can be minimized by avoiding overuse of surface-active materials and water-soluble polymers such as starches and wet-strength agents. Chemical defoamer formulations typically contain water-insoluble surfactants. They can also contain hydrophobic particles that help to rupture bubble surfaces when the surfactant molecules spread across those surfaces.

See also: **Packaging, Recycling and Printing**: Paper Recycling Science and Technology. **Papermaking**: Coating; Overview. **Pulping**: Chemical Pulping; Fiber Resources; Mechanical Pulping; Physical Properties.

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Environmental Control

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Introduction

The basic operations of the paper industry involve the conversion of renewable resources using chemicals, energy, water, and human ingenuity to produce a universal consumer product. Wastewater, air emissions, and both dry and waterborne solids are generated during the process. Heat and noise also are generated and disbursed into the environment. The objectives of this article are to identify the sources of these emissions and the processes by which they can be managed.

An overview of the paper manufacturing process suggests that the sequence of events can be divided into distinct phases. The first phase involves the recovery of papermaking fiber from either wood or recycled fiber resources. The second phase involves the purification of the liberated fiber and preparation of that fiber for the papermaking process. The final phase includes formation of the paper mat and modification of its surface to meet specific moisture resistance, strength, and optical properties for designated paper or paperboard applications.

The pulping operation and papermaking operations often run at separate locations, while integrated operations combine both pulping and papermaking facilities at one manufacturing site. The pulping phase is accomplished using several different processes ranging from full chemical pulping to thermal and mechanical defibering with a large variety of sequential treatment combinations involving chemical, thermal and/or mechanical processes in between. The chemical pulping operations often are accompanied by a variety of complex chemical recovery processes depending on the chemicals involved.

The fiber purification processes involve both mechanical and chemical processes to remove unacceptable components and to brighten the fiber for specific applications.

The papermaking phase commonly involves the dispersion of the fiber in large quantities of water and other additives to modify optical, chemical, and physical properties. The thin slurry is distributed on a continuous moving forming fabric allowing the water to separate from the wet fiber mat. The wet mat is then pressed against an absorbent fabric to dewater the wet mat. The partially dewatered mat is dried by evaporating most of the remaining moisture to form a paper or paperboard sheet.

Depending on the use of the paper it may also have been surface treated with sizing to minimize moisture penetration and to prevent ink from feathering on a printed page or coated with additional material and/or treated mechanically to modify its surface and optical properties. Coating followed by calendaring are common treatments to obtain papers with excellent printing quality characteristics.

Before dealing with the treatment of some specific waste streams, it is important to recognize some of the waste streams that are characteristic of the production phases. Characterizing each of these by-product streams and assessing their reuse alternatives will enable the diversion of some of the waste streams to reuse elsewhere in the manufacturing sequence.

The following figures (**Figures 1** to **5**) depict several of the steps in the production of paper and identify some of the major emissions from the various stages. The process schemes describe the liberation of fiber from wood or the recovery of fiber from recycled paper sources (post consumer) through

	Process stage	By-products
	Roundwood	
Chip preparation	Wood handling	Dust, dirt, bark
	Debarking	Bark and shower water with wood extractives, suspended solids
	Chipping	Noise
	Chip screening	Undersize and oversize chip
	Wood chips	
Chemical pulping	Pre-steam	Vent volatile wood extractives
	Cook chips	Vent odorous digester gases
	Wash cooked chips	Discharge spent liquor (weak black liquor)
	Blow chips to blow tank	Vent odorous blow vent gases
	Brown stock washing	Vent washer hood gases
	Screen brown stock	Collect uncooked chips and knots
	Liberated chemical fiber	

Figure 1 Chemical pulping processes.

	Process stage	By-products
	Weak black liquor	
Recovery furnace operation	Evaporated	Foul condensate and vapor
	Reduced inorganics	Smelt and particulates
	Oxidize organics	SO_x, NO_x, CO_2, particulates$_x$
	Dissolve reduced chemicals	Odorous gases and insoluble dregs
	Green liquor	
Liquor production	Caustizing green liquor	Odorous gases and precipitate
	Clarify cooking liquor	Lime sludge
	Cooking liquor	
Lime kiln operation	Lime washing	
	Filtering	Weak cooking liquor
	Calcining	SO_x, NO_x, CO_2, particulates
	Slaking	Insoluble dregs
	Regenerated lime	

Figure 2 Chemical recovery processes associated with the Kraft process.

	Process stage	By-products
	Waste paper/paperboard	
Pulping of waste paper and board	Hydro-pulping	Hydropulper rejects
	Removal of heavies	Heavy rejects
	Removal of lightweight material	Light rejects
	Liberated secondary fiber	
Deinking	Washing or flotation	
	Deinking	Ink sludges
	Deinked fiber	

Figure 3 Recovery of post consumer fiber.

the purification stages and the production of paper or paperboard. The recovery of cooking chemicals from the major pulping process is included to emphasize the cyclic nature of the Kraft pulping process.

	Process stage	By-products
Bleaching	*Clean liberated fiber*	
	Multistage bleaching process	Soluble organics and inorganics
	Bleached fiber	

Figure 4 Chemical purification and paper making.

	Process stage	By-products
	Fiber stock	
Stock preparation	Refining	Soluble organics and fines
	Final cleaning and screening	Cleaner and screen rejects
	Prepared stock	
Sheet formation and dewatering	Diluted with white water	
	Distributed on paper machine	
	Water drained from slurry	Excess white water
	Water pressed from wet mat	Pressate wastewater
	Evaporate moisture in sheet	Humidity, heat, particulates
	Paper sheet	
Surface treatment	Apply surface size	Volatile organic compounds
	Evaporate moisture	Volatile organic compounds
	Apply coating surface treatment	Volatile organic compounds
	Coated paper sheet	

Figure 5 Stock preparation and papermaking.

Air Emissions and Control Processes

Sources

Air emissions from the manufacturing process include: dust from wood handling, chemical recovery operations, the recovery furnace and the calcining operation, and the drying processes associated with moisture removal from paper and applied coatings. Odorous gases are generated during the chemical pulping and chemical recovery operations. Odorous gases characteristic of the Kraft process include: sulfides (mercaptans) and total reducible sulfides (TRS) that are detectable in the 1–20 ppb concentration range. Small quantities of noxious gases are generated from the bleaching process that volatilize as fugitive emissions. Fugitive emissions including chlorinated organic compounds, such as chloroform, originate in small quantities from the chlorine bleaching process. In addition to the emissions from the manufacturing process the generation of power and steam needed to operate the manufacturing facility also generate air emissions. Energy generated from fossil fuels, biomass, and the incineration of wastes all involve the combustion of hydrocarbon material. The possible byproducts from the combustion include: CO_2, CO, H_2O, NO_x, SO_x, particulate matter, and waste energy (heat). The amount of each of these by-products depends on the fuel used in the process and the energy requirements of the facility.

Control

Particulates can be recovered by filtration (bag house operations), scrubbing (absorption), or settling induced by gravity or by electrostatic mechanisms. Gases are recovered either by collection in another media or by chemical conversion to a more benign compound. Media alternatives include the adsorption of the gases material on to a solid substrate or the absorption into a liquid media. The media selected may include chemicals that will ultimately react with the compounds sorbing the gaseous constituent.

Particulates

Treatments for particulates suspended in air are of three types: one is dependent on their density, the second is dependent on their physical size, and the third is dependent on generating a unique force that can be applied to the particle as it passes through a control device.

The density dependent control processes are based on the particle's inertia. Because of its inertia, the particle will tend to continue moving in a straight line as the carrier fluid (air) is forced to change direction. The resulting path of the particle is to impact (and be collected) on a collecting surface. The most common inertial control device, effective on relatively large particles (greater than 30 μm diameter), is a cyclone collector. Since the centrifugal force depends on the rate of directional change that takes place in the fluid stream, cyclones with small diameters are more effective but require larger pressure drops. A number of cyclones can be configured into a single body to save space. Scrubbers can be used to improve particle collection efficiency by first collecting the particles in a liquid droplet followed by the separation of the droplet from the gas stream. The liquid can be introduced in a number of ways including:

- a venturi device preceding the cyclone
- a liquid spray inside the cyclone
- directing the particle laden gas into a liquid before going into the cyclone.

The inertial phenomena also can be used effectively by impinging the gas flow through open structure forcing the gas to make many directional changes causing the particles to impact onto wetted surfaces within the erratic structure. One advantage with these control devices is that they can operate continuously. As the collected particles are continuously flushed from the collecting surfaces, the operation of the control device does not need to interrupt its operation to be cleaned.

The collection methods based on physical size are essentially screening processes. Particles that are larger than the openings in the filter media are trapped in the media, thus separating the particles from the fluid stream. Fabric filters are commonly configured with a number of cylindrical collection surfaces bunched in a common housing. The 'bag house' filter is limited to dry conditions and requires some interruption of the collection process to dislodge the collected material. The filter tends to plug as the surface becomes clogged with particulates and needs to be cleaned periodically. The cleaning cycle involves taking a portion of the filter off-line and cleaning it by back flushing with a burst of air or shaking it to dislodge the collected material. Collection efficiency and pressure drop depend on the size of the openings in the filter media.

The third type of collector functions by charging the particles electrically and exposing the charged particle to a surface with the opposite charge. The electrostatic forces cause the particle to migrate to the collecting plate where they accumulate. In this collection device the accumulated particulates are dislodged by shaking the plate, causing the accumulated layers of particles to slough off and fall to the bottom of the precipitator. Since the particles come off as a conglomerate, they are not re-entrained in the gas stream and thus are separated from the gas. This process is effective for very small particles but is limited by the dielectric property of the gas, which is heavily influenced by high temperature and the presence of moisture.

Gases

The controls for gases (sulfur oxides, sulfides, nitrogen oxides, volatile organics) might include or incorporate collection, destruction, or prevention. Collection can be accomplished by either absorption or adsorption while destruction can be accomplished by chemical reaction induced by either thermal destruction or imposed reactions. Prevention is the first choice where this alternative is feasible.

Absorption involves the transfer of the gas from the carrier gas to a liquid stream. The transfer is accomplished by contacting the carrier gas with an appropriate liquid in which the contaminant is soluble or with which it will react to form a soluble compound or precipitate.

Adsorption is used to transfer the contaminant to a surface. A highly porous surface is particularly effective. A good example is the use of activated carbon to adsorb volatile organic compounds.

Thermal processes utilize high temperature with or without a catalyst to convert the contaminant into benign compounds, or compounds that have less effect on the environment. Chemical reactions include specific reactions to convert contaminants into more agreeable compounds. Typical examples include oxidation of hydrocarbons to carbon dioxide and water or reactions that produce passive materials that do not have any impact on the environment.

One example of a prevention effort is the oxidation of odorous sulfides to sulfur oxides to reduce the foul odor associated with the spent cooking liquor generated in the Kraft pulping process.

Wastewater Emissions and Treatment Processes

Sources

Wastewater sources probably are the must numerous of all of the emissions sources from the paper manufacturing industry. Some mills use water to wash logs before treating the logs in a drum debarker, while others use high-pressure water to hydraulically debark the logs. In either case the wastewater generated contains both soluble and suspended solids.

The fiber liberation and purification processes also generate significant wastewater discharges. Except for accidental releases and leakage, all of the waterborne wastes from the chemical pulping process goes to chemical recovery. Chemical recovery releases foul condensate, and sludge from the slaking and smelting processes. Waterborne wastes from mechanical and thermal pulping processes, however, generate significant amounts of both dissolved and suspended solids.

Wastewater Treatment

To minimize maintenance concerns in the wastewater treatment train and to stabilize flow rates and loads many treatment systems include barrier screens and equalization basins. Barrier screens prevent oversize pieces of suspended solids from getting into the inlet flow stream that might interfere with the process equipment. Equalization basins serve to mix intermittent high concentration and large flows in a storage basin to provide a consistent feed rate to conventional primary and secondary treatment operations.

The primary clarifier is intended to remove the suspended solid portion of the wastewater. The primary treatment process is usually dependent on gravity settling to separate the suspended material from the liquid suspension. Because the settling rate is proportional to the square of the diameter of the particle, the raw wastewater is sometimes treated with coagulants that encourage individual particles to agglomerate forming large flocs. A typical primary clarifier is designed to handle between 500 and 1000 gpd/ft^2 of surface area removing 80–90% of the suspended material. Because some of the oxygen-demanding material is the suspended material itself or is attached to the suspended material, the removal of suspended material can also remove a significant fraction of the oxygen-demanding waste load. Another method of removing suspended material involves the use of a flotation clarifier. The flotation clarifier also used additives to agglomerate the suspended material with an air bubble, thus creating a particle that is less dense than the fluid causing the coagulated particle to float to the surface. The floating material can be skimmed from the surface and thus separated from the bulk of the liquid.

Biological treatment is intended to reduce the oxygen demanding components (biochemical oxygen demand, BOD) in the wastewater entering the secondary treatment system. The removal of the BOD components is accomplished by allowing bacteria to consume the BOD, usually in the presence of excess oxygen. The treatment occurs in aerated stabilization basins, activated sludge systems, large oxidation basins, or other biological contact processes. The key components in the process are aerobic bacteria, dissolved oxygen in water, and the oxygen-demanding material. The required residence time depends on the temperature, concentration of bacteria, concentration of oxygen, the BOD_5 load and nitrogen and phosphorus nutrients. The optimum temperature range is 20–30°C, the ideal BOD_5/N/P ratio is approximately 100/5/1, and the desired pH range is from 6.5 to 7.5, while residence times range from 3 h to more than 60 days. The residence times are 3–24 h for the activated sludge process, 5–10 days for the aerated basin process, and from 20 to 60 days for a storage aeration pond. The activated sludge process achieves BOD reductions in a short residence time by concentrating the bacteria in a highly oxygenated basin and recycling the bacteria by settling them in a clarifier and immediately returning them to the aeration chamber where they are combined with the flow of fresh wastewater. Another way to shorten the residence time is to inject oxygen-enriched air in the aeration chamber. The aerated stabilization basin process supplements the oxygen concentration by introducing oxygen by aerating the basin using surface mixers or subsurface aeration. The storage aeration process uses natural aeration of the basin's contents as the wind provides a natural wave action. The lower oxygen and bacteria concentrations require a longer retention time. This process generally follows one of the other aerobic processes. All of the above processes suspend the bacteria in the wastewater to accomplish the BOD reduction. The 'trickling filter' and 'rotating biological contactor' arrange to have the bacteria fixed on a structural media and provide for alternate contact between the bacteria and the BOD in the water and oxygen in air. The trickling filter requires a larger footprint than the activated sludge process but requires less energy to operate the system. These fixed media biological treatment processes are not widely used in the industry.

Another alternative for the treatment of mill wastewater is anaerobic treatment. As the name implies the process operates in the absence of oxygen. The carbon components are oxidized to CO_2 and reduced to CH_4. The methane gas is recoverable and can be used to provide heating to maintain reactor temperature or other combustion applications. The optimum temperature is approximately 35°C. One advantage of this process is that the amount of sludge produced per unit reduction of BOD is reduced to between 20% and 35% of that produced from the aerobic process. The anaerobic process is most effective for high BOD loads. This alternative is currently used at only a few pulp and paper installations and most of these are large covered-basin systems.

Effluent waters typically are treated by conventional means; primary treatment is followed by secondary treatment as needed. Mills in urban settings are likely to provide only primary treatment of their effluent before it goes to a municipal wastewater treatment facility. Mills in a more isolated setting would need to provide both primary and secondary treatment before discharge to a natural estuary or receiving water.

Solid Waste Sources and Management Alternatives

Sources

The solid waste components that accumulate around a manufacturing facility are the most diverse of all of the waste categories. Waste sources include: process wastes, raw material wastes, production wastes, spills, housekeeping, maintenance and remodeling wastes plus the residues that are generated by the treatment processes to manage air and water emissions. Solid wastes are generated from wood processing, chip preparation, pulping residuals, screening and cleaning rejects, and from nonpulpable components from secondary fiber sources. Sludges from wastewater treatment activities and recovered bottom ash and fly ash from power generation and incineration of other solids, fly ash from the recovery furnace, and fly ash from the calcining kiln are the result of environmental controls. Shipping containers, packaging materials, surplus and worn-out equipment, combined with numerous cleaning, housekeeping, maintenance and manufacturing remnants also contribute to the solid waste stream.

Wood pulping Process wastes generated by the industry are mostly derived from either organic sources (biomes or sludges containing biomes) or inorganic chemicals derived from inorganic minerals. Typically the largest source of organic waste comes from the log preparation, debarking, and chip screening operations. Some additional organic residual comes from the washing stages following the digester containing incompletely digested wood chives and knots. These mechanically separated materials can be dried and burned in the energy and power generation facilities associated with the mill. The resulting ash (both bottom ash and fly ash) plus the ash from the auxiliary fuel are additional waste components that need to be handled. Small quantities of solids are recovered from the purification and stock preparation processes that precedes the paper making operation.

Chemical recovery Chemical recovery operations generate a couple of inorganic wastes in the form of smelt dissolving dregs, green liquor clarifier and lime slaking dregs and fly ash from both the recovery furnace and the lime kiln. The fly ash components recovered from both of these sources are reintroduced back into the chemical recovery cycle.

Secondary fiber The recover of papermaking fiber from post consumer waste paper and paperboard generate a large variety of solid wastes. Nonpulpable material, dirt, sand and grit, staples, adhesives, sealing tape, labels, plastics, and packing materials are all separated from the reusable fiber. These materials each contribute to the wastes that are generated from the secondary pulping process. In the event that deinking and chemical purification of the secondary fiber is warranted, additional sludge containing ink, coating, and filler materials and soluble by-products are generated.

Treatment

Because of the diversity of materials that constitute the solid waste fraction, the treatment options are more diverse. Some of the materials are recyclable, some combustible, some can be land applied or composted while other fractions seem to have so little value that the most common option is to secure them in a well-designed landfill.

A major share of the solid waste stream is recovered because of its intrinsic value. Scrap metals, worn parts, and surplus equipment are notable examples. Components that are routinely replaced, shipping containers, and remodeling wastes are encouraged to be recycled by the supplier. Items of little intrinsic value generated by maintenance and housekeeping are commonly transferred to a waste disposal agent.

Organic wastes have a significant heating value; however, only those materials that can be effectively dewatered are viable candidates for energy recovery. Bark and wood wastes that are easier to dewater and dry are more likely to contribute to the energy needs of the mill. Most organic sludge materials are difficult to dewater though it is not unusual for these materials to be burned. Because of the moisture content of these wastes the remaining alternatives for treatment include biological treatment, land application/composting, or storage in a landfill.

Wastewater treatment sludges originate from either primary treatment or secondary (biological) treatment. Sludges from primary treatment will have either a high fiber content or a mix of fiber and filler material. Secondary treatment sludge is characterized as having a large amount of microbiological residue that is very effective at retaining moisture. The particular characteristics of each of these sludges prescribes how these sludges can be handled.

Secondary sludges have a large microbial cell content and are extremely difficult to dewater or stabilize. These sludges are difficult even to landfill because of their water content and unstable flow characteristics. One solution used often is to combine primary and secondary sludges to facilitate dewatering of the secondary portion. Alternatives for treatment include additional biological treatment, composting and anaerobic digestion. These additional processes reduce the quantity of the waste, which generally is easier to dispose.

Beneficial Use

Recycling is the most likely alternative for handling the largest share of solid wastes generated by a mill. Undersized and oversized chips are either burned for energy generation or the oversized are processed in a rechipping operation. Some operations focus on incompletely digested wood which can be treated in two different ways. One is to use the undigested wood as fuel and the second is to return it to the digester for another pass through the system.

Other beneficial uses for materials such as wastewater treatment solids include land application/composting, burning for energy, or use in by-products such as animal bedding, absorbent materials, concrete, fuel pellets, etc. Ash can also be used as a construction material or in by-products such as concrete.

Thermal Sources and Discharge

Thermal releases are associated with steam and power generation, pulping, chemical recovery, and drying process emissions. Manufacturing facilities recover and recycle as much of the thermal energy from these processes as practical. The lowest temperature energy residuals are discharged to the atmosphere as hot air or moisture generated by cooling tower operations or building vents. Some thermal energy is typically also released in wastewater discharges.

Noise Sources and Control

Noise is generated by the vibrations of rotation machinery and pumps, and by the flow of fluids through throttling valves. Treatment generally is accomplished by redesign and isolating rotating machines. Many pieces of equipment are mounted on vibration isolating pads and often are contained with noise insulated enclosures. Personal hearing protection is often used to protect personnel from the noise associated with some parts of the manufacturing process.

Summary

It is important to recognize that the various treatments of wastes (air, water, solids, heat, and noise) are often interdependent. The treatment of one type of waste can impact another type of waste. Management of any one of these environmental concerns can in turn affect other areas. Wastewater treatment commonly generates some sludge solids. Incineration of solids commonly generates some emissions to the air. Treatment of air pollutants generates either solid or liquid wastes. It is also important to recognize that most processes produce some by-products along with the desired product.

With these facts in mind, it makes sense to minimize the production of pollutants by modifying the manufacturing processes rather than treating pollutants after they are formed. The definitive solution to the environmental issues is to eliminate pollution sources where technically and economically feasible, minimize their production as much as practical, recycle by products as much as possible, and safely manage the remainder. The hope is that we can minimize waste streams and make them nontoxic and benign to our environment and us.

See also: **Packaging, Recycling and Printing**: Paper Recycling Science and Technology. **Papermaking**: Coating; Overview; Paper Raw Materials and Technology; World Paper Industry Overview. **Pulping**: Bleaching of Pulp; Chemical Pulping; Chip Preparation; Fiber Resources; Mechanical Pulping; New Technology in Pulping and Bleaching.

Further Reading

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