in the machines, causing production loss and safety hazards.

Opportunities for Improvement and Barriers to Progress

Major changes in the paper-making process have occurred in the period from 1975 to 2000. Today's digital world requires much-increased production of pulp and paper. Paper recycling and environmental issues concerning chemical releases have forced the pulp and paper industry to change their processes. The fierce competition within the pulp and paper industry has resulted in many company mergers, a smaller total number of pulp and paper mills, and significantly increased production capacity per mill. Furthermore, factories are no longer allowed to "run a river through their plant" and dump the processed water back into the environment without cleaning it first. There is a clear trend of decreasing the amount of process water, recycling and reusing the water in closed-loop systems, and cleaning the water before releasing. This results in a more corrosive process environment.

Paper mills in the United States are traditionally constructed of a combination of carbon steels and stainless steels. In general, production systems run cleaner if all machinery in contact with the process stream would be constructed of corrosion-resistant alloys, which effectively reduce the general corrosion rate. Although stainless steel can be susceptible to other forms of corrosion, such as stress corrosion cracking of weld heat-affected zones, the use of stainless steel reduces the formation of thick corrosion scales and significant wall loss can be prevented.

¹ CC Technologies Laboratories, Inc., Dublin, Ohio.

An important barrier to immediate implementation of a complete change from carbon steel to stainless steel is the value of this investment. To resolve this, companies gradually exchange their equipment, when process upgrades are made. Pulp and paper mills are factories that involve a series of consecutive pieces of equipment, each with a different useful service life. At the end of the service life, when production is severely affected by the age of the equipment, equipment is completely replaced.

The European paper and pulp industry has demonstrated success in using a chlorine-free bleaching process for selected pulp grades. Substitutes for chlorine include ozone, oxygen, and peroxide. The Metsä-Rauma pulping plant was opened in Europe in 1996, and is one of a kind as it is made entirely of stainless steel. By using this material for each process, the maintenance costs associated with equipment are significantly reduced in comparison to those for carbon steel equipment. The capital investment for this pulping plant was \$550 million. The capital investment costs for a new state-of-the-art integrated mill are estimated at \$1 billion.

Recommendations and Implementation Strategy

A large portion of the corrosion cost lies in maintenance of carbon steel components. In many paper mills, corrosion management is concentrated around the maintenance groups, which primarily deal with all outages, replacements, and equipment inspections. The objective of the maintenance work is to ensure that production runs continuously. While some mills may have dedicated corrosion engineers on staff, most do not. It is recommended that awareness among maintenance engineers be increased so that corrosion maintenance can be conducted cost-effectively and in a timely manner. Furthermore, it was shown in the case study (Metsä-Rauma pulping plant) that replacement of the carbon steel components with stainless steel significantly reduces the corrosion maintenance costs. Hence, despite a higher initial cost, the use of corrosion-resistant alloys is recommended.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Total corrosion maintenance costs range between \$1.97 billion and \$9.88 billion. The corrosion cost for pulping is only \$808.5 million.
Change perception that nothing can be done about corrosion.	All-stainless steel equipment effectively reduces the general corrosion rate.
Advance design practices for better corrosion management.	Use more corrosion-resistant alloys. Prevent pulp build-up.
Change technical practices to realize corrosion cost-savings.	Regular inspections and preventive maintenance have proven to be effective in maintaining uninterrupted operation.
Change policies and management practices to realize corrosion cost-savings.	Corrosion is dealt with from a maintenance point of view. The “do nothing” approach is not the most cost-effective method.
Advance life prediction and performance assessment methods.	The current approach of do nothing and replace equipment at the end of a service life allows for upgrades; however, accurate life predictions may prevent unscheduled outages.
Advance technology (research, development, and implementation).	There are currently no all-stainless steel plants in the United States. Integration of this material in the pulp and paper industry would follow the European example.
Improve education and training for corrosion control.	Maintenance personnel deal with corrosion once failure has occurred. Few companies have dedicated corrosion engineers on staff.

TABLE OF CONTENTS

SECTOR DESCRIPTION	W1
Background	W1
Environmental Issues	W3
Water Usage	W3
Chemical Usage and the Cluster Rule	W3
AREAS OF MAJOR CORROSION IMPACT	W3
Step 1. Pulp Production	W4
Mechanical Pulping	W5
Semi-Chemical Pulping	W5
Chemical Pulping	W5
Step 2. Pulp Processing and Chemical Recovery	W5
Kraft Pulping Chemical Recovery	W6
Sulfite Pulping Chemical Recovery	W7
Step 3. Pulp Bleaching	W7
Traditional Bleaching Techniques	W7
Environmentally Friendly Techniques	W7
Step 4. Stock Preparation	W7
Step 5. Paper Manufacturing	W8
Wet-End Operations	W8
Dry-End Operations	W9
Determining Corrosion Cost for the Pulping Industry	W9
Determining Corrosion Cost as a Percentage of Maintenance	W11
CORROSION CONTROL METHODS	W12
Equipment Design	W12
Process Design and Corrosion Inhibitors	W13
Weight Loss Coupons	W13
Inspection and Preventive Maintenance	W14
CORROSION MANAGEMENT	W14
CHANGES FROM 1975 TO 2000	W15
The Digital World	W15
Recycling and Environmental Issues	W15
Recovered Paper	W15
Competition Issues	W15
CASE STUDY FOR THE PULP AND PAPER INDUSTRY	W16
Metsä-Rauma Pulp Mill – Totally Chlorine-Free Production	W16
REFERENCES	W16

LIST OF FIGURES

Figure 1.	The division of paper and pulp mills in the United States and Canada in 2000.....	W1
Figure 2.	Total production of wood pulp, paper, and paperboard in the United States for the period 1993 to 1999 in metric tons.....	W2
Figure 3.	<i>Pulp & Paper Week</i> monthly price index for March 1993 to March 2000	W2
Figure 4.	Flow diagram for the paper-making process	W4
Figure 5.	Paper machine used to transform processed pulp into paper product	W8

LIST OF TABLES

Table 1.	Top five highest amounts of toxics release inventory (TRI) chemicals released in 1995 by pulp and paper facilities	W3
Table 2.	Estimated annual corrosion cost (1998 dollars) for the U.S., Canadian, and world pulping industry in 1975 and 1996, based on calculations by Singbeil, using 1974 data from Davy and Mueller and the <i>1998 Fact & Price Book</i>	W10
Table 3.	Total annual corrosion costs for wood pulp, paper, and paperboard production as determined from 1998 production data, total maintenance costs, and estimates of percent corrosion costs of the total maintenance costs.	W12

SECTOR DESCRIPTION

Background

The pulp and paper industry is a vital part of the U.S. economy. In 1998, the United States used an estimated 318 kg (700 lb) of paper per person⁽¹⁻²⁾ per year.² This included newspapers and magazines, toilet paper, printer and copier paper, tickets, receipts, pictures, stamps, packaging paper, and various other products. In 1998, the U.S. paper and allied products industry reported total sales of \$164.9 billion, with \$3.6 billion in earnings. In addition, in 1998, the wood pulp, paper, and paperboard industry ran at capacities of 93.6 percent, 92.3 percent, and 92.2 percent, respectively. According to the U.S. Environmental Protection Agency (EPA),⁽³⁾ approximately 16 percent of the world's pulp mills were located in the United States.

The Lockwood-Post's Directory, which provides annual statistics on the U.S. pulp and paper industry,⁽¹⁾ reported the total number of pulp and paper mills in the United States and Canada (see figure 1). The ratio of these two major components of the paper-making process appears to be similar for the two countries. Paper mills and pulp mills are often located on the same site and owned by the same company. In addition, the mills may be connected and have processes that are partially integrated. Therefore, this count may vary according to the method used to determine what is considered as "one mill." The production amount of the different paper products (pulp, paper, and paperboard) produced in U.S. mills from 1993 to 1999, shown in figure 2, remains relatively constant.

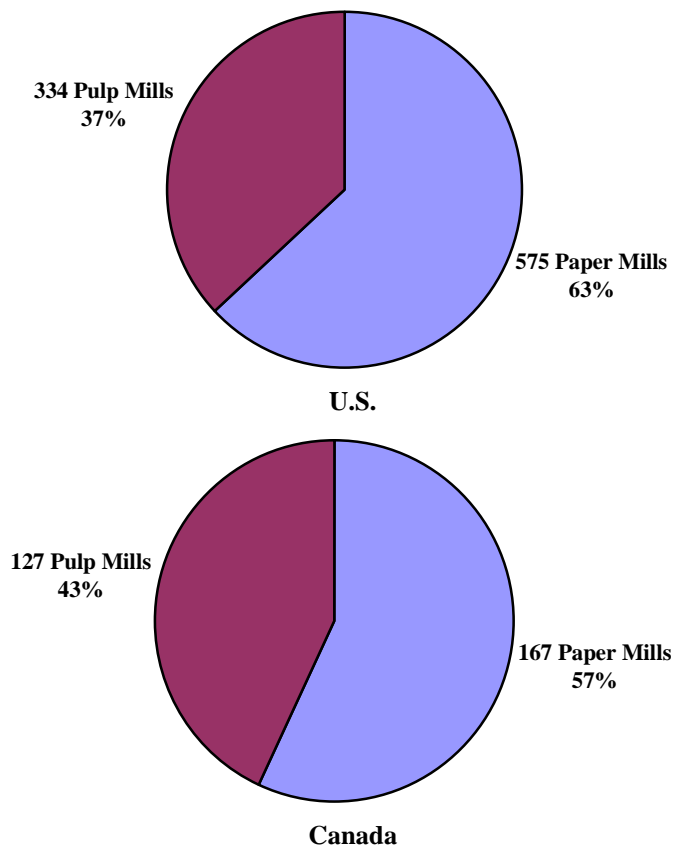


Figure 1. The division of paper and pulp mills in the United States and Canada in 2000.⁽¹⁾

² Based on 91.66 million short tons (83.2 metric tons) of paper and paperboard used (paper and paperboard produced minus exports plus imports)⁽¹⁾ within the United States, divided by the U.S. Census Bureau's estimate of 266 million people within the United States in 1997.⁽²⁾

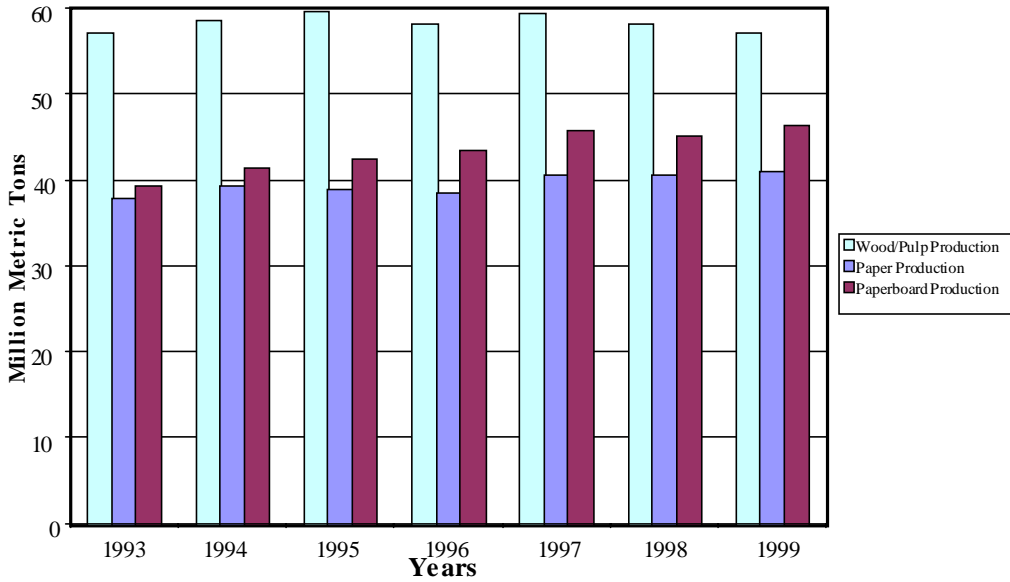


Figure 2. Total production of wood pulp, paper, and paperboard in the United States for the period 1993 to 1999 in metric tons.⁽¹⁾

Although the production of paper products has remained relatively constant over the years, the market prices of pulp, printing and writing paper, and containerboard have fluctuated significantly. This fluctuation has had a direct effect on capital investment and asset management strategies. The website <http://paperloop.com>⁽⁴⁾ provides a monthly price index of the average prices of major commodity grades, an example of which is shown in figure 3. The figure shows the considerable price fluctuations, even on a monthly basis. A price increase or decrease of 25 percent over a 6-month period is not uncommon.

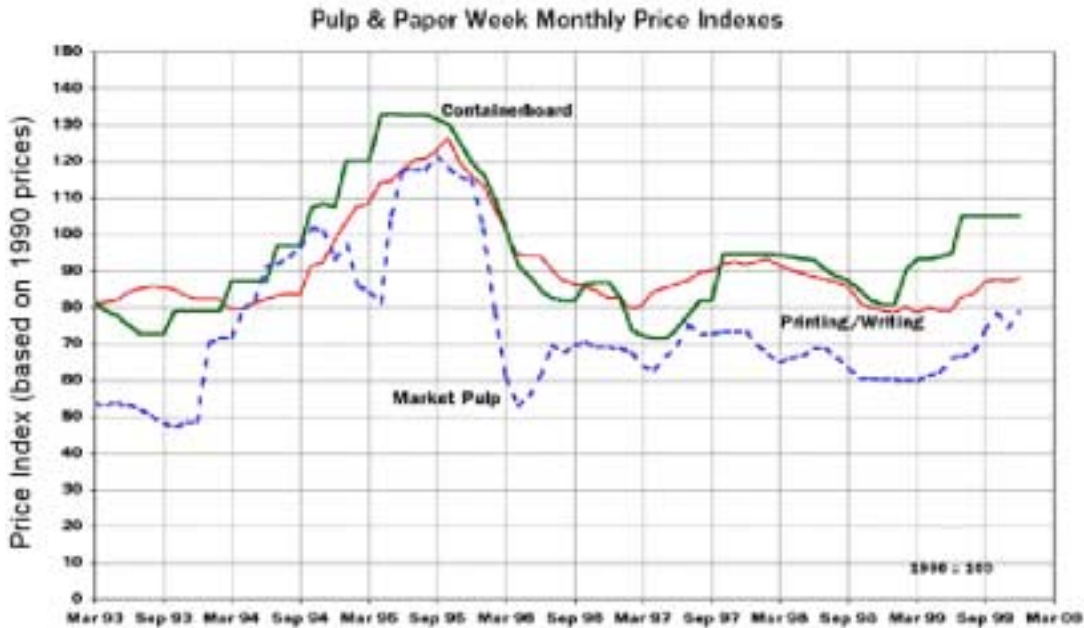


Figure 3. Pulp & Paper Week monthly price index for March 1993 to March 2000.⁽⁴⁾

Environmental Issues

Water Usage

Environmental issues involving the pulp and paper industry require that water usage by pulp and paper mills be reduced because they are among the largest industrial process water users in the United States. A typical pulp mill uses about 64 m³ (17,000 gal) of water per ton of pulp produced, which is a decrease from approximately 379 m³ (100,000 gal) per metric ton in the 1940s.⁽³⁾ Today, the pulp and paper industry uses a lower volume of process water, recycles and reuses more water, and cleans water before releasing it, all in an effort to reduce costs as well as respond to increasingly strict environmental regulations.

Chemical Usage and the Cluster Rule

In 1995, according to the EPA,⁽⁵⁾ the combined pulp and paper manufacturers released a total of 105.5 million kg (232.6 million lb) of toxics release inventory (TRI) chemicals into the air, water, or land. The top five highest amounts of TRI chemicals released in 1995 are listed in table 1.

Table 1. Top five highest amounts of toxics release inventory (TRI) chemicals released in 1995 by pulp and paper facilities.⁽⁵⁾

CHEMICAL	TOTAL NUMBER OF RELEASES	AVERAGE RELEASE PER FACILITY (in metric tons)
Methanol	62,657	358
Hydrochloric Acid	11,022	68
Ammonia	6,643	34
Sulfuric Acid	5,864	40
Chloroform	4,464	55

The environmental hazards related to the TRI chemicals led the EPA to create the pulp and paper cluster rule,⁽⁶⁾ which limits the total allowable amount of chemicals released through process water, exhaust gases, and solid waste. Because of the cluster rule, operational processes are closed to a greater degree than in the past, creating more aggressive conditions and increasing corrosion-related problems.

AREAS OF MAJOR CORROSION IMPACT

The paper-making process consists of various steps, from pulp production to paper manufacturing, as illustrated in figure 4. The following sections discuss the impact of corrosion during the five major steps of this process: (1) pulp production, (2) pulp processing and chemical recovery, (3) pulp bleaching, (4) stock preparation, and (5) paper manufacturing.

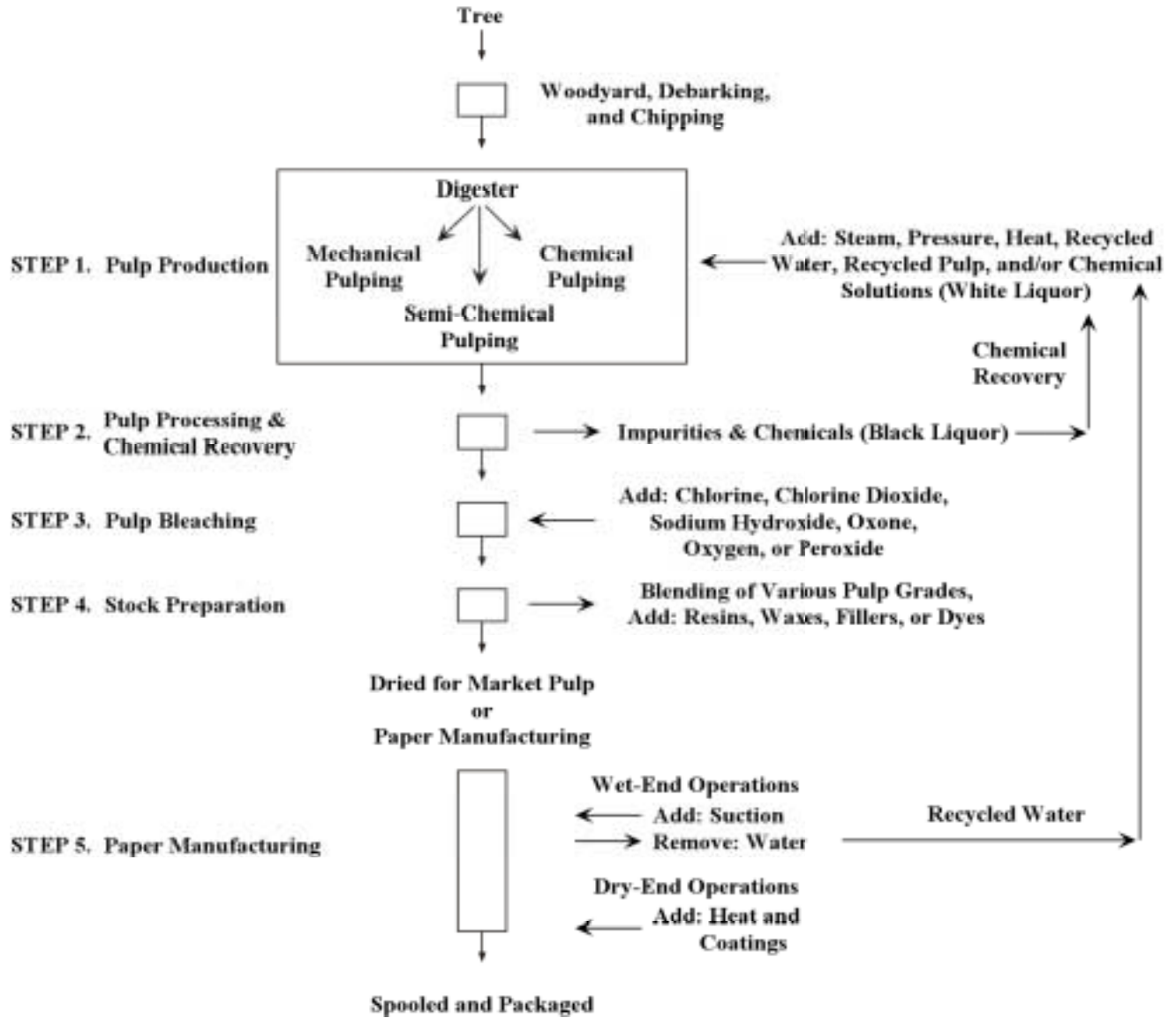


Figure 4. Flow diagram for the paper-making process.

Step 1. Pulp Production

There are several different methods of pulp production to make different strengths and grades of paper. The most common classifications are chemical, mechanical, or semi-chemical pulping techniques. The Lockwood-Post’s Directory⁽¹⁾ reported that in 1998, 58.2 million metric tons (64.2 million short tons) of wood pulp were produced in the United States. Of that, 49.4 million metric tons [54.4 million short tons (84.7 percent)] were produced through chemical pulping techniques, 5.3 million metric tons [5.9 million short tons (9.1 percent)] were produced through mechanical pulping techniques, and the remaining 3.6 million metric tons [4.0 million short tons (6.2 percent)] were produced through semi-chemical pulping techniques (see figure 4). In the following paragraphs, these three pulping processes are described in more detail, based on the 1995 EPA Office of Compliance Sector Notebook Project for the pulp and paper industry.⁽⁷⁾

Mechanical Pulping

Mechanical pulping utilizes steam, pressure, and high temperatures instead of chemicals to tear the fibers. The fiber quality is greatly reduced because mechanical pulping creates short, weak fibers that still contain the lignin that bonds the fibers together. The presence of the lignin limits the amount that the pulp may be bleached because the lignin binds with the bleaching chemicals. Newspaper and paperboards are typical products of the mechanical pulping process. Mechanical pulping requires materials such as 300 series stainless steel to prevent corrosion.

Semi-Chemical Pulping

Semi-chemical pulping techniques use weak chemical solutions composed of sodium sulfite (Na_2SO_3) and sodium carbonate (Na_2CO_3) to help digest the lignin in the pulp. In addition to the chemical solutions, mechanical refining is used to separate the fibers.

Chemical Pulping

Chemical pulping uses various chemicals to produce long, strong, and stable fibers and to remove the lignin that bonds the fibers together. The chemicals used will vary depending on the type of chemical pulping used. In the United States, there are two main types of chemical pulping performed: Kraft (sulphate) pulping and sulfite pulping. The corrosion rate in these processes can be significant depending on the amount and kind of chemicals and the type of materials used.

Lockwood-Post's Directory⁽¹⁾ reported that chemical pulping is approximately 85 percent of the total pulping industry. Within this total, Kraft pulping produced approximately 83 percent [49.2 million metric tons (54.2 million short tons)] of the pulp processed in the United States in 1997. In this process, the lignin bonds of the pulp are dissolved by using alkaline sulfide in a digester at approximately 170 °C (338 °F) for 4 hours. Traditionally, carbon steel has been used as a material of construction. However, because of erosion from particles in the solution and corrosion from an increase in sulfur content due to system closures, stainless steel types 304L and 316L have been used as cladding for the carbon steel digesters. Although stainless steels are generally considered resistant to Kraft liquors, regular inspection must be performed because intergranular stress corrosion cracking (IGSCC) may occur in the heat-affected zone (HAZ) of the weldments.⁽⁸⁾ Specific stainless steel grades used in Kraft pulping digesters and connecting pipes are duplex stainless steels 2205 and 2304 and austenitic stainless steel 312.⁽⁸⁾

The sulfite pulping process produced approximately 1.9 percent [1.1 million metric tons (1.2 million short tons)] of the pulp processed in the United States in 1997.⁽¹⁾ This acid pulping process uses cooking liquor of sodium bisulfite or magnesium bisulfite in a pulp digester with a pH of 3.⁽⁸⁾ Type 316 stainless steel is normally used as a minimum alloy because the sulfur dioxide can degrade to sulfuric acid. Sulfuric acid can lead to corrosion of stainless steels depending on the temperature, pressure, and pH of the system. SCC has been observed in the HAZ of weldments in the pulp digesters in the presence of sodium hydroxide. Because of stress corrosion cracking susceptibility of the austenitic stainless steels, duplex stainless steel 2205 is often used in pressure vessels and tanks.

Step 2. Pulp Processing and Chemical Recovery

To further remove impurities and recycle the cooking liquor, also known at this stage as black liquor, the pulp is processed through a series of washes. The removal of the black liquor takes place in washers and is necessary to reduce the chemical costs of the liquor, generate energy from pulp residue burned in the recovery boiler, and prevent the cooking liquor from binding to the bleach chemicals. In addition, by recycling the cooking liquor back into the pulping process, environmental issues and costs are negated since there are no chemicals that must be discharged from the system.

Kraft Pulping Chemical Recovery

To recover chemicals from the black liquor, the slurry goes through a chemical recovery process, such as the Kraft pulping chemical recovery. The liquor passes through evaporators, recovery boilers, and causticizers to eventually produce white liquor.

The first step of chemical recovery is the evaporation process, which increases the concentration of solids from approximately 15 percent to more than 60 percent. The concentrated slurry contains approximately 50 percent organic solids and 6 percent total sulfur in the form of sodium sulfate (Na_2SO_4) and sodium thiosulfate ($\text{Na}_2\text{S}_2\text{O}_3$) and is placed into a recovery boiler. The organic solids are burned for energy while the inorganic process chemicals, also known as smelt, flow through the floor of the recovery boiler to be recausticized. Mills with high levels of closure operate at high levels of sodium chloride (NaCl). Typically, the NaCl concentration in black liquor is approximately 12 percent in closed systems.

Corrosion on the fireside of the recovery boiler is accelerated by the presence of reduced sulfur species. The hydroxide mixtures present within the black liquor are extremely corrosive to the recovery boilers, which are typically made of Type 304L stainless steels.⁽⁹⁾ Several phenomena in the recovery section cause different forms of corrosion to occur simultaneously, including: (1) corrosion under ash build-up, (2) corrosion in the thin condensation layers, and (3) high-temperature metal/gas interactions.

1. Ash build-up on the heat exchanger tubes can occur in recovery boilers when the incineration of the liquid waste is incomplete. The deposited ashes decrease the efficiency of the heat exchanging process. Under-deposit corrosion may occur in the form of crevice corrosion or pitting.
2. Condensation can occur in the ductwork between the recovery boiler and the off-gas scrubbers when the hot gases cool down to a temperature below their flash point, before reaching the scrubber. Localized attack in the condensate phase can be very severe ($>1,000$ mpy)³ and can be accelerated by the alternating process of condensation and revaporization. The concentration of corrosive species in the thin condensed layer is highest just before complete revaporization.
3. High-temperature metal/gas interactions in the recovery boiler include oxidation, carburization, and sulfidation. The kinetics of these processes vary with the concentrations of the burned black liquor waste and the temperature in the recovery boiler. High-temperature gaseous attack does not require an aqueous or molten salt electrolyte. Continued scale growth at the metal surface results in progressive metal consumption and decreased wall thickness of the boiler tubes and boiler walls.

Recausticizing

Recausticizing is the process used to transform the inorganic smelt recovered from the recovery boiler into white liquor so that the chemicals may be recycled. According to Westin,⁽¹⁰⁾ the recycled inorganic chemicals are discharged as molten smelt from the recovery boiler and then dissolved using water to form green liquor. Any unwanted substances are precipitated out. Lime is then added to the clarified green liquor to produce sodium hydroxide (NaOH) from the remaining sodium carbonate (Na_2CO_3). The resulting solution (white liquor) contains sodium hydroxide, sodium sulfide (Na_2S), and a solid phase of calcium carbonate (lime mud). Before the white liquor is recycled back to the digester, the white liquor is clarified further to remove the lime mud.

³ 1,000 mpy = 1,000 mils per year = 1 in per year.

Sulfite Pulping Chemical Recovery

An alternative process is sulfite pulping chemical recovery. The chemical recovery system of sulfite pulping differs from that for the Kraft process discussed previously. The magnesium-based and calcium-based recovery systems are the most corrosive recovery systems for sulfite pulping.⁽¹¹⁾ Pitting and crevice corrosion under scale deposits are the major corrosion concerns. The sulfite pulping process contains greater amounts of sulfite (SO₃), hydrogen sulfide (H₂S), and hydrochloric acid (HCl) than those used in the Kraft pulping process. Because of the presence of these corrosive species, the internal portions of the recovery boilers and the evaporators are generally constructed of reinforced plastics, Type 316L stainless steel, Type 317L stainless steel, or nickel-based alloys. To prevent pitting and crevice corrosion, scale build-up should be prevented, wet-dry zones should be avoided, and chloride concentrations should be kept to a minimum.

Step 3. Pulp Bleaching

Pulp bleaching is performed on the pulp in order to increase its brightness. Bleaching is an extremely corrosive process that is executed under acidic conditions with strong oxidants such as chlorine, chlorine dioxide, sodium hydroxide, and hydrogen peroxide. In 1993, roughly half of the 65 metric tons (72 million short tons) of pulp used in paper production in the United States was bleached.⁽⁷⁾

Traditional Bleaching Techniques

The EPA⁽⁷⁾ describes the bleaching process as normally having three to five stages in which the pH of the pulp is alternated between acid and alkaline conditions. During the acid cycle, chemical reactions between the bleach and the lignin bonds turn the pulp lighter in color. During the alkaline cycle, the reaction products from the acid stage are removed.

According to Thorpe,⁽⁸⁾ chlorine dioxide has similar corrosivity to chlorine. Suitable materials for bleach washers using chlorine and chlorine dioxide are super austenitic 6 percent to 7 percent molybdenum stainless steels such as 25-4 SMO or 25-6 Mo. Routine cleaning, maintaining a high surface quality, and pickling of weldments with nitric and hydrofluoric acid help protect against corrosion.

Environmentally Friendly Techniques

In recent years, less chlorine and more sodium hydroxide have been used for bleaching. Currently, chemical pulps and the de-inking of secondary fibers are the primary users of chlorine bleaching techniques. The European paper and pulp industry has demonstrated success in using a totally chlorine-free bleaching process for selected pulp grades.⁽⁷⁾ Such substitutes for chlorine are ozone, oxygen, and peroxide.

Duplex 2205 stainless steel is used to prevent SCC in the oxygen delignification process between 90 °C (194 °F) and 120 °C (248 °F).⁽⁸⁾ However, bleaching processes that include ozone or peroxide generally require Type 316 stainless steels.⁽¹²⁾

Step 4. Stock Preparation

After bleaching, the pulp is processed into (liquid) stock that can be transferred to a paper mill. This processing is performed to get the required paper product and quality specified. It can include blending various pulps together, beating and refining, dispersion in water, and the addition of any wet additives such as resins, waxes, fillers, or dyes for coloring.⁽⁷⁾

Many pulp mills have a paper mill adjacent to them; therefore, transferring the products is not costly. The pulp mills, which produce market pulp, dry the pulp and transfer it by truck, train, or ship. The equipment used to store

and transport the pulp can undergo crevice corrosion and pitting; therefore, they are usually completely or at least partially clad with Type 304L stainless steel.

Step 5. Paper Manufacturing

The creation of the paper is performed through wet-end and dry-end operations. These are discussed below.

Wet-End Operations

Using a paper production machine (see figure 5), the processed pulp is converted into a paper product.

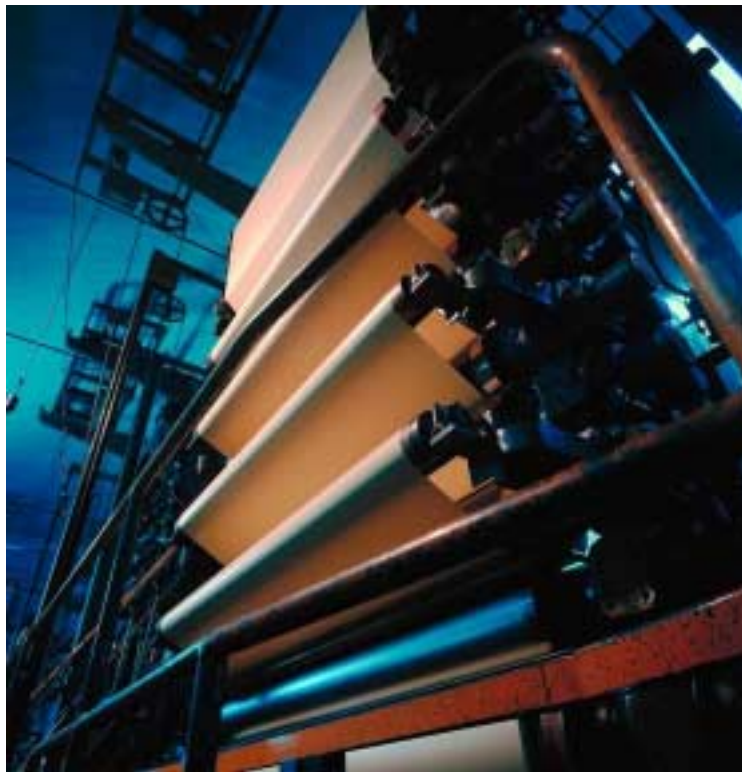


Figure 5. Paper machine used to transform processed pulp into paper product.

At the beginning of this stage, the water content of the paper is greater than 99 percent.⁽¹³⁾ The most common machine utilized is the Fourdrinier paper machine.⁽⁷⁾ In the wet-end operation, the slurry of pulp is deposited onto a continuously moving belt that suctions the water from the slurry using gravity, vacuum chambers, and vacuum rolls. The continuous sheet then moves through additional rollers that compress the fibers and remove the residual water.

Thorpe⁽⁸⁾ describes the traditional process as having a stock with a pH of 4.5 to 6. These paper machines process water, known as white water, which contains sulfate (200 to 500 ppm) and chloride (100 to 200 ppm), with little or no recycling. With recycling, the sulfate content can increase to 1,000 ppm, the chloride content can increase to 400 ppm, the dissolved organic compounds can increase to 1,000 ppm, and the temperature can vary between 50 °C (122 °F) and 60 °C (140 °F).

The suction rolls, which are used to remove the water from the paper as it begins its drying process, experience general corrosion, fatigue failures, pitting, and microbiologically influenced corrosion (MIC) due to exposure to stock and white water, deposits of paper fiber present in crevices, and bacterial growth. In addition, the inside diameter of the drilled holes within the suction rolls experience fatigue failures due to the presence of high stress concentrations. Studies have also shown that sodium thiosulfate ($\text{Na}_2\text{S}_2\text{O}_3$) in stock and white water systems can result in severe pitting.⁽¹⁴⁾

According to Thorpe,⁽⁸⁾ the drilled holes in the suction rolls, along with crevices and deposit sites, experience the growth of microbes as a result of high temperatures [40 to 50 °C (104 to 122 °F)], dissolved organic materials, and dissolved inorganic salts. Microbiological attack occurs beneath deposits on the microbiological slime and increases with the degree of closure of the paper mill.

To prevent general corrosion, fatigue failures, and MIC within the suction rolls, duplex stainless steels are used.⁽⁸⁾ Furthermore, the suction holes in the rolls should remain unblocked and the applied load on the rolls should not exceed the design load. Regular inspection for cracking may prevent catastrophic failure and process outages.

Dry-End Operations

Following the pressing of the wet-end operations, the continuous sheet is compressed by steam-heated rollers to allow the fibers to begin bonding together. Coatings are then applied to add to the surface appearance before the sheet is spooled for storage.⁽⁷⁾

Corrosion problems within the paper machines include chloride pitting and crevice corrosion, thiosulfate pitting, and microbiological attack. A minimum of Type 304 stainless steel should be used.⁽⁸⁾

Determining Corrosion Cost for the Pulp and Paper Industry

In 1998, Singbeil⁽¹⁵⁻¹⁶⁾ estimated the total corrosion cost for the pulp and paper industry using cost data collected by Davy and Mueller in the period 1968 to 1971 and presented in 1974.⁽¹⁷⁾ The (old) cost data were combined with the 1998 production volumes, paper prices, and production statistics from the Lockwood-Post's Directory.⁽¹⁾

Table 2 shows Singbeil's results as calculated from the amount of various types of pulp produced in the United States, Canada, and the world, along with the corresponding costs. Singbeil's calculations do not include downtime as a result of corrosion-related problems. The data shown are presented in metric tons and 1998 U.S. dollars as calculated using an implicit price index of the gross domestic product (GDP) for Canada to correct for inflation. The comparison is made under the assumption of similar corrosion issues in 1975 versus 1998, while in fact, the process of paper-making has changed significantly. Today's corrosion issues are different from 1975 because of changed water and chemical usage.

Table 2. Estimated annual corrosion cost (1998 dollars) for the U.S., Canadian, and world pulping industry in 1975 and 1996, based on calculations by Singbeil,⁽¹⁵⁾ using 1974 data from Davy and Mueller⁽¹⁷⁾ and the 1998 *Fact & Price Book*.⁽¹⁸⁾

UNITED STATES		ESTIMATED CORROSION COST		1975 DATA		1996 DATA	
		Per Short Ton*	Per Metric Ton**	Production***	Corrosion Cost	Production***	Corrosion Cost
		1975 CAN\$	1998 U.S.\$	Metric Tons x 1,000	1998 US\$ x million	Metric Tons x 1,000	1998 US\$ x million
Mechanical		\$1.45	\$4.67	4,004	\$18.7	5,372	\$25.1
Semi-Chemical		\$1.83	\$5.89	3,103	\$18.3	3,500	\$20.6
Sulphate (Kraft)	Bleached	\$5.08	\$16.36	12,819	\$209.7	28,751	\$470.3
	Unbleached	\$3.20	\$10.31	13,814	\$142.4	19,439	\$200.3
Sulfite	Bleached	\$3.71	\$11.95	1,587	\$19.0	1,172	\$14.0
	Unbleached	\$1.83	\$5.89	332	\$2.0	-	-
Other Pulp		\$2.65	\$8.53	1,241	\$10.6	-	-
Market****		\$3.20	\$10.31	3,940	\$40.6	7,584	\$78.2
Total Corrosion Cost		TOTAL		40,840	\$461.2	65,818	\$808.5

WORLD		ESTIMATED CORROSION COST		1975 DATA		1996 DATA	
		Per Short Ton*	Per Metric Ton**	Production***	Corrosion Cost	Production***	Corrosion Cost
		1975 CAN\$	1998 US\$	Metric Tons x 1,000	1998 US\$ x million	Metric Tons x 1,000	1998 US\$ x million
Mechanical		\$1.45	\$4.67	6,007	\$28.0	10,973	\$51.2
Semi-Chemical		\$1.83	\$5.89	233	\$1.4	381	\$2.2
Sulphate (Kraft)	Bleached	\$5.08	\$16.36	5,082	\$83.1	10,798	\$176.6
	Unbleached	\$3.20	\$10.31	1,315	\$13.6	1,435	\$14.8
Sulfite	Bleached	\$3.71	\$11.95	515	\$6.2	331	\$4.0
	Unbleached	\$1.83	\$5.89	1,443	\$8.5	435	\$2.6
Other Pulp		\$2.65	\$8.53	226	\$1.9	-	-
Market****		\$3.20	\$10.31	4,888	\$50.4	9,676	\$99.7
Total Corrosion Cost		TOTAL		19,709	\$193.1	34,029	\$351.2

Table 2. Estimated annual corrosion cost (1998 dollars) for the U.S., Canadian, and world pulping industry in 1975 and 1996, based on calculations by Singbeil,⁽¹⁵⁾ using 1974 data from Davy and Mueller⁽¹⁷⁾ and the *1998 Fact & Price Book*⁽¹⁸⁾ (continued).

CANADA		ESTIMATED CORROSION COST		1975 DATA		1996 DATA	
		Per Short Ton*	Per Metric Ton**	Production***	Corrosion Cost	Production***	Corrosion Cost
		1975 CAN\$	1998 US\$	Metric Tons x 1,000	1998 US\$ x million	Metric Tons x 1,000	1998 US\$ x million
Mechanical		\$1.45	\$4.67	22,752	\$106.2	34,420	\$160.7
Semi-Chemical		\$1.83	\$5.89	5,651	\$33.3	5,727	\$33.8
Sulphate (Kraft)	Bleached	\$5.08	\$16.36	25,534	\$417.7	73,966	\$1,210.0
	Unbleached	\$3.20	\$10.31	21,149	\$217.9	31,768	\$327.4
Sulfite	Bleached	\$3.71	\$11.95	4,279	\$51.1	3,550	\$42.4
	Unbleached	\$1.83	\$5.89	3,386	\$20.0	1,158	\$6.8
Other Pulp		\$2.65	\$8.53	4,815	\$41.1	12,227	\$104.3
Market****		\$3.20	\$10.31	20,069	\$206.8	37,895	\$390.5
Total Corrosion Cost		TOTAL		107,635	\$1,094.2	200,711	\$2,276.0

* Davy and Mueller, "Pulp and Paper Industry Worldwide Corrosion Costs," *Pulp and Paper Industry Corrosion Problems, Vol. 1*, NACE, Houston, TX, 1974.

** Extrapolated using implicit price index of 4.234 GDP for Canada 1969–1998, assume \$0.69 US\$/CAN\$; 1 short ton = 0.9072 metric ton.

*** Pulp production data for 1975 and 1996 extracted from *International Fact & Price Book 1998*, PPI, Belgium.

**** Market pulp defined as pulp of any grade produced for export – not destined immediately for paper or board production. It is excluded from other totals.

The 1975 survey by Davy and Mueller used data from 1968 to 1971 to estimate the cost of corrosion in 1975 Canadian dollars (CAN\$) of the pulp and paper industry to be between CAN\$1.60 per metric ton (CAN\$1.45 per short ton) for mechanical pulp production and CAN\$ 5.09 per metric ton (CAN\$5.08 per short ton) for fully bleached Kraft pulp production. Singbeil⁽¹⁵⁾ extrapolated this data using an implicit price index GDP of 4.234 for Canada as a measure of inflation. The estimated cost of corrosion in 1998 U.S. dollars (US\$) for different kinds of pulp ranged from US\$4.67 per metric ton (US\$4.24 per short ton) for mechanical pulp to US\$16.36 per metric ton (US\$14.84 per short ton) for fully bleached Kraft pulp. The table shows that the annual estimated cost of corrosion for the pulping industry in the United States is \$808.5 million

Determining Corrosion Cost as a Percentage of Maintenance

For the current research project, Singbeil⁽¹⁶⁾ was asked which areas of the pulp and paper-making processes experience the highest corrosion rates. In addition, Singbeil was asked to estimate the annual cost of materials aging, including corrosion, repairs, replacement materials, preventive maintenance, and periodic inspection as a percentage of the total annual maintenance budgets. Dividing the pulp and paper industry into three major product areas, the estimates were 40 to 60 percent of the maintenance budget for the production of bleached market pulp, 35 to 50 percent of the maintenance budget for fine papers, and 25 to 30 percent of the maintenance budget for paperboard. The remaining portions of the maintenance budgets were attributed to regular wear and tear of the equipment.

These percentages can be used only as rough estimates because the severity of corrosion is dependent on the age, condition, and materials of the mill. Today's older pulp and paper mills still contain significant amounts of

carbon steel. New mills are being constructed with greater amounts of stainless steel and corrosion-resistant materials. As a result, it is expected that less maintenance will be required in the future in order to overcome corrosion-related problems.

In a 1995 study published by Pulp & Paper International and the Maintenance Association of the Paper Industry (MAPI),⁽¹⁹⁾ it was estimated that maintenance costs in the pulp & paper industry range from \$28.70 per metric ton (\$26.04 per short ton) to \$143.65 per metric ton (\$130.32 per short ton). The total cost of corrosion can be calculated by multiplying these values by the 1998 production statistics for fine papers, bleached market pulp, and paperboard, as reported in the Lockwood-Post's Directory⁽¹⁾ and the estimated corrosion costs as a percentage of the total maintenance costs (see table 3).

Table 3. Total annual corrosion costs for wood pulp, paper, and paperboard production as determined from 1998 production data,⁽¹⁾ total maintenance costs,⁽¹⁹⁾ and estimates of percent corrosion costs in the total maintenance costs.⁽¹⁶⁾

PAPER PRODUCT TYPE	1998 PRODUCTION ⁽¹⁾		TOTAL MAINTENANCE COST ⁽¹⁹⁾		CORROSION COST IN MAINTENANCE ⁽¹⁶⁾		TOTAL	
	Short Tons	Metric Tons	\$ / Short Ton*		%		\$ x million	
	x 1,000		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Wood Pulp	64,183	58,226	\$26.04	\$130.32	40	60	\$1,003	\$5,019
Paper	44,777	40,621	\$26.04	\$130.32	35	50	\$583	\$2,918
Paperboard	49,719	45,132	\$26.04	\$130.32	25	30	\$389	\$1,945
TOTAL							\$1,974	\$9,881
TOTAL 1998 SALES = \$164.9 BILLION					FRACTION		1.20%	5.99%
AVERAGE: \$5.928 BILLION								

*\$26.04 / short ton = \$28.70 / metric ton; \$130.32 / short ton = \$143.65 / metric ton.

The table shows that the total annual corrosion costs for the pulp, paper, and paperboard industry, as determined as a fraction of the maintenance cost, ranges from \$1.97 billion to \$9.88 billion (average: \$5.928 billion). These estimates are 1.20 percent and 5.99 percent, respectively, of the total 1998 sales of \$164.9 billion for the entire U.S. pulp and paper industry, as reported in the Lockwood-Post's Directory.⁽¹⁾ In comparison, Singbeil calculated the cost of corrosion in the pulping industry at only \$808.5 million (see table 2).

CORROSION CONTROL METHODS

Corrosion control methods in the pulp and paper industry include equipment design, process design, and the use of corrosion inhibitors. Using any of these techniques reduces or eliminates corrosion within a system.

Equipment Design

Pulp and paper equipment design consists of proper material selection in conjunction with the process chemicals and the prevention of stagnant process fluids in the equipment.

Low-alloy carbon steel would be the material of choice if corrosion were not a problem; however, for many processes, stainless steel and even nickel-base and titanium alloys are required for better performance in corrosive environments. Current U.S. pulp and paper mills are constructed of about one-third carbon steel and two-thirds stainless steel.⁽¹²⁾ Within the group of stainless steels, there are several alloy grades. Their relative cost is dependent on the concentration of the major alloying elements (Cr, Ni, Mo, etc.), the volume produced, and the form in which it is supplied (tube, pipe, plate, or block). In general, stainless steels are 10 percent to 20 percent more expensive than low-alloy carbon steels.

Stagnant and slow-flowing process fluids in pulping equipment can occur in crevices and water traps. Fluid stagnation often leads to an increase in concentration of the chemicals and the local creation of a severe environment in which pitting and crevice corrosion may occur. By designing drain holes and easy access to the equipment, stagnant solution can be removed. Slow-flowing fluids containing a solid fraction of pulp may deposit a layer of pulp on the bottom of piping and reservoirs. Under-deposit corrosion mechanisms, such as crevice corrosion and pitting, may occur. If equipment is designed with sufficiently fast and/or turbulent flow, deposit formation can be controlled. In addition, regularly scheduled cleaning and proper equipment maintenance can prevent the buildup of pulp and decrease the amount of stagnant solutions.

Process Design and Corrosion Inhibitors

Corrosion rates in mill equipment also depend on the chemical composition within each section of the process. The chemical composition varies from mill to mill depending on the processes involved, the closure of the mill's systems, the desired paper grade, the speed of the process, and the amount of pulp or paper being produced.

In general, the corrosivity of an environment will increase when the temperature is increased, when the pH is reduced, when the dissolved solids content increases, and when the chloride and sulfur compound concentrations are increased. Therefore, by monitoring the process and maintaining the proper temperature, pH, dissolved solids content, and chloride and sulfur compound concentrations, the amount of corrosion can be controlled.

In some processes, corrosion inhibitors can be added to the process to mitigate corrosion. Continued measurements of the process chemistry should be made to ensure that the correct dosage of the added corrosion inhibitor is maintained.

Preventive strategies for corrosion control in the pulp and paper industry include the verification of average corrosion rates, using weight loss coupons, regular inspection, and preventive maintenance. Preventive strategies are considered during the design and construction phases when new equipment is made, or when existing equipment is refurbished or repaired. Corrosion prevention techniques focus on minimizing the initiation of corrosion altogether, while corrosion control techniques are used to minimize the propagation of ongoing corrosion.

Weight Loss Coupons

Weight loss coupons are commonly used as a means to measure the average corrosion rate in a process or in the atmosphere of a pulp or paper plant. This technique is relatively cheap and easy to use, because all it requires are some pieces of metal that are weighed, exposed for a period of time, and weighed again. Using the difference between the weight of the coupon before and after the test, the average corrosion rate can be calculated. An advantage of this technique is that several coupons of different materials can be exposed simultaneously.

By performing weight loss tests, engineers can estimate the corrosiveness of an environment over a period of time. If the corrosion rate is determined to be too high, preventive measures can be taken to prolong the remaining life of the equipment. The preventive actions can include the addition of a corrosion inhibitor, a change in the process, an application of anti-corrosion coatings, or the addition of a cathodic protection system.

Inspection and Preventive Maintenance

An additional method to monitor the corrosion rate is through regular visual inspection of all parts of the equipment that are exposed to corrosive environments. These inspections use nondestructive examination (NDE) to reveal corrosion pits, crevice corrosion, or wall thinning before they will affect or stop the production process or degrade the paper to below its product quality specifications.

Regular inspection is performed as part of the maintenance program in plants. The results of the inspections are used to plan equipment repairs during scheduled shutdowns and to take action to maintain optimum production quality and quantity.

CORROSION MANAGEMENT

In dealing with corrosion issues, several philosophies have been developed to determine the most cost-effective solutions to continue production in order to maximize profit. These philosophies include a “do nothing” approach, a “do everything” approach, and a “do what it takes” approach.

By doing nothing to prevent corrosion problems, machinery is essentially used until it fails. As a result, the failed equipment must be completely replaced, causing high capital costs, loss of production due to downtime, lower quality products, and even catastrophic failure in the worst case scenario. The “do nothing” approach, which is often found within the pulp and paper industry, is not a cost-effective solution in the long run. For example, in the case of a northeastern paper mill’s bleach plant that produced 1,322 metric tons (1,200 short tons) per day, the cost of a complete shutdown was estimated to be \$240,000 / operating day using the industry standard of a \$220 contribution / metric ton (\$200 contribution / short ton).⁽²⁰⁾

The “do everything” approach is to prevent corrosion as much as possible. This includes monitoring corrosion and using protective techniques such as cathodic protection, inhibitors, and protective coatings. This philosophy is also not very cost-effective due to the high investment costs involved.

In many mills, corrosion management is concentrated around the maintenance groups. Maintenance engineers deal with all outages, replacements, inspections of the equipment, and corrosion as an integrated part of their work. The objective of their work is to ensure that production runs continuously 24 hours per day, 7 days per week. Their primary concerns are safety, equipment integrity, and product purity. Examples of corrosion affecting production are corrosion products polluting the paper and corrosion of rolls scarring the sheets of paper. Corrosion of components may result in fractures or leaks in the machines, causing production loss and safety hazards. Critical equipment such as pressure vessels, boilers, and tanks are usually inspected using nondestructive examination (NDE) to determine repair and replacement schedules.

Some larger mills employ one or more in-house corrosion specialists or metallurgists to deal with corrosion problems. In addition, they contract out to obtain the assistance of consultants that specialize in corrosion in the pulp and paper industry. In recent years, material properties expertise has become the responsibility of the equipment suppliers so that the individual mills can rely on the specified equipment design life.⁽¹⁹⁾ Finally, organizations such as the Technical Association of the Pulp and Paper Industry (TAPPI) and the National Association of Corrosion Engineers (NACE) offer assistance to overcome issues common to the pulp and paper industry.

CHANGES FROM 1975 TO 2000

Over the past 25 years, processes and the thought put into those processes have changed dramatically. Today's digital world has had a tremendous effect on the required production of the pulp and paper industry. In addition, recycling and environmental issues have forced the pulp and paper industry to change their processes. Finally, the competition within the pulp and paper industry has changed the way companies solve their maintenance issues.

The Digital World

The increased use of computers, the internet, electronic documents, and data storage has two seemingly opposing effects. The fact that data are transmitted in electronic format reduces the amount of paper used for printing reports or letters. On the other hand, the increased use of computers and the easily accessible "print" button, while printing paper is relatively inexpensive, increases the need for greater amounts of products from the pulp and paper industry.

A second phenomenon that has increased the use of paper over the last 25 years is the dramatic increase in commercial mailings. These everyday letters and brochures, which are delivered to almost every residence and business and offer various services and products, are commonly called "junk mail." This term shows the low value that people attribute to these paper products, while their use is widespread.

Recycling and Environmental Issues

The use of chemicals and the use of large amounts of water in paper production are under increased scrutiny in recent years. Due to this scrutiny, closed-loop system processes are more frequent. Closed-loop system processes lead to an increase in corrosion-related problems because of increased temperatures and larger concentrations of chemicals present in the closed-loop process streams. At the same time, recent developments in bleaching processes using ozone, oxygen, and peroxide have reduced the amount and concentration of chlorine products used. These changes actually tend to decrease the corrosivity of the process streams in the bleaching operation, thereby, allowing lower grades of stainless steel to be used.

Older mills have been converted for new processes. For example, due to the use of different chemicals in modern pulping processes, a variety of corrosion problems are observed that were not observed before. Chlorine-free bleaching processes are being developed to minimize dioxins based on chemicals such as O₂, O₃, ClO, H₂O₂, and peracetic acid.

Recovered Paper

Another topic of importance to the paper and pulp industry is recycling. With the development of de-inking technologies, 45 percent of all paper used by Americans was recovered in 1998.⁽²¹⁾ According to the EPA,⁽⁷⁾ the American Forest and Paper Association (AF&PA) has set a goal of 50 percent recycling by its members in 2000. Despite these percentages, the U.S. utilization of secondary fibers, which are taken from recycled paper, is only approximately 30 percent of the total fibers used for the production of paper. In comparison, resource-deficient countries, such as Japan, approximate 50 percent secondary fiber usage of the total fibers used for the production of paper. As decontamination technology progresses, secondary fibers will play an increasing role in the supply of paper.

Competition Issues

The competition within the pulp and paper industry has required mills to produce more product than ever before at a faster rate at less cost. In order to keep an advantage over other operating mills, secrecy and lack of information have become issues.

Maintenance's role in the pulp and paper industry has also changed.⁽¹⁹⁾ The monitoring of corrosion rates, the implementation of preventive measures, and the adjustment of the production processes to minimize the severity of corrosion are actively being pursued.

CASE STUDY FOR THE PULP AND PAPER INDUSTRY

Metsä-Rauma Pulp Mill – Totally Chlorine-Free Production

The objective of this case study is to show that changes in production methods affect the optimum material selection for production equipment and change corrosion issues. In new construction, such as the Metsä-Rauma pulp mill in Finland, the best corrosion design can be implemented. However, existing plants must be modified to accommodate changing corrosion conditions.

One example of different materials of construction is the replacement of carbon steel with stainless steel, which has been occurring in the United States over the last two decades. Because of the high cost to replace equipment and because of the fact that current carbon steel equipment may still operate for a longer time before reaching its useful life, mills continue to operate with corroding equipment as long as possible. In many cases, it is more economical to maintain and operate aging mills than to pay for the cost of an entirely new mill with the most modern anti-corrosion design.

In March 1996, a 570,000-metric ton/year (628,000-short ton/year) capacity, single-line, softwood pulp mill was opened in Metsä-Rauma, Finland. The Metsä-Rauma facility produces bleached softwood Kraft pulp that is manufactured totally chlorine-free (TCF) by using only oxygen, ozone, and hydrogen peroxide. According to Pulp and Paper International, the capital costs invested in the mill were approximately \$550 million, the construction time was 22 months, and the mill has 180 employees. Metsä-Rauma was built adjacent to the UPM-Kimono paper mill, which helped to reduce the overall cost of the mill by sharing resources and equipment.

The Metsä-Rauma pulp mill is the first TCF pulp mill in the world. This is a different type of mill than the previously used elemental chlorine-free (ECF) pulp mill. The capital cost of the TCF Metsä-Rauma mill was approximately \$17 million less than the construction of a similar ECF mill would have been because the absence of chlorine dioxide allowed for a simpler design of the bleaching plant and a smaller volume reactor. Stainless steels were used for construction of the TCF bleaching plant instead of the glass fiber-reinforced plastic or titanium that had been used in ECF mills.⁽²²⁾ In fact, the facility is one of a kind as it is made entirely of stainless steel.⁽¹²⁾

With the mill's aim of gradually closing the bleaching water cycles, the water consumption and effluent discharges are less than one-third of those in modern conventional mills. Metsä-Rauma's water consumption of 16.5 m³/metric ton (15 m³/short ton) of pulp includes 11 m³/metric ton (10 m³/short ton) for cooling water.⁽²²⁾ By using the proper grades of stainless steel for each process, the maintenance costs associated with equipment made from carbon steel will be significantly reduced. For comparison, it is estimated that a new state-of-the-art integrated mill (pulp and paper together) would cost approximately \$1 billion.⁽³⁾

REFERENCES

1. *2000 Lockwood-Post's Directory of the Pulp, Paper, and Allied Trades*, Miller Freeman Publications, Inc., United News & Media Company, 1999.
2. K.E. Deardorff, *National Population Trends*, U.S. Census Bureau, September 21, 1998, www.census.gov.
3. United States–Asia Environmental Partnership (USAEP), www.usaep.org, August 2000.

4. Paperloop.com, www.paperloop.com, September 2000.
5. U.S. Environmental Protection Agency (EPA), Sector Notebook Project, Sector Notebook Data Refresh – 1997, May 1998.
6. Unified Air Toxics, www.epa.gov/ttn/uatw/pulp/pulppg.html, August 2000.
7. U.S. Environmental Protection Agency, Office of Compliance, Sector Notebook Project, Standard Industrial Classification 261–265, Profile of the Pulp and Paper Industry, Washington, D.C., September 1995.
8. P.H. Thorpe, “Selection and Fabrication of Stainless Steels for the Pulp and Paper Industry,” *Corrosion & Prevention, 98 Proceedings*, P.H. Thorpe and Associates, November 1998, pp. 109–115.
9. A. Harrison, “Corrosion Control Offers Paper Mills a Method of Cost Control,” *Pulp Paper*, Vol. 68, No. 10, October 1994, pp. 135-136.
10. K. Westin, www.chemeng.th.se, August 2000.
11. ASM International, *Metals Handbook, Vol. 13: Corrosion*, Ninth Ed., 1987, pp. 1186–1218.
12. A. Tuthill, Nickel Development Institute, Personal Communication, August 2000.
13. Quebec Forest Industries Association, www.aifq.qc.ca, August 2000.
14. R.M. Uschan, and L.C. Trick, “Corrosion Control Needs of the Pulp and Paper Industry,” *American Papermaker*, 57(9) (Sept. 1994), 58(2).
15. D. Singbeil, 9th International Symposium on Corrosion in the Pulp and Paper Industry, Ottawa, Ontario, Canada, May 1998.
16. D. Singbeil, Personal Communication, August 2000.
17. M.F. Davy and W.A. Mueller, “Pulp and Paper Industry Worldwide Corrosion Costs,” *Pulp and Paper Industry Corrosion Problems, Vol. 1*, NACE, Houston, TX, 1974, pp. 1-6.
18. “Pulp Production Data for 1975 and 1996,” *International Fact & Price Book 1998*, PPI, Belgium.
19. D. Guest, “Single Suppliers Find the Way Forward on Maintenance,” *Pulp & Paper International*, December 1, 1995, www.paperloop.com.
20. J. Adams, “Cost of Maintenance Shutdown Delays Can Offset Expected Production Gains,” *Pulp & Paper Magazine*, October 1993, <http://www.paperloop.com>.
21. American Forest & Paper Association (AF&PA), www.afandpa.com, October 1999.
22. “Rauma Opens With the Aim of Closing Up,” *Pulp and Paper International*, June 1996.