Clean Technologies In U.S. Industries:

Focus on Pulp & Paper

Prepared by:

United States-Asia Environmental Partnership

The Civil Engineering Research Foundation

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Acronyms

AET	Alliance for Environmental Technology
AF&PA	American Forest and Paper Association
AOX	adsorbable organic halides
BAT	best available technology
BOD	biochemical oxygen demand
CERF	Civil Engineering Research Foundation
COD	chemical oxygen demand
DCS	distributed control systems
DOE	U.S. Department of Energy
ECF	elemental chlorine-free
EPA	U.S. Environmental Protection Agency
MACT	maximum achievable control technology
NCASI	National Council for Air and Stream Improvement
PIMA	Paper Industry Manufacturers Association
TAPPI	Technical Association of the Pulp and Paper Industry
TCF	total chlorine-free
TSS	total suspended solids
US-AEP	U.S.-Asia Environmental Partnership
USAID	U.S. Agency for International Development
USD	U.S. dollars
WWW	World Wide Web

Foreword

This document was prepared by the Civil Engineering Research Foundation (CERF) under contract to the U.S.-Asia Environmental Partnership (US-AEP), a program of the U.S. Agency for International Development (USAID). The mission of US-AEP is to match Asian environmental needs with U.S. environmental experience, expertise, technology, and practices.

This report gives a brief overview of the U.S. pulp and paper industry, with an emphasis on efforts to incorporate pollution prevention and clean technologies into its manufacturing operations. It is not intended to be a comprehensive industry guide or study. Rather, this report can be used as guidance material for those seeking general information about the U.S. pulp and paper industry and its use of technologies and processes that reduce or prevent pollution.

Information used to prepare this report was gleaned largely from government agencies, trade associations, and the World Wide Web (WWW) and was limited to resources that were free of charge and readily accessible. No original data collection or analysis was done to support the preparation of this document.

Acknowledgments

The United States-Asia Environmental Partnership (US-AEP), a program of the U.S. Agency for International Development (USAID), is a ten-year effort to mobilize public and private sector resources to assist Asia in sustaining economic development, while improving the environment. The program is designed to match Asian environmental needs with U.S. environmental experience, technology, and practice. To meet these goals, the Clean Technology and Environmental Management (CTEM) element of US-AEP undertakes a wide variety of activities, including tracking and reporting to interested parties the status of various industries in the United States, identifying clean technologies and practices used in U.S. industry that can be transferred to the Asian marketplace, and assisting in technology transfer by identifying opportunities for collaboration and information sharing, along with providing written and other resources to both Asian and U.S. industries.

The Civil Engineering Research Foundation (CERF), the nonprofit research affiliate of the American Society of Civil Engineers (ASCE), serves to facilitate, coordinate, and integrate research in the design, construction, and environmental industries and the civil engineering profession, providing leadership for research within this fragmented industry. CERF's mission is to serve as an industry-guided organization to enhance the quality, timeliness, and effective delivery of innovation, research, and information into practice, while ensuring coordinated efforts and activities among institutions with similar agendas. In supporting the CTEM program of US-AEP, CERF staff have drawn on the knowledge and expertise of the community they serve—those companies that design, build, and sometimes operate or maintain facilities for the manufacturing sector—to identify clean manufacturing technologies and processes used by various industries, including textiles, pulp and paper, food processing, and metal fabrication.

CERF would like to thank Dr. Ronald Slinn, principal of Slinn and Associates, for his support in providing technical information on the pulp and paper industry.

1. Executive Summary

This report gives a brief overview of the U.S. pulp and paper industry, with an emphasis on efforts to incorporate pollution prevention and clean technologies into its manufacturing operations. It is not intended to be a comprehensive industry guide or study. Rather, this report can be used as guidance material for those who are seeking general information about the U.S. pulp and paper industry and its use of technologies and processes that reduce or prevent pollution.

The United States is the largest consumer of pulp and paper products in the world. The U.S. pulp and paper industry, which supplies the bulk of this demand, is larger than the next four largest producers of pulp and paper outside the United States combined. In 1995 the per capita consumption of paper in the United States was 331 kilograms. The next closest country in per capita consumption is Japan, which used 238 kilograms per person.

The U.S. pulp and paper industry is recognized worldwide as a high-quality, large-volume, low-cost producer that benefits from a large consumer base, a modern technical infrastructure, an adequate supply of raw materials, and a highly skilled labor force. It follows, then, that many of the major technological innovations in the industry, including those in clean technologies and processes, occur in the United States. The term "clean technologies" is defined as **"manufacturing processes or product technologies that reduce pollution or waste, energy use, or material use in comparison to the technologies that they replace."**

Key resources used by the industry include the following:

Water. The pulp and paper industry is the largest user (per ton of product made) of industrial process water in the United States. A typical modern mill uses 16,000 to 17,000 gallons of water per ton of pulp produced. This is down from the average of 100,000 gallons per ton that was typical in the mid-1940s.

Fiber Resources (Furnish). Wood provides the virgin fiber resource or *furnish* for virtually all of the papermaking pulp capacity in the United States. Nonwood fiber sources, common in many parts of the world (most notably India and China), represent a minuscule percentage of the raw material used to make pulp in the United States. Secondary (i.e., recycled) fibers are the next most common fiber source for papermaking in the United States. About 70% of U.S. mills use some fraction of secondary fibers as furnish for pulp production, and about 200 facilities rely exclusively on secondary fibers for furnish.

Energy Use. Chemical pulping processes require on average the equivalent of more than 170 gallons of oil to produce one ton of pulp. Chemical pulping, however, generates process residues (i.e., black liquor from the kraft pulping process) from which process chemicals and energy can be recovered. In fact, over the past several decades, U.S. industry has come to rely more on these process wastes for its energy. Sources of fuel used by the pulp and paper industry include fuels, bark, process residue, and natural gas. Some mills produce enough process waste to meet all of their energy needs; in 1994, 57% of U.S. mills were completely energy self-sufficient in this manner.

Key environmental issues for the U.S. industry include the following:

Water. Primary issues of concern are biochemical oxygen demand (BOD); chlorinated organic compounds (particularly dioxin), which are often collectively measured as adsorbable organic halides (AOX); chemical oxygen demand (COD); total suspended solids (TSS); and aquatic toxicity. Reduction of water use in the industry is also a concern, although progress has been made in this area in the past several decades. Elimination of aqueous effluent from the manufacturing process is a goal of the industry worldwide.

Air. Primary issues of concern are emission of nitrous oxides, sulfur oxides, and particulate matter. Air emissions from pulp making are typically highly odorous due to their high sulfur content, which leads the public to perceive the industry as "dirty."

Chemical Releases. The industry released approximately 218 million pounds of Toxics Release Inventory (TRI) chemicals to air, water, or land in 1993. This represents less than 4 percent by weight of the total quantity of chemicals released or transferred by all U.S. manufacturers that year; in general, releases of chemicals reported by the pulp and paper industry have been decreasing steadily over time. The top five reported TRI chemicals released to the environment by the pulp and paper industry are methanol, hydrochloric acid, sulfuric acid, chloroform, and ammonia.

Bleaching Operations. Chlorine used to bleach pulp leads to the formation of chlorinated organic compounds in effluent, which have been linked to adverse health effects in both humans and wildlife. The industry is undertaking methods to reduce formation of compounds in bleach plant effluent by using new chemicals and bleaching techniques.

The most significant regulatory topic of interest within the industry is the so-called **Cluster Rule,** which was proposed in late 1993 by the U.S. Environmental Protection Agency (EPA) and is expected to be promulgated in 1997. The Cluster Rule is a first-of-its-kind environmental standard that will prescribe integrated concentration limits for effluent and air emissions from pulp and paper mills for a wide variety of environmental parameters. By and large, industry is awaiting the promulgation of this rule to make major upgrades to their manufacturing equipment, because the prescribed limits on effluent and air emissions will likely dictate the type of technology needed to comply with the limits.

Clean technologies described in this document include the following:

- **Elemental chlorine-free (ECF) bleaching.** Use of chlorine dioxide in lieu of elemental chlorine to bleach pulp.
- **Total chlorine-free bleaching.** Use of chemicals not containing chlorine (e.g., oxygen and hydrogen peroxide) to bleach pulp.
- **Extended delignification.** Process modifications to remove additional lignin from pulp to reduce the use of bleaching chemicals.
- **Alternative pulping technologies.** Use of nontraditional chemicals and methods for pulping that reduce the use of sulfur-containing compounds.
- **Use of nonwood fiber sources.** Use of plants that are thought to be more sustainable in the long term than forest resources.
- **Black liquor gasification.** Use of gasification rather than a recovery boiler to recover chemicals used during pulping.
- **Sensors and process control.** Use of advanced techniques to control specific portions of the manufacturing process to reduce wastes and increase productivity.
- **Water use reduction and closed bleach/ effluent systems.** Reduction or total elimination of effluent from the manufacturing process.

Of these technologies, the ones that the United States is most readily adopting or most likely to adopt in future years include ECF bleaching, extended delignification, black liquor gasification, advanced sensors and process control, and water use reduction and closed effluent systems. Implementation of the Cluster Rule will act as a driver for technology implementation. Other trends for the future of the pulp and paper industry are noted in *Agenda 2020,* a document that outlines the research objectives for the United States, as agreed on by industry representatives and related trade and research organizations with support from the U.S. Department of Energy (DOE). The issues identified in this document will require attention and collaborative research among the industry, its suppliers, other institutions, and the government to ensure the health of the industry in this time frame. The six topics described in *Agenda 2020* are sustainable forest management, improved environmental performance, improved energy performance, improved capital effectiveness, recycling, and advanced sensors and controls. Historically, U.S. investments are driven by cost-effectiveness, regulatory mandates, and consumer demand for environmentally benign products. This trend is expected to continue as the industry moves into the twenty-first century.

2. Industry Background

2.1 Description and History

The United States is the largest consumer of pulp and paper products in the world. In fact, the U.S. pulp and paper industry is larger than the next four largest producers outside the United States of pulp and paper combined. In 1995 the per capita consumption of paper in the United States was 331 kilograms. The next closest country in per capita consumption is Japan, which used 238 kilograms per person.

The U.S. pulp and paper industry is recognized worldwide as a high-quality, large-volume, low-cost producer that benefits from a large consumer base, a modern technical infrastructure, an adequate supply of raw materials, and a highly skilled labor force. The current principal competition for this industry comes from Canada and Scandinavia. Export markets, which are becoming increasingly important for the economic health of the U.S. industry, include Canada, Mexico, and Japan.

2.2 Industry Demographics

There are approximately 555 facilities that manufacture pulp and paper in the United States. Of these facilities, about half are integrated facilities (i.e., manufacturing both pulp and paper products), half manufacture only paper products, and about 50 produce only market pulp. The latest statistics show that the pulp and paper industry employs about

198,000 people in the United States. In 1991 the pulp and paper industry, along with the converting industry (those facilities that make products from paper, such as cartons and envelopes) produced about US$75 billion in shipments. This represents about 4% of the value of shipments for the entire U.S. manufacturing sector.

Chemical pulping, specifically the kraft chemical pulping process, is the dominant pulp-making process used in the United States. It accounted for about 80% by weight of all U.S.-produced pulp in 1996. Semichemical and mechanical pulping comprise the remaining percentage of pulping capacity. Bleaching of chemical pulps is also common in the United States; about half of pulp tonnage produced in 1993 was bleached in some fashion. Semichemical and mechanical pulps are difficult and costly to bleach; thus, bleaching is rare in these instances.

Pulp and paper mills tend to be large and capital intensive. The cost of building a new, state-of-the-art integrated mill is estimated at US$1 billion. Mills tend to be collocated near forest resources for ease of transportation of raw materials: the southeast, northwest, northeast, and north-central portions of the continental United States.

Table 1 provides a brief listing of some of the largest companies and organizations associated with the U.S. industry. This list is not intended to be exhaustive, but rather to provide a short overview of industry players, which include pulp and paper mills, equipment and chemical suppliers, process design and consulting engineers, professional trade associations, and research institutions. Small mills tend to work directly with the supplier community to meet their day-to-day needs for operation and maintenance of equipment. For large-scale retrofits and redesigns, however, mills typically work with design and consulting engineers, who in turn work directly with manufacturers to specify the processes and equipment needed.

2.3 Use of Natural Resources

Water

The pulp and paper industry is the largest user (per ton of product made) of industrial process water in the United States. A typical modern mill uses 16,000 to 17,000 gallons of water per ton of pulp produced. This is down from an average of 100,000 gallons per ton, which was typical in the mid-1940s. Despite this order-of-magnitude improvement, reduction of water use is still a primary concern of the U.S. industry, and research to this end has been going on for several decades. A technical challenge facing the pulp and paper industry worldwide is to close off the effluent system completely, resulting in no aqueous discharge to the environment.

Fiber Resources (Furnish)

Wood provides the virgin fiber source or *furnish* for virtually all of the papermaking pulp capacity in the United States. Wood is an abundant natural resource in the United States and can be used to make a diverse array of paper products varying in use and strength. Nonwood fiber sources, common in many parts of the world (most notably India and China) represent a minuscule percentage of the raw material used to make pulp in the United States.

Secondary (i.e., recycled) fibers are the next most common fiber source for papermaking in the United States. These may consist of either preconsumer wastes (e.g., scrap waste from the mill itself) or postconsumer fiber that is recycled following use. About 40% by weight of paper produced in the United States is recycled following use; most of this paper comes from newsprint and corrugated boxes. In fact, worldwide, the recycling rate has increased as developed countries address the growing problem of solid waste disposal, of which paper is the largest component by both weight and volume. About 70% of U.S. mills use some fraction of secondary fibers as furnish for pulp production, and about 200 of the 550 facilities rely exclusively on secondary fibers for furnish. These fibers are processed to remove impurities such as glues and ink.

Energy Use

Pulp and paper manufacturing is an energy-intensive industry. Chemical pulping processes require on average the equivalent of more than 170 gallons of oil to produce one ton of pulp. Chemical pulping, however, generates process residues (i.e., black liquor from the kraft pulping process) from which process chemicals and energy can be recovered. In fact, in the past several decades, U.S. industry has come to rely more on these process wastes for its energy. **Table 2** summarizes percentages of energy sources used by the U.S. pulp and paper industry in the past three decades, in terms of percentage of total energy used by the industry as a whole. (For instance, in 1972 residual fuel oil was used to generate 21.2% of the energy used by the industry.) The estimates show that the proportion of the industry's energy use derived from fossil fuels has decreased dramatically, whereas dependence on process wastes has increased. Some mills produce enough process waste to meet all

Table 1: Key Organizations in the U.S. Pulp and Paper Industry		
Organization	**Headquarters**	**World Wide Web Address, if available**
MILLS		
International Paper	Mobile, AL	www.ipaper.com
Weyerhaeuser	Tacoma, WA	NA
Kimberly-Clark	Neenah, WI	www.kimberly-clark.com
Georgia-Pacific	Atlanta, GA	www.gp.com
Stone Container	Chicago, IL	www.azird.ord/stone
Champion International	Stamford, CT	www.championinternational.com
Mead	Dayton, OH	www.mead.com
Boise Cascade	Boise, ID	www.bc.com
Union Camp	Wayne, NJ	www.unioncamp.com
Jefferson Smurfit	St. Louis, MO	j-src.com/jsc
EQUIPMENT MANUFACTURERS		
ABB	Europe/Windsor, CT	www.abb.com
Beloit Corporation	Beloit, WI	www.beloit.com
Black Clawson	Middletown, OH	www.blackclawson.com
Ahlstrom Filtration	Chattanooga, TN	NA
Sunds Defibrator	Europe/Norcross, GA	www.sunds.com
CHEMICAL MANUFACTURERS		
Air Products and Chemicals	Allentown, PA	www.airproducts.com
Ciba-Geigy	Summit, NJ	www.ciba.com
Dow Chemical	Midland, MI	www.dowchem.com
3M Company	St. Paul, MN	www.3m.com
PROCESS DESIGNERS AND CONSULTANTS		
BE & K Engineering	Birmingham, AL	www.bek.com
Babcock and Wilcox	Barberton, OH	www.babcock.com
Bechtel	Houston, TX	www.bechtel.com
Jacobs-Sirrine Engineers	Bakersfield, CA	NA
Jaakko Poyry Fluor Daniel	Irvine, CA	www.fluordaniel.com

Table 1: Key Organizations in the U.S. Pulp and Paper Industry		
Organization	**Headquarters**	**World Wide Web Address, if available**
Parsons, Inc.	Pasadena, CA	www.parsons.com
Raytheon/Rust Engineering	Lexington, MA	www.raytheon.com
Simons Engineering	Vancouver, BC, Canada	www.hasimons.com
Stone & Webster	Boston, MA	www.stonewebster.com
PROFESSIONAL TRADE ASSOCIATIONS AND RESEARCH INSTITUTES		
Technical Association of the Pulp and Paper Industry (TAPPI)	Atlanta, GA	www.tappi.org
Institute for Paper Science and Technology (IPST)	Atltanta, GA	www.ipst.edu
National Council for Air and Stream Improvement (NCASI)	Research Triangle Park, NC	www.ncasi.org
Alliance for Environmental Technology (AET)	Washington, DC	aet.org
USDA Forest Products Laboratory	Madison, WI	www.fpl.fs.fed.us

Table 2: Energy Sources Used by the U.S. Pulp and Paper Industry, By Percentages

Energy Source: Self-Generated	1972	1994	Energy Source: Purchased	1972	1994
Spent pulping liquor	33.0	40.8	Residual fuel oil	21.2	6.0
Bark	4.5	6.6	Distillate fuel oil	1.0	0.3
Wood residues	2.0	7.3	Natural gas	21.1	16.9
Self-generated hydropower	0.4	0.2	Purchased electricity	4.4	6.4
Other	0.4	1.0	Coal	10.7	12.5
			Other	1.3	2.0
TOTALS	**40.3%**	**55.9%**		**59.7%**	**44.1%**

Note: The percentages for each source represent the fraction of total energy used by the pulp and paper industry in the year for which data are reported.

Reference: AF&PA, *Energy Monitoring System*, 1994.

of their energy needs. In 1994, 57% of U.S. mills were completely energy self-sufficient in this way.

Semichemical and mechanical pulping processes use less energy than chemical processes, but they do not generate spent pulping liquors from which energy can be recovered. Because of this, depending on the size of the manufacturing operation, use of these processes could result in a net loss of energy.

2.4 Waste Streams of Concern

Production of pulp and paper produces waste streams that must be managed, recovered, treated, and/or disposed of. **Table 3** presents a list of the waste streams produced and their associated contaminants of concern for kraft pulping. **Table 4** presents a list of waste streams produced by other pulping processes.

Effluent and air emissions from pulp and paper mills have been a focus of environmental concerns for the industry. Effluent waste streams include aqueous discharges from pulping, pulp processing, bleaching, and papermaking. Because of the large volume of water used in manufacturing, most mills operate their own primary and secondary wastewater treatment plants to remove solids and biochemical oxygen demand (BOD) from the effluent and to treat some fraction of chlorinated organic compounds (collectively measured as adsorbable organic halides [AOX]) and chemical oxygen demand (COD) prior to discharge to receiving waters or to a publicly owned treatment works (POTW). Of particular concern is the formation of chlorinated compounds in effluent as a result of using elemental chlorine (Cl_2) to bleach pulp. Some chlorinated compounds, particularly dioxin, have been linked to adverse biological effects on wildlife in receiving waters, as well as human health risks.

Air emissions result from burning fossil fuels and wood wastes for energy, from chemical pulping and evaporation of weak black liquor generated by kraft pulping, and from operation of furnaces in kraft chemical recovery systems.

Solid wastes produced by the industry include fiber lost during the pulping process and scrap paper wastes. Because, however, a large portion of fiber and paper wastes are recovered and recycled, solid wastes are of little concern compared with effluent and air emissions for the industry.

Spent liquor from nonwood pulping often contains a high silica content, which presents a challenge in liquor recovery processes. Nonwood pulping mills that use chemical recovery systems commonly use a similar technology to that used by wood pulp mills with a modification to remove silica, which would otherwise form a glass-like residue on the interior of the recovery furnace evaporators. This concern is not primary in the U.S. industry because only a small percentage of pulp is made from nonwood fiber sources.

Chemical Releases

Table 5 presents data that summarize the total amount of chemicals released by the pulp and paper industry over a four-year time frame. Data from 1992 and 1993 are reported estimates of quantities managed, whereas data reported for 1994 and 1995 are projections only. The chemicals for which these data are reported consist of the 316 chemicals that were listed in 1993 on EPA's Toxics Release Inventory (TRI). Currently, the list of TRI chemicals has been expanded to more than 600 chemicals, but up-to-date information on releases of all of these chemicals is not available for the pulp and paper industry.

Table 5 shows that the industry managed about 2 trillion pounds of chemical wastes in 1993. Of these wastes, approximately 218 million pounds were either released to air, water, or land, or shipped off-site for disposal. Although the pulp and paper industry had the highest TRI chemical releases per facility of all industries in 1993 (an average of 550,000 pounds), this represents less than 4% by weight of the total quantity of chemicals released or transferred by all U.S. manufacturers that year. Releases of chemicals reported by the pulp and paper industry have been decreasing steadily over time; 1993 statistics show an 8% reduction from 1992 and a 22% reduction since 1988.

The industry releases 87% by weight of its TRI chemicals to air, approximately 10% to water and POTW; 2% is transferred off-site or disposed of. This release profile differs from all other TRI-releasing industries, which average 93% to air, 6% to land, and 1% to water. The difference is attributable to the water-intensive nature of the pulp and paper manufacturing process.

The top five reported TRI chemicals released to the environment by the pulp and paper industry are:

- Methanol
- Hydrochloric acid
- Sulfuric acid
- Chloroform
- Ammonia.

Table 3: Waste Streams Produced and Contaminants of Concern for Bleached Kraft Pulping[1]		
Process Sequence	**Waste Stream Produced**	**Contaminants of Concern**
WATER		
Furnish preparation and handling	Water used in handling, debarking, and chip washing	total suspended solids (TSS) biochemical oxygen demand (BOD) color
Pulping	Weak black liquor from digester, liquor spills	BOD reduced sulfur compounds
Pulp processing	"White waters" from pulp screening, thickening, and cleaning	high volume of water TSS BOD
Pulp bleaching	Bleach plant washer filtrates, spills	chlorinated organic compounds, including dioxin adsorbable organic halides (AOX) BOD color
Wet end operations	Water collected as pulp dries, spills	TSS
Chemical recovery system	Condensate from weak black liquor evaporator	BOD reduced sulfur compounds
AIR		
Pulping	Emissions from digester	volatile organic compounds (VOCs)
Chemical recovery system	Emissions from weak black liquor evaporators	VOCs
	Emissions from recovery furnace	fine particulates total reduced sulfur (TRS) compounds nitrous oxides (NO_x)
Burners for energy production	Emissions from burner	coarse particulates NO_x SO_x

[1] Note: Although solid wastes are produced during pulp and paper making, they are not discussed here because they are of secondary importance from an environmental standpoint for the U.S. industry.

Reference: EPA, *Profile of the Pulp and Paper Industry*, EPA/310/R-95/015, September 1995.

Table 4: Waste Streams Produced and Contaminants of Concern for Other Pulping Processes[1]			
Process Sequence	**Waste Stream Produced**	**Contaminants of Concern**	**Relevant Pulping Processes**
WATER			
Furnish preparation and handling	Water used in handling, debarking, secondary fiber processing	TSS BOD color	sulfite chemical; semi-chemical; mechanical; secondary fiber pulping;
Pulping	Liquor from digester, liquor spills	BOD reduced sulfur compounds	sulfite chemical; nonwood pulping
Pulp processing	"White waters" from pulp screening, thickening, and cleaning	high volume of water TSS BOD	sulfite chemical; nonwood pulping
Wet end operations	Water collected as pulp dries, spills	TSS	sulfite chemical; semi-chemical; mechanical; secondary fiber pulping; nonwood pulping
Chemical recovery system	Condensate from liquor evaporator	BOD reduced sulfur compounds	sulfite chemical; nonwood pulping
AIR			
Pulping	Emissions from digester	VOCs	sulfite chemical; nonwood pulping
Chemical recovery system	Emissions from liquor evaporators	VOCs	sulfite chemical; nonwood pulping
	Emissions from recovery furnace	fine particulates total reduced sulfur (TRS) compounds NO_x sulfur oxides (SO_x)	sulfite chemical; nonwood pulping
Burners for energy production	Emissions from burner	coarse particulates NO_x SO_x	sulfite chemical; semi-chemical; mechanical; secondary fiber pulping; nonwood pulping

[1] Although solid wastes are produced during pulp and papermaking, they are not discussed here because they are of secondary importance from an environmental standpoint for the U.S. industry.

Reference: EPA, *Profile of the Pulp and Paper Industry*, EPA/310/R-95/015, September 1995.

Table 5: TRI Releases for the Pulp and Paper Industry									
				Waste Managed On Site			Waste Managed Off Site[2]		
Year[1]	Quantity of Production-Related Waste, (millions of pounds)	Percent of Waste Managed Onsite	Percent of Waste Managed Offsite	Percent Recycled	Percent Energy Recovery	Percent Treated	Percent Recycled	Percent Energy Recovery	Percent Treated
1992	2,080	90	10	5	10	74	.02	.02	3
1993	1,958	90	9	5	10	74	.02	.03	2
1994	1,991	-	8	5	11	73	.02	.03	2
1995	1,949	-	8	5	11	73	.02	.02	2

Reference: EPA, *Profile of the Pulp and Paper Industry*, EPA/310/R-95/015, September 1995.

[1] Years 1992 and 1993 are reported; years 1994 and 1995 are estimated.
[2] Remaining percentage of wastes managed off site were either *(a)* released to the environment through direct discharges to air, land, and water, and underground injection, or *(b)* disposed of off site without treatment. Statistics are not available to quantify releases to the environment or disposal without treatment.

Methanol accounts for 50% of all air releases and 40% of all releases to water.

EPA's Office of Air and Radiation maintains data on annual releases of several air pollutants for major U.S. industries. **Table 6** summarizes the estimated annual releases of a suite of common pollutants. The data show that, compared to other manufacturing sectors, the pulp and paper industry is a primary releaser of carbon monoxide, nitrogen dioxide, and sulfur dioxide.

3. Environmental Issues and Regulations

The pulp and paper industry is subject to U.S. environmental regulations for effluent, air emissions, and solid wastes.

Effluent guidelines have been in place for the pulp and paper industry since 1974; updated guidelines were issued in 1977 and 1982. Effluent guidelines fall under the purview of the Clean Water Act (CWA), which is intended to restore and maintain the chemical, physical, and biological integrity of the nation's surface waters. Under the CWA, the National Pollutant Discharge Elimination System (NPDES) program controls direct discharges of effluent into navigable waters. Permits for discharge are issued either by EPA or a state environmental agency and require regular and periodic characterization, measurement, and monitoring of effluent and its contents. Many mills in the United States hold NPDES because they discharge large volumes of effluent to streams and rivers. Parameters often regulated by NPDES permits in the pulp and paper industry include BOD, COD, chlorinated organic compounds, temperature, and aquatic toxicity.

The industry is also subject to specific provisions of the Clean Air Act (CAA), which is designed to protect and enhance the nation's air resources to protect public health and welfare. The Clean Air Act establishes limits for air pollutants such as carbon monoxide, nitrous oxides, sulfur oxides, and particulate matter, all of which are pollutants of concern for the U.S. pulp and paper industry.

Mills may also generate a number of waste streams that are subject to regulations of the Resource Conservation and Recovery Act (RCRA), which outlines requirements for identification, treatment, storage, and disposal of hazardous wastes.

Cluster Rule: An Integrated Rulemaking

The current and most significant regulatory topic of interest within the U.S. pulp and paper industry is the so-called "Cluster Rule," which was proposed in late 1993 by EPA and is expected to be promulgated in 1997. The Cluster Rule is a first-of-its-kind environmental standard that will prescribe integrated concentration limits for effluent and air emissions

Table 6: Releases of Selected Air Pollutants		
Pollutant	**Tons Released Per Year**	**Rank Among U.S. Manufacturing Industries**
Carbon monoxide (CO)	624,291	2
Nitrogen dioxide (NO_2)	394,448	1
Particulate matter of diameter of 10 microns or less (PM10)	35,579	5
Total particulates (PT)	113,571	4
Sulfur dioxide (SO_2)	541,002	2
Volatile organic compounds (VOCs)	96,875	7
Reference: EPA Office of Air and Radiation, Aerometric Information Retrieval System (AIRS) data base, May 1995.		

from pulp and paper mills for a wide variety of environmental parameters. The rule will apply to most pulp and paper manufacturers in the United States and will be enforced by EPA with appropriate participation and coordination with state regulatory agencies.

The Cluster Rule will call for, although not specifically mandate, adoption of best available technologies (BAT) for effluent treatment and maximum achievable control technologies (MACT) for air emissions to control these waste streams. These technologies are presumably commercially available and economically feasible for mills to adopt; parameter limits in the rule were derived with the assumption that mills would use these treatment technologies.

The Cluster Rule will undoubtedly set environmental standards that other countries will seek to model in their own regulations and requirements for their domestic industries. Compliance with the effluent limitations established in the Cluster Rule will be required of U.S. mills three years from the date of promulgation. Air emissions limits will be enacted in three phases.

The time lag between the date the rule was proposed and its predicted promulgation has been caused in part by industry's response to several of the tenets of the original draft rule. During that time, the industry provided EPA with information about its environmental performance and predicted costs of industry compliance with the rule. In turn, EPA has revised and refined the language and parameter limits for the Cluster Rule to respond to the industry's input, as well as input from independent environmental organizations. Based on industry's current understanding of EPA's responses, the final Cluster Rule is expected to contain effluent limitations on the following parameters:

- Total suspended solids (TSS)
- Biochemical oxygen demand (BOD)
- A suite of chlorinated organic compounds, including a "non-detect" limit for dioxin. Currently, the detection level for dioxin in aqueous effluent is 10 parts per quadrillion; in sludges and end products, it is 1 part per trillion.
- Adsorbable organic halides (AOX), a less costly surrogate measure of a range of chlorinated organic compounds.

Current industry understanding is that the specific provisions for air emissions in the Cluster Rule are likely to be superseded by broader and possibly more stringent parameter limits in the more recently proposed Air Quality Standards under the CAA.

Some tenets of the Cluster Rule are still being debated. For instance, industry is generally opposed to the use of AOX as a surrogate measure for several chlorinated organic compounds. The range of compounds measured by AOX vary widely in degree of toxicity, persistence in the environment, and potential for bioaccumulation. Industry asserts that most of the AOX fraction is composed of less chlorinated compounds that exhibit lower to no toxicity and fewer to no adverse ecological effects when discharged to the environment, compared to compounds with a higher degree of chlorination.

U.S. mills are waiting until promulgation of the Cluster Rule to make major upgrades to their manufacturing equipment, because the prescribed limits on effluent and air emissions will likely dictate the type of technology needed to comply with the limits. For instance, to comply with effluent limits, it is likely pulp will have to be bleached with chemicals other than elemental chlorine (Cl_2), which may require some mills to change or update their bleaching plants. Recently, a new kraft pulp mill was required to use a catalytic converter to remove organic compounds in their air emissions to obtain an operating permit. This requirement is much more stringent than the current scope of the most recent version of the Cluster Rule and serves as an example of why industry is waiting to make large-scale capital investments.

4. Clean Technology Developments

This section provides a brief description of clean technologies and pollution prevention techniques used by the U.S. pulp and paper industry. These technologies vary in their acceptance and adoption by industry, which will also be discussed. "Clean technologies" are defined as **"manufacturing processes or product technologies that reduce pollution or waste, energy use, or material use in comparison to the technologies that they replace."**

The technologies described in this section are:

- Elemental chlorine-free bleaching
- Total chlorine-free bleaching
- Extended delignification
- Alternative pulping technologies
- Use of nonwood fiber sources
- Black liquor gasification
- Sensors and process control
- Water use reduction and closed bleach/effluent systems

A Note on Pulp Bleaching and Clean Technology

Bleaching methods are of considerable importance when discussing clean technologies for the pulp and paper industry; thus, much of the effort in clean technology development is intended to minimize the environmental impacts of this process step. For many decades, the global pulp and paper industry relied on elemental chlorine (Cl_2) as an efficient and inexpensive pulp-bleaching agent. Scientific evidence suggests, however, that elemental chlorine reacts with precursors, namely lignin, to form chlorinated organic compounds (e.g., dioxin) that are believed to be carcinogenic to humans based on results of laboratory studies with animals. The presence of these chlorinated compounds has also been linked to adverse ecological effects on wildlife in receiving waters.

4.1 Elemental Chlorine-Free (ECF) Bleaching

Description. ECF bleaching substitutes chlorine dioxide (ClO_2) for elemental chlorine (Cl_2) in the mill's bleach plant. Because of differences in its chemistry and reaction with lignin, use of chlorine dioxide in place of elemental chlorine has been demonstrated to improve the overall environmental performance of the bleaching operation.

Benefits. Studies have shown the following benefits for ECF bleaching over the use of elemental chlorine:

- Effluent concentrations of chlorinated organic compounds were reduced as much as fivefold to tenfold.
- Compounds formed have a lower degree of chlorination than those detected when using elemental chlorine.
- Concentrations of dioxin in effluent were substantially decreased or nondetectable.
- Toxicity, adverse ecological effects, degree of persistence in the environment, and potential for bioaccumulation were lower.

Status of Use in the United States. Production of ECF-bleached pulp in the United States has increased by nearly 2,000% since 1990, and the use of ECF bleaching is expected to increase in the United States with promulgation of the Cluster Rule. At the end of 1995, ECF bleaching constituted over 30% of the bleached chemical pulp market in the United States.

4.2 Total Chlorine-Free (TCF) Bleaching

Description. TCF bleaching of pulp uses nonchlorinated chemicals, such as oxygen (O_2), hydrogen peroxide (H_2O_2), or ozone (O_3), sometimes aided by enzymes. TCF bleaching processes were developed to reduce or eliminate the formation of chlorinated compounds in bleach plant effluent.

Benefits. The benefits of using TCF bleaching are similar to those seen when using ECF bleaching, including:

- Formation of chlorinated compounds in effluent, including dioxin is reduced or eliminated.
- Toxicity, adverse ecological effects, degree of persistence in the environment, and potential for bioaccumulation were lower.

Status of Use in the United States. The U.S. industry is leaning toward widespread adoption of ECF bleaching over TCF, for several reasons:

- TCF bleaching has been shown to reduce pulp yield by as much as 6%, which represents a cost to the industry.
- Some studies show a link between TCF bleaching and reduction of pulp quality, strength, and brightness.
- The process may decrease the recyclability of the finished paper because of reduced pulp quality.
- Capital investments are higher for TCF bleaching than for ECF because concurrent process modifications must be made in tandem to optimize the process (e.g., equipment for extended delignification or increase in capacity of recovery boiler).
- There is no current or future regulatory mandate or perceived domestic demand that will call for the use of TCF bleaching over any other bleaching process.

4.3 Extended Delignification Processes

Description. Several processes are available to remove *residual lignin* (lignin remaining in the pulp following traditional chemical pulping) from pulp. **Table 7** describes the specifics of each process in more detail.

Benefits. The presence of lignin in most pulps makes them difficult and costly to bleach. Removal of even an incremental amount of residual lignin via extended delignification processes can significantly reduce the volume of bleaching chemicals needed to achieve a target brightness level, resulting in cost savings for bleaching and treatment of bleach plant effluent. The challenge of extended delignification is to remove as much residual lignin as practicable without sacrificing pulp yield.

Status of Use in the United States. Many U.S. mills are awaiting the promulgation of the Cluster Rule to determine whether implementation of extended delignification will be necessary to comply with proposed statutory limits on bleach plant effluent. In general, extended delignification processes are added when the calculated cost savings and payback period justify its use in a particular mill. Oxygen delignification appears to be favored over ozone delignification due to its lower operating costs. Chemical catalysts to aid delignification are used by only a small number of mills; use may increase as research to optimize the process progresses.

4.4 Alternative Pulping Technologies

Description. Several chemical pulping methods that do not use conventional cooking chemicals have been developed by industry and research institutions. **Table 8** provides a description of these methods.

Benefits. The primary impetus for this research is to eliminate the use of sulfur compounds in pulping, which reduces or eliminates air emissions of sulfur compounds and helps avoid nuisance odors caused by the presence of sulfur. Some of these processes are also less energy-intensive than traditional pulping techniques.

Status of Use in the United States. Most of these techniques are still being researched and are not yet economically feasible or technologically ready for full-scale implementation. As research continues, these methods may become more favorable for implementation.

4.5 Use of Nonwood Fiber Sources

Description. Many nonwood plants and grasses can be used as a fiber source for papermaking. By a wide margin, the most common nonwood fiber used for papermaking is straw, followed by bagasse, bamboo, and kenaf. Nonwood fiber can be used in addition to or in place of wood fiber in papermaking. Each nonwood fiber source is pulped in a manner specific to its composition. Spent liquor generated from pulping of nonwood fibers is similar in composition to wood pulp but often contains a high silica content. Silica must be removed during liquor recovery because it would form a glassy residue on the interior of the recovery furnace. Fluidized-bed furnaces may be used to recover liquor from nonwood pulping in place of a conventional recovery furnace. They are less costly than conventional recovery furnaces, but less efficient because their operation requires the use of a greater amount of "external" energy than a conventional furnace; thus, the tradeoffs in energy consumption and performance between these two recovery systems must be considered when making purchasing decisions.

Benefits. Proponents of nonwood-fiber papermaking contend that nonwood sources are more easily renewable than forests and that nonwood-fiber manufacturing processes have fewer and less harmful environmental impacts than those for wood fiber papermaking.

Table 7: Description of Extended Delignification Processes		
Process	**Description**	**Comments**
Modification of cook time or temperature	Either the cooking time for pulping or the pulping temperature is increased to provide extended delignification. This process is relatively simple to control and does not require specialized equipment or chemicals.	Extended cooking generally leads to loss of pulp yield above 95 percent lignin removal and may result in loss of pulp strength.
Extended cook	The pulping process is extended by adding cooking liquor to the pulp in stages rather than as a single "dose." Lignin removal is as high as 97 percent (a 50 percent increase over pulping alone), which reduces the volume of bleaching chemicals needed by 35 percent.	Extended cooking increases the solids content of the black liquor, making additional demands on recovery furnace capacity, which may necessitate installation of a larger furnace. Capital investment for extended cook equipment can be substantial.
Oxygen Delignification	A mixture of elemental oxygen (O_2), sodium hydroxide (NaOH), and magnesium hydroxide (MgOH) is mixed with the pulp following pulping and pumped into a pressurized reactor to provide up to a 50 percent reduction in residual lignin. Oxygen can be generated onsite, which is generally less costly in the long run than off-site purchase. This process increases the heating value of the black liquor solids, so that a greater amount of energy can be derived by burning solids in the recovery furnace.	The use of oxygen delignification increases operating costs, but these increases are offset to some degree by reduced bleaching chemical requirements and by the increased heating value of the black liquor. Capital costs for oxygen delignification must take into account the increased heating value of black liquor solids, as well as the specialized equipment needed.
Ozone delignification	This process is similar to oxygen delignification. Ozone (O_3) and sulfuric acid (H_2SO_4) are mixed with the pulp in a pressurized reactor prior to pulp washing to provide up to 50 percent removal of residual lignin. Like oxygen delignification, the process also increases the solids content of the black liquor, making it necessary that the recovery furnace handle the additional capacity. Because ozone is unstable and corrosive, it must be generated on site, and pH and temperature of the cook as well as pulp washing must be carefully controlled and monitored.	Ozone is less selective in solubilization of lignin than oxygen or kraft pulping chemicals; thus, this process results in loss of pulp yield and strength. Generation of ozone is energy intensive, and cooling water is needed to absorb heat from the strongly exothermic reaction between the ozone and the pulp. The equipment used for ozone delignification is similar to that used for oxygen delignification, and capital and operating costs are similar.
Chemical catalysts for delignification: *anthraquinone*	Addition of anthraquinone to kraft cooking liquor has been shown to provide extended delignification without reducing pulp quality. Pulp yield can also increase by as much as 2 percent, which raises the mill's pulp productivity rate. Pulp treated with anthraquinone can be cooked at a lower temperature, which decreases energy use requirements.	The cost of the addition of anthraquinone to pulping liquor is partially offset by increased yield, reduced bleach chemical consumption, and reduced costs of effluent treatment.

Table 7: Description of Extended Delignification Processes		
Process	**Description**	**Comments**
Chemical catalysts for delignification: *polysulfide*	Addition of polysulfide to the kraft cooking liquor provides many of the same benefits as anthraquinone, including increase in pulp yield.	The heating value of the black liquor solids is reduced by using this chemical, and pulp strength also decreases. The process typically requires installation of oxidation equipment for the white liquor used in kraft pulping. Addition of polysulfides is a viable option for mills considering upgrading to an extended cooking process, because the increased solids loading to the recovery furnace caused by extended cooking is offset by the decrease in heating value of the black liquor solids, making it possible to increase delignification of pulp without having to upgrade liquor recovery.
Chemical catalysts for delignification: *mix of anthraquinone and polysulfide*	The use of a mix of anthraquinone and polysulfide in the cooking liquor has been demonstrated to provide not only extended delignification but also to increase pulp yield higher than that achieved by either of the two chemicals used alone.	The mechanism responsible for this incremental increase in yield is not clear; results of testing have been mixed. Dosages and optimal mix "recipe" have not yet been clearly defined. Research in this area is ongoing.

Table 8: Description of Alternative Pulping Technologies		
Process	**Description**	**Comments**
Acetic acid-based pulping	Acetic acid is used to pulp wood chips at pressures typically lower than those used for traditional kraft pulping. This method produces pulps that are similar in strength and yield to those made using other chemical pulping processes. Acid can be recovered from the process via distillation.	Distillation is energy-intensive. Also, acid losses through the process, despite recovery efforts, can be substantial, resulting in costly chemical purchases.
Organosolv pulping	Organic chemicals, including alcohol, ethanol, and methanol, are used to pulp wood. There are several proprietary pulping methods that use these chemicals. Chemicals can be recovered and reused.	Because the chemicals used are volatile, pulping processes must be sealed and spill-proof because of health risks due to worker exposure. Spills can also be a fire and explosive hazard. Some pulps made from hardwood are less strong when pulped with organic chemicals. The process may be most economical for small-scale mills.
Biopulping	Microorganisms such as fungi or xylanases are used to pulp wood (or nonwood) fibers. Use of microorganisms has been found to maintain pulp yield and strength and to decrease the energy requirements per unit of pulp produced.	The cost-effectiveness of this process is severely restrained by the slow rate of delignification achieved, compared to traditional pulping processes. This technique may be most appropriate for pulping of nonwood fibers.

Status of Use in the United States. Research in nonwood fiber pulping (particularly with kenaf) is ongoing in the United States. Wood and secondary fiber, however, are expected to remain as the dominant fiber sources within the U.S. industry because of their abundance and high quality domestically. The United States thus has relatively limited experience with processes and technologies for nonwood pulping on a large-scale basis.

4.6 Black Liquor Gasification

Description. Black liquor gasification is being researched as an alternative technology to a conventional kraft recovery furnace. Gasification is used to recover the energy and the chemicals in the black liquor solids generated during kraft pulping. Instead of direct burning of the solids, the volatile components of the black liquor are gasified. Sodium is recovered from the black liquor at the gasifier, whereas sulfur is recovered when the product gas is cleaned using a scrubber. The sodium and sulfur are then processed to regenerate the kraft pulping chemicals. The cleaned product gas stream is used to power a turbine or combined-cycle gas and steam turbine to generate heat and energy for the mill's use. Gasification systems have on average smaller capacities than traditional recovery furnaces. The use of multiple gasifiers would probably be required to match the energy and production needs for larger mills.

Benefits. Proponents of this technology assert that black liquor gasification used in conjunction with gas turbine cogeneration systems has the following advantages over traditional recovery furnaces:

- Higher overall energy efficiency
- Lower volume of gas requiring treatment
- Lower emissions (both gaseous and particulate)
- Higher inherent safety; no explosion hazard posed by molten smelt, which is present in recovery furnaces
- Higher adaptability to handling variations in liquor capacity by using multiple gasifiers or by other process modifications

Proponents also assert that gasification will become economically competitive with traditional recovery furnaces in the next few decades.

Status of Use in the United States. It is not yet cost-effective for U.S. mills to implement full-scale black liquor gasification systems to recover kraft process chemicals. Research on this technology is ongoing in both the United States and in Europe, particularly Sweden.

4.7 Improved Sensors and Process Control

Description. Development of improved sensors and controls for pulp and paper manufacturing processes is a research priority for the industry worldwide. Of particular interest is control of ECF bleach plant operations. The challenge for the bleach plant operator is to add the lowest volume of bleaching chemicals necessary at the right location(s) in the bleaching tower and between stages to achieve target pulp brightness. To control bleach plant operations properly, parameters such as pulp brightness, bleaching chemical concentration, and lignin content of the pulp (i.e., kappa number) should be measured both before and after bleaching to assess the predicted versus actual effectiveness of bleaching, so that the operator can make adjustments to bleach chemical addition in a timely manner. Currently, few mills use sensors to measure pulp quality after bleaching; rather, pulp samples are collected and analyzed in a separate laboratory, which can take up to two hours to report information back to the operator. By then, incoming pulp quality may have changed, and adjustments and corrections based on this information might be inappropriate for new conditions.

For application in an ECF bleach plant, process controls using "fuzzy logic" appear to have an advantage over traditional control methods. "Fuzzy" theory takes both human experiences and traditional controls into account in the control solution and has proved effective for nonlinear systems in which measurements and process variables are interdependent. ECF bleaching lends itself well to "fuzzy" control schemes; results for one ECF bleach plant showed that variations in pulp quality and brightness were lower for operations using "fuzzy" controls versus traditional controls.

Benefits. Sensors and controls, if designed and positioned within the manufacturing process properly, can help improve the environmental and energy performance of existing and developing technologies used in the industry, while also maintaining the performance specifications of the finished product.

Status of Use in the United States. Most pulp and paper mills currently use distributed control systems (DCS) for controlling operations. Functions (e.g., opening or closing a valve or starting or stopping of a motor) can be performed by an operator at a terminal, or controlled by an algorithm that uses process information, including information from sensors. Competition among manufacturers of DCS equipment is intense.

Controls employing "fuzzy logic," however, are still in development for both ECF bleach plants and other industry operations and there are few large-scale commercial installations at existing mills.

4.8 Water Use Reduction and Closed Bleach/Effluent Systems

Description. The global pulp and paper industry is faced with the challenge of water-use reduction and, ultimately, elimination of effluent altogether. Such mills are often referred to as "minimum impact mills." This closed-loop approach is viewed as "next generation" mill technology, as researchers develop efficient ways to reuse water and steam that are currently treated and discharged to receiving waters or treatment works. As a first step in closing the effluent system of a chemical pulp mill, the industry is attempting to reduce or eliminate discharges from the bleach plant, which is a primary focus of the environmental concerns for the industry. Bleach plant effluent may be recovered jointly with black liquor or in a separate recovery system for evaporation or steam generation.

Although mills will move toward closed-loop systems, material mass balances still dictate that process residuals such as sludges will require management and possibly off-site disposal or incineration. Makeup water may need to be added to the process occasionally to account for evaporation, spills, leaks, water bound in sludges and residuals, and other losses.

Benefits. Water use reduction or complete elimination of aqueous discharges from the pulp and paper-manufacturing process would provide obvious cost savings and environmental benefits. These benefits, however, would need to be weighed against the costs of redesigning and operating an effluent-free production process. Costs for new equipment, redesign, retrofits, and construction would be offset to some degree by reduction or elimination of wastewater treatment and off-site disposal of other process wastes, but the degree to which these costs are offset is largely unknown at this time.

Status of Use in the United States. There are no known totally closed effluent plants operating in the United States, although a handful are reportedly operating in Canada and Scandinavia. Research efforts in this area are expected to be intensive in the next several years. A closed effluent plant is technologically easier to achieve and more economically feasible for mills that use mechanical or semichemical pulping methods rather than chemical pulping. Mills that produce nonchemical pulps will thus be the primary focus of this research and technology development.

5. Future Trends

The U.S. pulp and paper industry has met with related trade organizations, research institutions, and governmental agencies on an ongoing basis to discuss the future of the industry from both an economic and environmental standpoint. One outcome of these continuing collaborations is a document that outlines a consensus perspective on the desired state of the industry in 25 years, with an emphasis on technology-related issues, most of which are environmental in nature. *Agenda 2020* was published in November 1994 by the American Forest and Paper Association (AF&PA). The issues identified in this document will require attention and collaborative research among the industry, its suppliers, other institutions, and the government to ensure the health of the industry in this time frame. *Agenda 2020* outlines the research objectives for the United States, as agreed on by industry representatives and related trade and research organizations with support from the U.S. Department of Energy (DOE). The six topics on the research agenda are:

- **Sustainable forest management.** Although trees are expected to dominate as a paper fiber source in the United States, the growing and harvesting of substantially increased yields from existing land resources without negative impacts on soil stability, water quality, biodiversity, and indigenous wildlife habitats will be necessary. The impacts of clear cutting and monocultures of single-species, man-made plantations must also be recognized.

- **Environmental performance.** Improved environmental compatibility of conventional and developing pulp and papermaking processes is the focus of the research needs in this category. Attention will be directed to the effects of those processes on human health, energy/ environmental tradeoffs, and reduction of emissions and effluent that have potentially harmful consequences. Complete closure of the effluent system is a major goal for mills of the future.

- **Energy performance.** Given the degree of energy intensity in the industry's fundamental processes, research efforts will be directed to environmentally benign, low-cost energy sources, including recovery and gasification of process residues.

- **Improved capital effectiveness.** The economically optimal size of a modern pulp and paper mill, combined with the high cost of the favored kraft recovery process contribute to the industry's standing as the most capital-intensive among manufacturing industries.

- **Recycling.** Solid waste reduction, improved fiber recovery systems, and enhanced development of "urban forests" will continue to be priority environmental targets of the U.S. industry.

- **Sensors and controls.** The complexity of current processes and the need to comply with increasingly stringent operating and environmental permits call for maximum efficiency through the use of increasingly sophisticated, online measurement and expert/control systems.

Other apparent trends within the U.S. industry are the following:

- Implementation of the Cluster Rule will act as a driver for technology implementation for ECF bleaching and for extended delignification (using oxygen). ECF bleaching will likely emerge as the preferred process over TCF bleaching or use of elemental chlorine.

- Research and progress will continue on development of techniques to reduce or eliminate greatly water use and process effluent from both bleach plant and whole-mill operations.

Historically, U.S. investments are driven by cost-effectiveness, regulatory mandates, and consumer demand for environmentally benign products. This trend is expected to continue as the industry moves into the twenty-first century.

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