Primitive people over countless ages communicated with each other or expressed themselves by audible sounds and visible symbols carved in wood or stone, impressed in clay, or painted on the walls of caves. As society progressed, these sounds and signs developed into language; symbols became alphabets, and records of important events could then be written on clay tablets. The Egyptians simplified record-keeping with the introduction of papyrus sheets, formed from the reeds of the papyrus plant, about 3000 B.C. The word paper is derived from papyrus.

During later periods of civilization, scribes kept handwritten records on parchment and hand-formed paper, chiefly for the ruling classes. The hope of written communication for the masses first came with the development of the printing press about 500 years ago. This created a demand for paper, so varieties of fibers and process methods were vigorously investigated for use in paper manufacture. In the early days of the American colonies, the fibers were obtained from rags; but by the nineteenth century, the demand for paper had increased so much that the quantity of rags available was insufficient to supply the need, and wood fibers began to find use in paper pulp.

The pulp and paper industry has since grown to produce not only paper for records, documents, and books, but also heavier grades for packaging, and plain and corrugated liner board for shipping containers, such as drums and cartons. Despite the relative light weight of the finished product, pulp and paper constitute one of the major tonnage products in the United States; it may soon challenge the output of the steel industry in annual production. The production of the major varieties of paper and board are shown in Table 30.1.

Today paper is almost entirely derived from wood, and since only about half of the weight of timber brought to the pulp mill is cellulose, researchers over the years have actively sought uses for the remaining 30 to 50% released during chemical pulping. They have developed a variety of by-products which include turpentine for the paint and coatings industry, tall oil for the manufacture of chemical intermediates, lignosulfonates as surface-active agents and dispersants, and such other products as yeast, vanillin, acetic acid, activated carbon, and alcohol. Table 30.2 shows the major categories of the components of wood.

Subsidiary operations in many pulp and paper mills include the manufacture of plywood, particle board, and chipboard, as well as the production of alpha cellulose, which is a dissolving pulp used in the manufacture of cellulose acetate.

Probably no industry has done as much in reclaiming waste products as the pulp and paper industry. Scrap paper is collected, sorted into grades for repro-
cessing, and converted into new grades of tissue, book stock, container board, and other useful forms. Approximately 20% of the output of the paper industry is reused by secondary fibers processing plants.

**WATER: A BASIC RAW MATERIAL**

The manufacture of pulp and paper requires large volumes of water. Since its earliest days, the industry has located almost exclusively along major rivers. The first mills used water not only to make pulp and paper, but also for hydraulic power, by damming the stream to produce the head needed to drive water wheels which operated the grinding stones to convert wood to pulp. Many modern mills are located at the site of these early mills and continue to use hydraulic power for operation of grinders or of hydroelectric turbines.

The water required by a modern pulp/paper mill varies considerably with the pulping process, the availability of water, the bleaching sequence, and restrictions on wastewater discharge. Table 30.3 shows the water requirements for older and newer mills, based on the type of production.
The pulp and paper industry is a large user of water because the pulp is washed with water at several points in the process, and water is used to convey the pulp fibers from their initial production in the pulp mill through various refining operations, and finally to the paper machine, where it may be introduced to the forming wire at a slurry concentration which is 99% water and only 1% fiber (called 1% consistency in paper mill terminology). Whereas older mills used as much as 50,000 gal per ton of finished paper product, modern mills have closed up their systems to reduce the amount of water required and therefore the volume of waste to be treated. In a modern unbleached pulp/paper mill, producing linerboard, the consumption may be as low as 10,000 gal/ton (42 m³/t), and in a bleached pulp/paper mill the requirement may be approximately 15 to 20,000 gal/ton (63 to 83 m³/t). So, in a mill producing about 1000 tons/day (907 t/day), which is typical of southeastern U.S. kraft mills, the water treatment plant may be required to produce about 20 mgd (7570 m³/day), of mill water for process and boiler makeup. Under certain circumstances, some smaller mills producing grades of product not harmed by high salinity have been able to close up and reduce freshwater makeup to less than 5000 gal/ton (21 m³/t).

Of the variety of pulping operations in use throughout the world, most fall into one of three categories: mechanical pulp, chemical pulp, or secondary fiber (reclaimed paper).

For most types of timber used to supply the pulp mill, the logs are cut to a convenient length and debarked in a device such as the barking drum shown in Figure 30.1. Since the bark is a significant portion of the raw material, the water used in the debarking operation is recycled and the bark removed, dewatered, pressed, and used as fuel for steam generation in specially designed bark boilers. Excess water from this operation is often high in BOD, because of the wood sugar extracted in the debarking process, and high in coliform organisms from the exposure of the tree to animal life both in the forest and in the wood yard.

### TABLE 30.3 Net Water Use for the Manufacture of Pulp and Paper Products

<table>
<thead>
<tr>
<th>Pulp manufacturing process:</th>
<th>Typical gal/ton*</th>
<th>New mills, gal/ton*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbleached kraft</td>
<td>15,000–40,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Kraft bleaching</td>
<td>15,000–35,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Unbleached sulfite</td>
<td>15,000–50,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Sulfite bleaching</td>
<td>30,000–50,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Semichemical</td>
<td>8,000–40,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Deinked</td>
<td>20,000–35,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Groundwood</td>
<td>3,000–48,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Soda pulp</td>
<td>60,000–80,000</td>
<td>65,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Paper manufacture:</th>
<th>Typical gal/ton*</th>
<th>New mills, gal/ton*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine paper</td>
<td>8,000–40,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Book or publication grades</td>
<td>10,000–35,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Tissue</td>
<td>7,000–45,000</td>
<td>15,000</td>
</tr>
<tr>
<td>Kraft papers</td>
<td>2,000–10,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Paperboard</td>
<td>2,000–15,000</td>
<td>8,000</td>
</tr>
</tbody>
</table>

* Gal/ton × 0.0042 = m³/t.
GROUNDWOOD PULP

In the production of mechanical pulp, logs are loaded into the magazine of a grinder (Figure 30.2) in which they are pressed against a grinding wheel. Abrasion separates the bundles of fibers into individual strands, and except for a relatively small percentage of organic matter extracted during the grinding operation, the lignin which holds the fibers together remains in the finished pulp, so that the pulp yield is quite high. The yield varies with the type of wood being ground but is generally on the order of 90%; that is, 90% of the weight of wood fed to the grinder becomes pulp available for paper manufacture.
Although the organic material extracted from the wood fiber during grinding is a small percentage of the fiber weight, it is a significant addition to the water; so the water wasted from the groundwood pulping operation is quite high in organic matter.

Paper produced from groundwood pulp is weak and has poor aging properties. For that reason it is used for manufacture of newsprint, where strength and aging properties are not critical factors. Even with newsprint, to provide the strength needed on a modern printing press, some chemical pulp, usually about 15%, is blended into the groundwood pulp to produce a satisfactory sheet.

**THERMOMECHANICAL PULPING**

Thermomechanical pulping (TMP) is a new process producing a mechanical pulp superior to groundwood in strength. Used in newsprint, it permits a reduction of chemical pulp in the furnish, at the same time producing a stronger sheet. But its major contribution to the industry is its ability to reduce chemical and water usage, with carrythrough benefits in waste treatment, while producing a pulp comparable to chemical pulp in many respects.

In the TMP process (Figure 30.3), wood chips are washed with recycled water,
which may be white water or filtrate containing pulping chemical residues. This is macerated in a screw press to a homogeneous slush, and passed continuously through a steam-heated digester. This softens the fibers and permits them to separate later at boundaries which are relatively free of lignin. This improves refining, conducted in three stages following the digester. The refined pulp is screened, cleaned, and adjusted to the required consistency for bleaching. As with groundwood, hydrosulfite and hydrogen peroxide are the bleaching chemicals.

**CHEMICAL PULPING**

To improve the qualities of pulp fiber, early research workers developed chemical processes to dissolve the lignin and other organic materials holding the fibers together, releasing the fibers without extensive mechanical working. There is a continual development of new modifications to these basic chemical processes to meet modern needs for high-quality product and minimum wastewater contamination.

The basic chemical processes in use today are categorized as acid, neutral, or alkaline pulp processes, as shown by Table 30.4.

<table>
<thead>
<tr>
<th>pH environment</th>
<th>Acid</th>
<th>Neutral</th>
<th>Alkaline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anionic species</td>
<td>$\text{SO}_2$, $\text{HSO}_3^-$</td>
<td>$\text{HSO}_3^-$, $\text{SO}_3^{2-}$, $\text{HCO}_3^-$, and $\text{CO}_3^{2-}$</td>
<td>$\text{HS}^-$, $\text{S}^{2-}$, and $\text{OH}^-$</td>
</tr>
<tr>
<td>Cationic species</td>
<td>(1) $\text{H}^+$—acid sulfite</td>
<td>$\text{Na}^+$</td>
<td>$\text{Na}^+$</td>
</tr>
<tr>
<td>and process designation</td>
<td>(2) $\text{Na}^+$—sodium base</td>
<td>(1) Neutral sulfite</td>
<td>(1) Kraft</td>
</tr>
<tr>
<td>(3) $\text{NH}_4^+$—ammonium base</td>
<td>(2) Neutral sulfite—semichemical*</td>
<td>(2) Kraft—semichemical*</td>
<td></td>
</tr>
<tr>
<td>(4) $\text{Ca}^{2+}$—calcium base</td>
<td>(3) Chemiground*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(5) $\text{Mg}^{2+}$—magnesium base</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* In these processes, liquor is used to soften the wood before grinding.

In all of the chemical pulping processes, a chemical solution is prepared and fed to a digester, a vessel in which it is mixed with wood that has been cut into chips to permit the liquor to penetrate effectively and produce a uniform pulp. The mixture is then cooked for a specified period at the optimum temperature for the particular process and the type of wood being pulped. Most digesters operate on a batch basis, but there is increasing use of continuous digestion processes.

At the conclusion of the digestion period, the contents of the digester are discharged into a blow tank. Because the liquor is at a high temperature, steam and volatile components from the wood flash off. These are condensed, and organic by-products may be produced from the condensed liquid. The quenching of the vapor provides heat for process water and also controls air pollution by concentrating and collecting sulfur compounds for burning.
RECOVERING PROCESS INGREDIENTS

The pulp from the blow tank is washed to remove the spent pulping liquor; the pulp then goes to further processing and the washwater containing the spent pulping chemicals is usually reclaimed. Because the liquor contains organic matter extracted from the wood, when concentrated by evaporation the organic material reaches a concentration level that permits the liquor to be sprayed into a furnace for burning, the combustion of organic matter providing the Btu's for evaporation of the liquor to dryness. The chemicals in the liquor become molten, and the molten products (smelt) collect at the bottom of the furnace for recovery. This recovery procedure does not apply to calcium-base sulfite cooking liquors. Since there is no practical way to recover the calcium-base liquor, the calcium-base sulfite process has practically disappeared. Magnesium-base sulfite liquors are recovered, but not exactly as described above.

Chemical recovery has been in operation for many years in the kraft process, because the process would not be economical without such recovery. The chemicals recovered are returned to the process through a chemical recovery operation which will be described later. The chemicals recovered from the NSSC process (neutral sulfite—semichemical) cannot be used directly again in the process, but can be used as makeup to a kraft mill. Because of this, some pulp mills have both kraft and a semichemical process; if the pulp mill is strictly an NSSC mill, it may recover its chemicals in a dry bead form, providing a product which can be supplied to a nearby kraft mill.

Because these pulping operations use sulfur-containing chemicals, many of which have a high odor level, sophisticated processing equipment is required to avoid leakage, which could result in air pollution. These sulfur compounds have a high oxygen demand, so it is equally important to avoid leakage of pulping liquors to the sewer, where they would impose a load on the waste treatment plant. Not only do these liquors have a high chemical oxygen demand (COD), but they also contain the organics extracted from the wood, and are therefore high in BOD.

The yield from chemical pulping is considerably less than from a groundwood operation, where the organic remains attached to the cellulose fiber. The extraction of lignin and hemicellulose is so effective in chemical pulping that the kraft process has a yield on the order of less than 50% compared with a semichemical pulping yield of about 70% and the groundwood pulp yield of about 90%.

THE KRAFT PROCESS

As an example of the chemical pulping operation, the kraft process, which produces about 75% of the total pulp output of the United States, is illustrated by Figure 30.4. In this process, chips and white liquor are measured into a digester, and the mixture is then brought up to about 350°F (177°C) either by direct steam injection or by recirculation of liquor through a steam-heated exchanger on the side of the digester. At the completion of the cooking period, which may take 2½ to 3 h, the contents of the digester are discharged to the blow tank, the vapors from which are used for heating water. In the process turpentine may be recovered, a significant by-product in pulping softwood. Noncondensible gases, such as H₂S and SO₂, are released for separate treatment to control sulfurous emissions.
FIG. 30.4 Kraft process flow sheet. Note that the pebble lime (CaO) may go to a slaker or may be slaked in the causticizer.

FIG. 30.5 A typical brown stock washing system.
The pulp is sent to the brown stock washers to remove the spent pulping liquor which may lower pulp quality. There are usually three stages of washing (Figure 30.5) with water flowing countercurrent to the pulp, picking up pulping chemical to become a weak black liquor containing approximately 10 to 12% total solids. This liquor is concentrated to over 55% total solids in an evaporator producing a strong black liquor so high in organic solids that it will burn when sprayed into the recovery furnace. Salt cake (the industry term for Na$_2$SO$_4$) is also added to the recovery furnace to provide makeup to the sulfur-bearing liquor to account for losses at various points in the circuit. In the recovery furnace, the sulfate is reduced to sulfide and some of the caustic is converted to carbonate by contact with the CO$_2$-containing gases produced from combustion of the organic matter. These materials become molten at the furnace temperatures, and the molten salts, called smelt, drain down the furnace tubes and collect at the bottom of the furnace. They are tapped off into the smelt dissolving tank.

![Magnesium-base sulfite pulp flow sheet](image)

**FIG. 30.6** Magnesium-base sulfite pulp flow sheet.
Recovered weak liquor quenches and dissolves the smelt, producing green liquor that must be clarified before it can be regenerated. The dregs from the clarifier contain valuable chemical, so they are washed and the weak liquor returned to the dissolving tank. The green liquor, which contains sodium carbonate, is then causticized by the addition of lime, converting the sodium carbonate to sodium hydroxide and producing calcium carbonate precipitate. The product of the liming operation is white liquor, which must be clarified before it can be returned to the digester. The mud produced from the clarifier is almost entirely calcium carbonate. This is washed and filtered, and the cake is fed to a kiln, which burns the calcium carbonate to calcium oxide for recycle.

The operation of a modern kraft mill is so tight that the amount of salt cake required for makeup to account for liquor losses is typically in the range of only 25 to 50 lb per ton (12 to 25 kg/t) of pulp. The condensates produced at the digester and evaporator vary in quality: those produced directly from the condensation of boiler house steam can usually be returned to the boiler plant, but even here, careful monitoring is required to make certain that leakage does not occur in the system to spoil the condensate and cause problems with steam generation. Other condensates may be used for pulp washing and other washing operations. The poorest grade of condensate from the kraft process, sour condensate, must be stripped of its volatile sulfur compounds, and it usually remains so badly contam-

FIG. 30.7 NSSC pulping process.
inated that it must be sent to the waste treatment plant. It is a common source of problems in the operation of the waste treatment plant.

Using the kraft mill as a pattern, Figures 30.6 and 30.7 show the chemical pulping for the magnesium-base sulfite process and for the neutral sulfite-semichemical process, respectively. The sources of wastewater contamination in these circuits are similar to those found in the kraft mill.

**PULP PROCESS UNITS**

In the chemical pulping operation itself, the major items of equipment are the digester, the blow tank, vapor recovery, and pulp washers.

These are the basic units shown on the reference diagrams of chemical pulping operations. Contamination of steam condensate or water with pulping liquors can occur in the digester, except where direct injection of steam into the digester may be practiced. Two types of digesters are shown in Figures 30.8 and 30.9: the first is a batch-type digester in the kraft industry, where the liquor is externally circulated through a heat exchanger in which leakage of liquor into the condensate is always a potential threat. The second illustration shows a continuous digester, which also has external heat exchangers for heating of liquor or washwater with steam, again providing potential for leakage of contaminants into steam condensate.

The washers shown in Figure 30.5 were originally designed only to improve pulp quality by removing excess liquor. Operation of the washwater countercurrent to the pulp flow also allowed recovery of relatively strong liquor. With the attention today on minimizing wastewater discharge, the pulp washer also provides a potential point of reusing excess water from the paper mill or contaminated condensates from the pulp mill. In recycling these wastewaters to the washer, the original intent of washing to produce an acceptable pulp must be kept in mind; for example, certain pulp mill condensates are so badly contaminated with odorous sulfur compounds that they are unacceptable for pulp washing because they would impart this odor to the finished pulp.

After the pulp has been washed and the liquor reclaimed, there are a variety of devices for purifying the pulp to the extent necessary for its end use in paper, board, or chemical manufacture. The major devices are thickeners, refiners, screens, and cleaners.

Some of these devices require that the pulp be diluted before it can be pro-
cessed and others require that the pulp be thickened. This change in consistency may be done in storage vessels, called stock chests, or directly by in-line mixing if dilution is the effect to be achieved. However, where concentration of the pulp is required, the pulp must be passed over a thickener (Figure 30.10) for removal of water. The water recovered from this thickening operation is recycled to the most convenient point in the pulping system.

Refiners are somewhat related to grinders, providing mechanical force to abrade the pulp fibers and reduce them to individual strands of cellulose. The two most common types of refiners are disk refiners (Figure 30.11) and Jordans (Figure 30.12). Screens are used to classify pulp fibers to a certain size, with the oversize particles being returned for reprocessing; screens are also used for the removal of undesirable materials from the pulp, such as knots and noncellulose debris (Figure 30.13).

Centrifugal cleaners are hydraulic cyclones that separate pulp fibers both on the basis of density and size. The more dense or oversize materials are sent to the periphery of the cyclone, and the acceptable fiber fraction is withdrawn from the center of the cyclone. Very often three stages of centrifugal cleaning are involved (Figure 30.14). The rejects from the first stage go to the second, rejects from the second go to the third, and rejects from the third are wasted or returned to a point where their values may be reclaimed, such as in the barking drum where some waste cellulose particles may remain with the bark to be reclaimed in the bark boiler.

These basic units are put together in a pulp mill in different ways depending on the nature of the wood being pulped, the pulping process, and the type of paper.

**FIG. 30.9** Continuous digester used in the manufacture of kraft pulp.
FIG. 30.10  Removal of excess water is often needed for pulp storage. This process is called deckering. These two types of deckers are commonly used for increasing consistency. (Top) This drum filter is thickening kraft fiber. (Bottom) Fiber dewatered through this vertical, slotted-screen decker is seen tumbling into the pulp discharge flume.  (Courtesy of Dorr-Oliver Incorporated.)
FIG. 30.11 (Top) In the disk refiner stock flows between rotating grooved plates, which separate bundles into individual fibers. (Bottom) Details of disk design. (Courtesy of Bolton-Emerson.)

or board being manufactured. Typical schematics for a groundwood mill, kraft mill, and semichemical mill are given in Figures 30.15, 30.16, and 30.17.

**BLEACHING**

If the final product is a bleached grade of paper or board, bleaching is done in the pulp mill. Chlorine and chlorine compounds are most commonly used for bleach-
Rotary screens can handle large flows and classify fibers by their size. These screens are installed ahead of a bleached kraft foodboard machine. (Courtesy of Black Clawson Company.)

In the Jordan refiner, stock is forced between a rotating plug and a stator, both of which have grooved surfaces or blades to break up fiber bundles.

FIG. 30.13 Rotary screens can handle large flows and classify fibers by their size. These screens are installed ahead of a bleached kraft foodboard machine. (Courtesy of Black Clawson Company.)

Flooding kraft pulp, but oxygen bleaching is assuming increasing importance in the industry. Typically, bleaching is accomplished in several stages, with the residues of the bleaching operation extracted from the pulp between these stages. A common example would be chlorination followed by caustic extraction as the first part of the sequence; this would be followed by hypochlorite bleaching, also followed by caustic extraction, with a final treatment with chlorine dioxide. In pulp mill terminology, this would be identified as CEHED bleaching. There is as yet no practical way to reclaim the materials extracted from the pulp during the bleaching operation, and these liquors constitute one of the major pollution problems in the pulp mill. This production of strong wastes from the bleaching operation is shown in a typical bleaching sequence diagram, Figure 30.18.
FIG. 30.14 Flow sheet showing three stages of centrifugal cleaning of pulp. (Courtesy of Bauer Bros. Co., a subsidiary of Combustion Engineering, Inc.)
FIG. 30.15  Groundwood mill process units.

FIG. 30.16  Kraft mill process units.
FIG. 30.17  NSSC process units.

FIG. 30.18  Kraft mill pulp bleaching, CEHED sequence.
When oxygen is included in the sequence, it is the first stage and replaces chlorination and extraction, significantly reducing the concentration of wastes and the load on the waste treatment plant.

Other bleaching agents include zinc hydrosulfite, which is used for bleaching groundwood pulp, sulfur dioxide alone, or chlorination followed by sulfur dioxide.

**PROBLEMS CREATED BY WATER**

There are a variety of water-related problems in the pulp mill in addition to those already mentioned. These include contamination of steam condensate, discharge of concentrated wastes that cannot be recovered, and nonrecoverable water containing organic matter and other reducing chemicals that produce a load on the waste treatment plant. One of the principal problems is foaming, induced by the surface-active nature of some of the organic matter extracted from the wood. Chemicals for foam control are commonly required at the screens and washers to maintain production capacity.

A more difficult problem to control is the production of scale in evaporators, where the gradual increase in concentration of both inorganic and organic solids causes the solubility limit of calcium sulfate and other materials to be exceeded. It is common practice to boil out an evaporator with water on a scheduled basis to keep this under control. Sometimes the water used for boilout can be reclaimed if it is sufficiently concentrated to justify putting into the evaporator circuit; some of the water used for this operation, however, must be wasted, and this imposes a load on the waste treatment plant.

As in so many other industrial operations using water, corrosion is a constant threat; for the most part it is kept under control by the selection of suitable alloys or plastics, but even alloys may be subject to corrosion where microbial activity may cause slime deposits. Fortunately many of the circuits are relatively hot, which in itself prevents slime growths, but microbial activity frequently develops in the cooler areas of the pulp mill system.

**SECONDARY FIBER RECOVERY**

Waste paper and board make up a major raw material resource for the paper industry. These wastes are sorted, and the choice between the different grades and their prices determines how they are reprocessed and the type of finished sheet produced and its cost. There are about 40 to 50 grades varying in quality from clean clippings from a paper converter (such as envelope stock) to newsprint and used paper bags. The poorest grade is unsorted (Mixed Grade No. 2).

The raw stock is reduced to slurry by agitating with hot water in a mixing tank (Figure 30.19). Strings and bailing wire are separated at this point. If the stock is printed matter and the finished pulp must be equivalent to virgin pulp, it is de-inked. This operation involves heating the stock to about 150°F (66°C) and adding chemical agents to release the ink from the fiber. Following this, the stock is screened and washed, either by flotation (Figure 30.20) or over side-hill washers. At this point, clay and other filler, which can amount to as much as 15% of the weight of the raw stock, are separated and removed from the system with the ink.
These separated wastes present a difficult disposal problem as these solids are hard to dewater. The dewatered cake can be used as landfill, which may still present a problem since land disposal sites near plants are becoming scarce.

The secondary fiber pulp may go directly to a cylinder machine for manufacture of paperboard. It may be bleached and dyed for the manufacture of tissue and toweling. Other products of secondary fiber processing include newsprint and writing papers. The same kinds of screens, thickeners, and cleaners may be used in processing reclaimed paper/board as are used in a mill processing virgin pulp, as described later.

**WATER REMOVAL FROM PULP**

The finished pulp is sent to the paper mill for conversion to paper or board. Dilution water, the majority of which comes from the paper machine wire pit, reduces the consistency of the pulp to less than 1%, and often below 0.5%, ahead of the paper machine. To convert this to the finished sheet, the 99.0 to 99.5% water must be reduced to produce a sheet usually containing less than 6% water.

The least costly way to remove water from the pulp is by drainage through a screen or wire, and this forms the basic part of most paper machine designs. Thereafter, water is removed at increasing increments of cost, first by vacuum, then by pressing, then by the blotting and pressing action of a felt blanket, and finally by evaporation as the sheet is carried over a multitude of stacks of steam-heated drums.
Flotation by dispersed air separates ink sludge released from recoverable fiber by de-inking chemicals. (Courtesy of Voith-Morden, Inc.)

FOURDRINIER MACHINE

The most common paper machine is the fourdrinier, illustrated in Figure 30.21. The water that drains through the endless wire belt is collected in a pit and returned to the flow of incoming pulp stock to maintain the consistency at the feed point (the headbox) at a constant value. Sizing chemicals may be added to the stock at the headbox to produce certain desired sheet qualities. Since the water from the wire pit, called white water, is continuously recirculated, the addition of
soluble chemicals, or chemicals that form soluble by-products, results in a gradual increase in the dissolved solids in the white water. The white water also contains fibers which escape capture on the sheet. Excess white water is bled from the system, usually passed through a device for reclaiming fibers (called a saveall), and returned upstream in the process, often as far upstream as the pulp mill.

The sheet leaving the fourdrinier machine, called the wet web, may contain 2 to 4 lb of water per pound of fiber (33 to 20% consistency). It has very poor strength, so a very delicate balance of output from the fourdrinier machine and throughput at the press rolls is necessary to keep the wet web from breaking. The sheet leaves the felt section at a moisture content of only 20 to 40%, and the long stacks of drying rolls evaporate this moisture, delivering the sheet to a final calender stack for smoothing, and then to the reel as a finished product with a moisture content of less than 6%. The overall schematic diagram of the paper machine and the drying section is shown in Figure 30.22.

In some paper mills, the paper may be treated on a special size press located at some point midway between the ends of the drying rolls.

As in the pulp mill, sometimes centrifugal cleaners are installed on the paper machine system for removal of foreign solid matter from the paper stock. There are several kinds of savealls used for recovering fiber from excess white water, a common one being a dissolved air flotation clarifier. A unit of this type will typically reduce suspended fiber from a concentration of 200 to 300 mg/L to a residual of 25 to 50 mg/L producing a float with a consistency of approximately 5%.

Most mills producing white grades of paper size the sheet with alum and rosin, which works best in a pH range of 4 to 5. There is no buffer capacity in this type of water system, so excess white water from paper processing can create problems when it is reused in the pulp mill or sent to waste treatment. This process also builds up sulfate concentrations in the white water system. Many of these mills
FIG. 30.23 Furnish in five forming vats is picked up by the bottom felt of this cylinder machine. Water is removed from the paperboard by suction and by pressing. The finished board is 5-ply, often distinguishable because of the variation in the pulps in each forming vat.
are now finding benefits to neutral-to-alkaline sizing, permitting them to close up the system further with minimal salinity increase and with a more favorable pH for corrosion control, recycle to the pulp mill, and final disposal.

**CYLINDER MACHINE**

Another common type of paper machine is the cylinder machine, commonly found in smaller mills and often used for the production of heavier grades of paper board. A typical cylinder machine is shown in Figure 30.23. The finished sheet leaving the cylinder machine is processed similarly to the sheet leaving the fourdrinier, by a battery of steam-heated dryer rolls. Heavier board may be dewatered on a single dryer drum, the Yankee dryer (Figure 30.24).

On both types of machines the sheet must be trimmed to an exact width depending on customer requirements, and the trim is collected for repulping. This material and broke, the term for excess product which cannot be handled at the reel, are fed to a beater (Figure 30.25), where they are mixed with white water to produce a pulp of a consistency which can be returned to the pulp mill or held in a stock chest until it can be returned to the paper machine system.

**WATER-RELATED MILL PROBLEMS**

Given the conditions of organic fiber, cellulose, residual organics extracted from the wood, and warm, oxygenated water in the white water circuit, bacterial

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**FIG. 30.24** Yankee dryer. *(Courtesy of AER Corporation.)*
growths become one of the major problems of paper manufacture. If these
growths are not controlled, slimes form in the paper machine system and peri-
dicularly break loose to enter the circuit, find their way through the headbox onto
the paper machine, and develop as imperfections in the finished sheet. Equally
important, these growths lead to corrosive attack even in stainless-steel alloy sys-
tems. Therefore, one of the major problems in paper manufacture is microbial
control with chemicals that are effective and at the same time safe to handle.

The trend toward tightening up the paper system to reduce water consumption
has resulted in the buildup in the content of both inorganic and organic solids in
the white water system, accentuating the problems of slime control and corrosion
control. Figure 30.26 shows the results of corrosive attack of stainless steel caused
by slime formation and the action of anaerobic bacteria at the slime/metal inter-
face. Figure 30.27 shows sheet imperfections caused by bacterial colonies in the

FIG. 30.25  (Top) The hollander beater was an early device for refining pulp, and
is still used in many mills for repulping broke. (Bottom) Plant installation.
white water system. Foaming is another water-related problem that has been accentuated by the closing up of the paper mill white water circuit.

Because water is so important to the pulp and paper industry, it is common to find in modern pulp and paper mills a water treatment plant as sophisticated as

![FIG. 30.26 Corrosion of stainless-steel sieve in a paper mill caused by sulfate-reducing bacteria.](image)

FIG. 30.26 Corrosion of stainless-steel sieve in a paper mill caused by sulfate-reducing bacteria.

![FIG. 30.27 Sheet imperfections are caused by sloughing of slime mass into machine system. In this photo, the removal of the slime mass during calendering left a hole in the sheet.](image)

FIG. 30.27 Sheet imperfections are caused by sloughing of slime mass into machine system. In this photo, the removal of the slime mass during calendering left a hole in the sheet.

a municipal plant treating potable water. The quality of water required in the process varies with the grades of paper being produced and the specifications for these grades. These are generally summarized by Table 30.5. The standards shown in this table have been subject to many exceptions in past practice, and may be revised in the future as the industry learns what it can do with higher concentrations in the process water stream as mill systems are tightened to reduce discharge.
DESIGNING FOR THE FUTURE

Unfortunately, there are scant data to guide the designer of a new mill in the quality standards required for makeup water, which must be satisfactory not only in producing products that meet market standards, but also in conditioning the water to render it neither corrosive nor scale-forming under the wide variety of situations occurring in the pulp and paper mill.

For the most part, water treatment plants for new mills are designed based on past experiences and operating practices that may be quite different from the experiences the mill will encounter as pollution control restrictions become increasingly strict. One of the consequences of stricter discharge regulations may be a relaxation in product quality; for example, brightness has been associated with quality of fine paper, and there is little doubt that the brightness achievable today is beyond what is required for legibility of books and documents. This brightness is achieved at the expense of more severe chemical treatments in processing which add to the pollution load. A relaxation in brightness standards for paper products, then, would seem consistent with the goals of reducing the pollution load on the waste treatment plant.

Table 30.6 provides a general idea of the various uses of water in a typical pulp and paper mill and shows both volumes required and the wastes produced in a typical 500 ton/day (454 t/day) kraft mill with conventional chlorine and hypochlorite bleaching.

WASTE TREATMENT

The points of waste production will be apparent from a study of the flow sheets of the different pulp and paper manufacturing operations. In the present state of the art, most mills have tightened up their water systems to reduce discharge, but
Increase over solids level in mill water is usually quite high—on the order of 50 to 150 Ib per ton (25 to 75 kg/t) of product, or typically in the range of 100 to 300 mg/L. Suspended solids levels may be as low as 50% of the BOD values. Because these levels are not greatly different from municipal sewage plant loadings, the type of waste treatment facility installed in a pulp and paper mill is generally quite comparable to that found in municipal treatment plants. Table 30.7 shows the range of suspended solids and BOD loadings found in a variety of pulp and paper manufacturing operations. Figure 30.28 shows the layout of a bleached kraft mill using current technology.

Table 30.6 illustrates the flow of effluents from a typical 500 ton/day Kraft Mill (built in 1960 to 1965 period). The table shows the process, the type of mill, the effluent flow, the suspended solids, and the BOD loadings. The calculations for dissolved solids and BOD are based on the following conversions:

* Gal/ton \times 0.0042 = m^3/t.
* Lb/ton \times 0.501 = kg/t.

TABLE 30.6 Effluents from a Typical 500 Ton/Day Kraft Mill (Built in 1960 to 1965 Period)

<table>
<thead>
<tr>
<th>Process</th>
<th>Effluent, gal/ton*</th>
<th>Suspended solids, lb/ton†</th>
<th>BOD, lb/ton†</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Debarking</td>
<td>2,640</td>
<td>31</td>
<td>7</td>
</tr>
<tr>
<td>2. Cooking and washing</td>
<td>264</td>
<td>−</td>
<td>9</td>
</tr>
<tr>
<td>3. Screening and cleaning</td>
<td>26,400</td>
<td>31</td>
<td>20</td>
</tr>
<tr>
<td>4. Bleaching</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Acid</td>
<td>15,800</td>
<td>6</td>
<td>22</td>
</tr>
<tr>
<td>b. Caustic</td>
<td>10,500</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>5. Pulp sheet formation</td>
<td>1,050</td>
<td>2</td>
<td>−</td>
</tr>
<tr>
<td>6. Evaporation</td>
<td>1,850</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>7. Causticizing</td>
<td>1,320</td>
<td>0.2</td>
<td>−</td>
</tr>
<tr>
<td>8. Recovery furnace</td>
<td>3,960</td>
<td>0.2</td>
<td>−</td>
</tr>
<tr>
<td>Total</td>
<td>83,784</td>
<td>73.6</td>
<td>99</td>
</tr>
</tbody>
</table>

* Gal/ton \times 0.0042 = m^3/t.
† Lb/ton \times 0.501 = kg/t.

have not done so to the extent that dissolved solids build up over 5000 mg/L. (There are actually a few mills having zero discharge; they produce a relatively low-grade paper which, of course, carries the solids out of the mill in its moisture content.) There is substantial flow of excess water carrying with it the rejects from pulp cleaning, excess pulping liquor which could not be reclaimed, dregs from the chemical recovery area, materials extracted from the pulp during bleaching, and excess clay and filler not retained by the sheet. Since a good portion of the wastes are organic materials extracted from the wood, the BOD of the combined wastes

Table 30.7 shows the sources of solids in an integrated mill.

Table 30.7 - Sources of Solids in an Integrated Mill

<table>
<thead>
<tr>
<th>Area</th>
<th>Suspended solids, mg/L</th>
<th>Dissolved solids, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodroom</td>
<td>500–700</td>
<td>700–800</td>
</tr>
<tr>
<td>Pulp mill (bleach plant)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caustic extract</td>
<td>60–80</td>
<td>4000</td>
</tr>
<tr>
<td>Acid extract</td>
<td>60–80</td>
<td>1500</td>
</tr>
<tr>
<td>Total</td>
<td>200–250</td>
<td>1800</td>
</tr>
<tr>
<td>Recovery plant</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Paper machines</td>
<td>400–700</td>
<td>300–400</td>
</tr>
</tbody>
</table>

* Increase over solids level in mill water.

is usually quite high—on the order of 50 to 150 lb per ton (25 to 75 kg/t) of product, or typically in the range of 100 to 300 mg/L. Suspended solids levels may be as low as 50% of the BOD values. Because these levels are not greatly different from municipal sewage plant loadings, the type of waste treatment facility installed in a pulp and paper mill is generally quite comparable to that found in municipal treatment plants. Table 30.7 shows the range of suspended solids and BOD loadings found in a variety of pulp and paper manufacturing operations. Figure 30.28 shows the layout of a bleached kraft mill using current technology.
for wastewater treatment for discharge to a nearby receiving stream. In this particular plant, the primary clarifiers handle only those wastes carrying over 50 mg/L suspended solids. After clarifying these wastes, the effluent is combined with the remaining low solids streams (such as bleach plant effluent) and treated in an extended aeration plant for biological reduction of organic solids. The digested waste is then processed through a final clarifier for discharge to the receiving water. Table 30.8 shows the analysis of the raw waste streams and the final effluent. The design of a treatment system of this type requires months of pilot plant study to determine the range of waste concentrations to be anticipated, to evaluate the performance of the aerobic digestion system under a broad range of temperatures and pH values and a study of the optimum procedures for dewatering and disposing of waste sludges.

Not only are large volumes of water needed for process, but also for the generation of steam. The pulp and paper industry is energy intensive, and the organic

**TABLE 30.8 Integrated Pulp/Paper Mill Waste Treatment**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From paper mill*</td>
</tr>
<tr>
<td>Suspended solids, mg/L</td>
<td>530</td>
</tr>
<tr>
<td>Alkalinity, mg/L as CaCO₃</td>
<td>224</td>
</tr>
<tr>
<td>pH</td>
<td>7.6</td>
</tr>
<tr>
<td>BOD, mg/L as O₂</td>
<td>233</td>
</tr>
<tr>
<td>COD, mg/L as O₂</td>
<td>930</td>
</tr>
<tr>
<td>TOC, mg/L as C</td>
<td>270</td>
</tr>
<tr>
<td>Conductance, µS</td>
<td>1200</td>
</tr>
</tbody>
</table>

* Fiber-containing streams.
+ Lower suspended solids streams.
‡ Without chemical coagulation.
§ Acidity.
matter (such as bark and lignin) extracted from the wood fits into the overall planning and design of a steam-generation system to utilize these wastes as a fuel source. Because large volumes of steam are needed on the paper machines, particularly the drying rolls, the industry optimizes the heat balance by condensing turbine exhaust on the machines, making it economical for the industry to produce its own electric power.

A flow diagram and heat balance of a steam generation plant in a typical kraft mill is shown in Figure 30.29. In an integrated kraft pulp/paper mill, a steam plant of this type will produce in the range of 5000 to 10,000 lb of steam per ton of production. The operation of the utilities system is so critical to the production process that the profit or loss of a mill requires efficient performance of the utility plant.
