Most of the forest resources in Europe, North America, Asia, and Australia have been utilized for paper production and other uses. So there seem to be valid reasons to look to NWF as a paper pulp source so that forests have sufficient time to rejuvenate and increase the forest cover. However, the research and development side of the papermaking industry has been focused on wood pulping technologies and equipment. Therefore, a lack of success and conservative attitudes with most non-wood initiatives stem from the application of wood pulping technology to non-wood fibers resulting in poor pulp quality and incorrect handling. This is generally true for digestion and refining operations, which tend to produce overcooked and over refined pulps due to the higher energy requirements of wood-based processes when they are used for non-wood fibers. Further, lack of will and financial support for the research and development wings of the paper industry, despite strong technical evidence of the potential of non-wood fibers, has resulted in the nonproliferation of this new concept. Nevertheless, there are many NWF-based paper mills already producing a wide range of paper grades. Finally, there is also a resurgence of initiatives for advancing the cause of the NWF paper industry to promote non-wood fiber as a cost-effective, high-quality competitive, and an environmentally friendly source for papermaking.

Further Reading

Casey J (1980) *Pulp and Paper Chemistry and Technology*, 3rd edn, vol. 1. New York: John Wiley.

Catling D (1982) *Identification of Vegetable Fibres*. London, UK: Chapman and Hall.

Dean WR (2001) Non-wood fibres, past, present and future. In: *Unpublished. Proceedings of the Pira Conference on Cost Effectively Manufacturing Paper and Paper Board from Non-Wood Fibre and Crop Residues*, Leatherhead, UK.

Deng M and Dodson CTJ (1994) *Paper: An Engineered Stochastic Structure*. Atlanta, GA: TAPPI Press.

Kocurek MJ (1993) *Pulp and Paper Manufacture*, vol. 3. Atlanta, GA: TAPPI Press.

Kocurek MJ (1996) *Pulp and Paper Manufacture*, vol. 5. Atlanta, GA: TAPPI Press.

Kocurek MJ (1997) *Pulp and Paper Manufacture*, vol. 1. Atlanta, GA: TAPPI Press.

Liu A (2000) *World Production and Potential Utilization of Jute, Kenaf and Allied Fibres*, Proceedings of the 2000 International Kenaf Symposium, Hiroshima, Japan.

McKinney RJ (ed.) (1995) *Technology of Paper Recycling*. UK: Blackie: Glasgow.

Paavilainen L (2001) Paper making potential of non-wood fibres. In: *Unpublished. Proceedings of Pira Conference on Cost Effectively Manufacturing Paper and Paperboard from Non-Wood Fibre and Crop Residues*, Leatherhead, UK.

Rance HF (1982) *Handbook of Paper Science*, vol. 2, *The Structure and Physical Properties of Paper*. Amsterdam, The Netherlands: Elsevier.

Roberts JC (1996) *The Chemistry of Paper*. Letchworth, UK: Royal Society of Chemistry.

Scott WE (1996) *Principles of Wet End Chemistry*. Atlanta, GA: TAPPI Press.

Singh SV (1995) *Advances in Pulp and Paper Research in India*. Dehradun, India: Indian Council of Forestry Research and Education.

Smook GA (1992) *Handbook for Pulp and Paper Technologists*. Vancouver, Canada: Angus Wilde.

Overview

G M Scott, State University of New York, Syracuse, NY, USA

Introduction

There is no denying that paper is very important in today's world. We use it for money, record-keeping, communication, personal hygiene, and many other uses personally, commercially, and industrially. We often take paper for granted: it is ubiquitous but essential in our lives. However, very few of us think about how it is made beyond that it is made from trees. Paper can be an extremely complicated product, both in its components and in its manufacture. For example, printing and writing paper has distinctly different properties from tissue. It is often difficult to use one type of paper for another purpose. (How many of us has tried to draw on a dinner napkin?) **Table 1** is a selected list of the variety of paper grades that are produced today.

Papermaking is ever-evolving and developing. As the needs of society change, the types of paper being produced have also changed. The personal computer revolution was supposed to bring about the 'paperless office' and make printed newspapers obsolete. Paper consumption has not decreased, however, due to the increased use and popularity of computers. The types of paper demanded by consumers have changed significantly. In keeping up with computer technology, grades of paper for use in ink-jet printers and for the home-printing of digital photographs have been developed. Per capita consumption of paper has been increasing steadily over the past decade. Worldwide, paper consumption is increasing at an even greater rate as developing countries make

Table 1 Examples of grades of paper made today. This list represents only a small fraction of the different grades of paper manufactured in the world

Printing and writing	Photographic
Facial tissue	Bathroom tissue
Tape backing	Grocery sack
Newsprint	Light-weight coated
Linerboard	Corrugating medium
Art paper	Parchment
Currency paper	Paperboard
Book	Index card
Construction paper	Paper cores
Cover paper	Electrical insulating
Envelope	Butcher paper
Medical paper	Glassine
Folder paper	Greeting card
Ink jet	Kraft
Label base	Laminating
Magazine	Napkin
Packaging	Tablet
Towels	Specialty

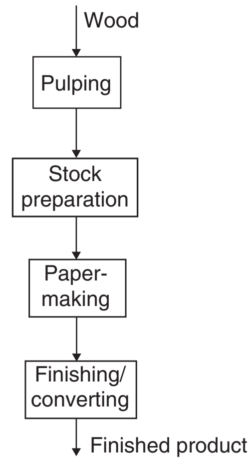

Figure 1 Overview of the papermaking process from wood to finished products. Pulping disassembles the wood into its component fibers while stock preparation prepares the fibers for papermaking. Papermaking reassembles the fibers into a sheet and finishing/converting makes that sheet into the final product.

increased use of paper. The paper industry is probably one of the most sustainable industries in the world. Its primary raw material, wood, is being replenished at a rate faster than consumption. Modern integrated paper mills are nearly energy self-sufficient. In addition, there is a well-established infrastructure for the recycling of paper.

Paper is typically defined as a 'felted sheet of fibers formed on a fine screen from a water suspension.' The key elements of this definition are that the raw material (pulp) has been previously reduced to individual fibers and suspended in water. This pulp is then treated and deposited on to a fine screen to remove the water, leaving a randomly oriented sheet that is subsequently consolidated and dried. In practice, modern paper also contains a variety of nonfibrous materials in order to give the paper its desired properties. These materials include clay, calcium carbonate, starch, and specialty chemicals that impart waterproofing, flameproofing, smoothness, and other properties. Paper thicker than 0.3 mm is often termed paperboard.

Figure 1 shows an overview of the papermaking process from wood to finished product. The wood is first pulped, or rendered into fibers, in one of two broad methods (*see* **Pulping**: Chemical Pulping; Mechanical Pulping). In stock preparation, mechanical action changes the surface properties of the fiber, allowing them to develop the papermaking properties that are desired. Different pulps (in terms of pulping methods and/or wood species) are blended with nonfibrous fillers and specialized chemicals. The papermaking process removes water from the sheet while forming and consolidating the sheet, which is dried to its final moisture content of approximately 5%. In the final step, finishing/converting, the final products of the process (e.g., envelopes, tablets, sheets, boxes) are produced from the large rolls of paper produced by the papermachine.

History of Papermaking

Given our definition of paper above, the first paper was reputedly made in China around AD 105 by Ts'ai Lun who was charged to find a new material for record-keeping. Papyrus, invented earlier by the Egyptians and not considered a true paper, was made by pounding strips of papyrus together to form a sheet. Ts'ai Lun pulverized the inner bark of mulberry tree, producing a pulp, and draining the fiber suspension using a fine screen. The resulting sheets were subsequently pressed and air-dried. For several centuries, China held a monopoly on papermaking, but eventually the technology traveled from China to Japan and Arabia, and into Europe by the eleventh century. By this time, cotton in the form of rags and linen was the primary source of raw materials for papermaking. A shortage of rags in the eighteenth century prompted papermakers to look towards other sources for fiber, especially wood. At this time, paper was still handmade one sheet at a time, using molds consisting of a fine wire screen (**Figure 2**). The invention in AD 1798 by Louis Robert of the papermachine, which could form a continuous sheet of paper, exacerbated the raw material shortage, prompting the development of the modern wood-pulping techniques in the nineteenth century. This century also saw many improvements in the continuous papermachine (**Figure 3**). While the basic concepts of papermaking remain unchanged since

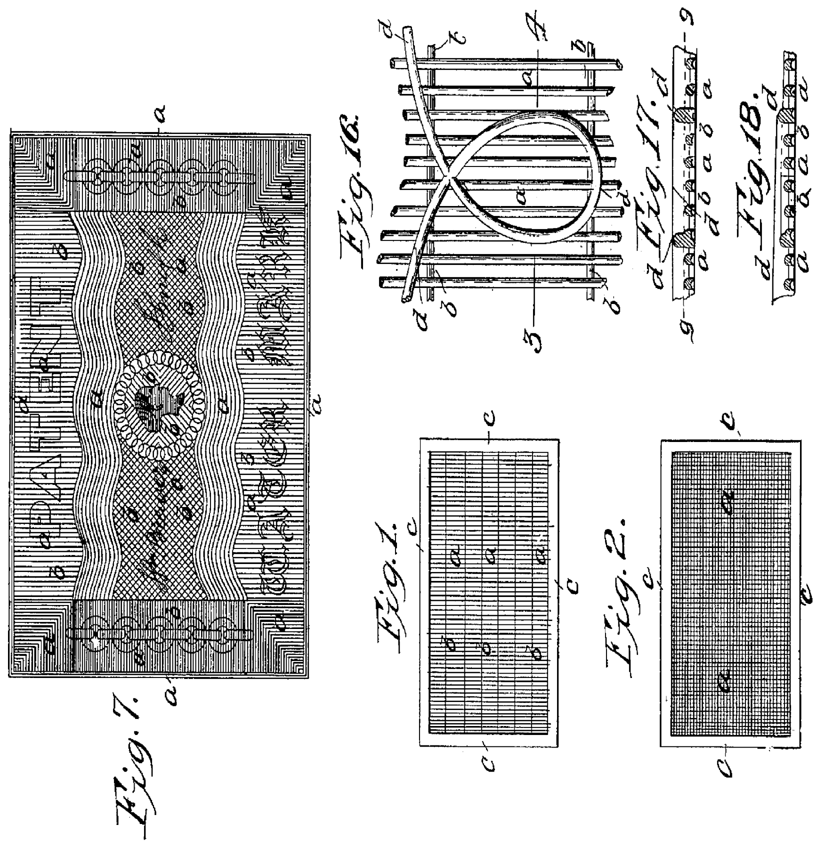

Figure 2 Patent drawing of mold for the handmaking of paper (US patent 7,979). This screen was hand-dipped into a slurry vat, drained, pressed, and removed for drying to produce paper one sheet at a time.

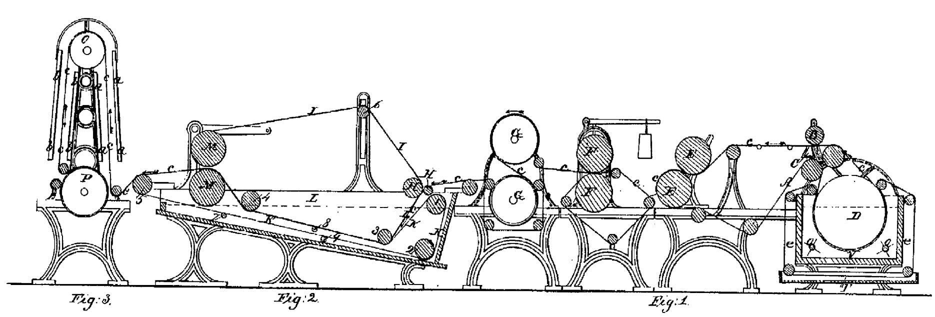

Figure 3 Patent drawing of early paper machine from the 1830s (US patent 8,698). All of the basic processes of a modern machine are present in this machine.

these developments, many refinements have led to the modern papermachine (**Figure 4**) that today operates at speeds of over 1800 m min^{-1}. **Table 2** summarizes the major historical milestones in the papermaking process.

Goals of Papermaking

Paper is an engineered product. The proper combination of raw materials and processing steps results in paper having the desired properties for a particular use. A large number of variables, from the raw materials to the type of equipment used, affect the final properties of the sheet (**Table 3**). It is the interaction of these variables that gives paper the properties needed for any particular grade. **Table 4** gives some of the desired properties of some common grades of paper as well as the typical pulp furnish used in that grade. As can be seen, different grades have significantly different properties, including printability, absorbency, and strength.

For example, newsprint must have excellent printability and opacity (so the writing on the back of the sheet does not show through). However,

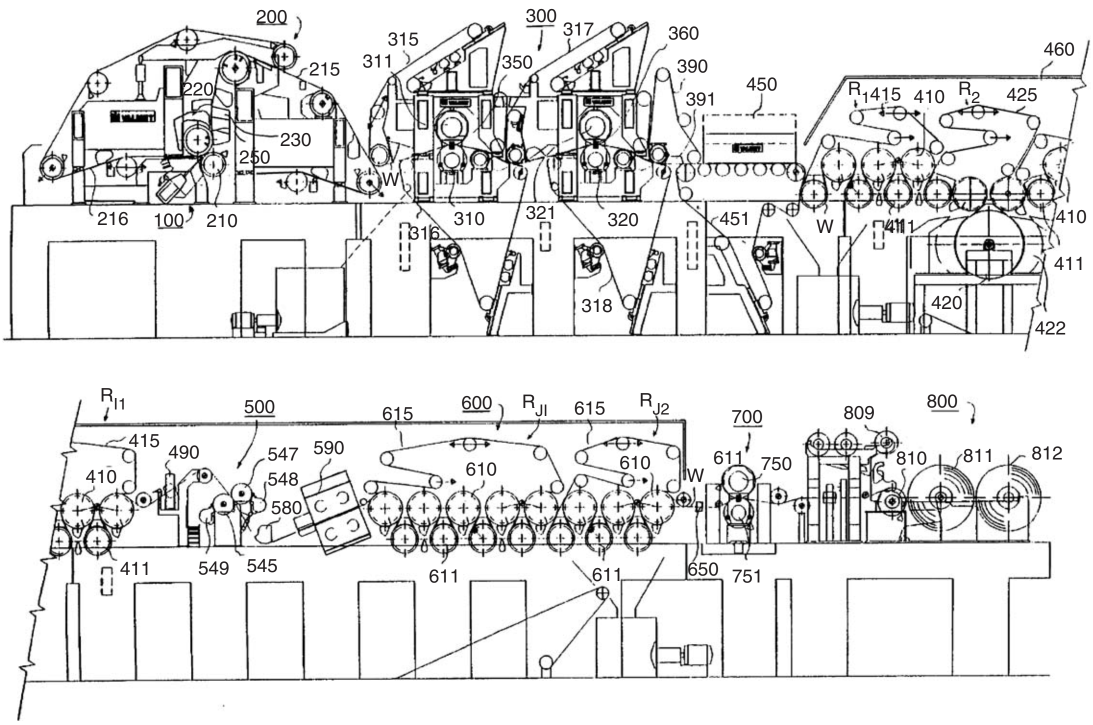

Figure 4 Patent drawing of modern paper machine (US patent 6,413,371). While much more complicated, this machine contains the basic operations of draining, pressing, and drying.

because of its limited life span of 1 day, it must be inexpensive. For newsprint, a thermomechanical pulp (TMP) is used. Printing and writing paper, having a much longer life span and higher brightness, uses more expensive bleached kraft pulp.

Papermakers use different raw materials for their furnish depending on the desired properties of the sheet. The different raw materials impart characteristic properties to the sheet (**Table 5**). While kraft (chemical) pulps are used for strength, they have relatively poor optical qualities. Mechanical pulps tend to be just the opposite. Fillers, such as calcium carbonate and clay, are inexpensive and impart excellent optical properties, but impart no strength to the sheet. Some specialty papers, such as paper for currency and bank notes, are made of nonwood fibers such as linen, flax, and cotton. Consumer demand has expanded the use of recycled fiber in many grades of paper. Some grades, such as tissue, toweling, and linerboard, are almost exclusively made from recycled fibers. Many other grades, such as printing and writing, have varying percentages of recycled fiber. Broke is internally recycled paper (e.g., off-specification paper) and is used in the furnish of most mills.

Paper Properties

The properties of paper can be divided into three main groups: physical, strength, and optical properties. **Table 6** summarizes the major tests that are performed on paper in these three categories. Physical properties are those that measure some structure of the paper such as grammage, thickness, and smoothness. Another physical property, density, ρ, is a function of the grammage, W, and thickness, t as $\rho = W/t$. Strength properties are those that measure the force or pressure needed to cause the paper to fail. Tensile, burst, tear, and folding endurance are all measurements of the ultimate failure of the paper in some prescribed manner. There are many more strength properties and measurement of paper; many of these are specific to certain grades of paper. Optical properties measure the paper's response to light, including brightness, color, and opacity. For some specialty grades of paper, some other properties are important, such as electrical properties. In other cases, the ability of the paper to resist water or oil penetration is very important. Each grade of paper has its own set of properties that must be met by the manufacturing process. The Technical Association of the Pulp and Paper Industry promulgates a complete set of testing methods for most of these paper properties.

Stock Preparation

Between pulping and the actual papermachine, the raw materials must be properly prepared. The

Table 2 Milestones in papermaking history

Year	Milestone
600 BC	Egyptians manufacture papyrus, which is not a true paper
440 BC	Greeks use parchment, the treated skins of sheep and goats
AD 105	Chinese invent the first true paper from the bark of the mulberry tree, reputedly by Ts'ai Lun in the court of Emperor Hedi
AD 610	Paper is made in Japan, where it becomes a part of the culture, being used for writing, fans, garments, and dolls
AD 704	Paper is made of cotton on the Arabian peninsula
AD 900	Paper (which was imported) used in Europe for papal proclamations
AD 1009	Papermaking introduced into Europe (Spain) and rags used as a raw material
AD 1330	Watermarked paper invented in Italy
AD 1411	First papermill constructed in Germany
AD 1453	Invention of the printing press greatly increases the demand for paper
AD 1588	Paper is made in England
AD 1680	Paper is made in Mexico
AD 1690	Paper is made in North America near Philadelphia
AD 1719	A shortage of rags for papermaking prompted investigations into other fiber sources, including wood
AD 1798	Invention of the continuous papermachine by Louis Robert
AD 1817	Development of the steam-heated dryer cylinders
AD 1840	Development of groundwood (mechanical) pulping process to allow paper to be made from wood
AD 1854	Development of soda process (chemical) which uses sodium hydroxide to digest wood
AD 1867	Development of sulfite process (chemical) which uses sulfites to digest wood
AD 1879	Development of kraft process (chemical) which adds sodium sulfate to the soda process
AD 1923	Development of twin-wire former
AD 1960	Development of the wet-end foil for dewatering
AD 1960s	Development of the synthetic press felts and nonmetallic wires

Table 3 Variables involved in papermaking from stock preparation to the paper machine

Raw materials	
Fiber furnish	
Type of wood	Softwood, hardwood
Time of harvest	Winter, summer
Location	Northern, southern, tropical
Pulping method	
Chemical	Kraft, sulfite
Semichemical	Chemimechanical pulp (CMP), chemithermomechanical pulp (CTMP), neutral sulfite semichemical (NSSC)
Mechanical	Groundwood, thermomechanical (TMP), refiner mechanical (RMP)
Recycled	Newsprint, old corrugated containers, mixed office waste, mixed paper
Fillers	Calcium carbonate, clay, titanium dioxide
Chemicals/additives	Wet strength agents, dry strength agents, starch, retention aids, defoamers
Stock preparation	
Refining	Beaters, disk refiners, conical refiners
Cleaning	Hydrocyclones
Screening	Pressure screens, sidehill screens
Paper machine operations	
Headbox	Open, air-padded, hydraulic
Forming section	Fourdrinier, twin wire, multiply former, cylinder former
Press section	Solid roll, extended nip, suction roll
Dryer section	Two-tier run, single felt, single-tier run
Size press	Coating, surface treatment
Calender stack	Number of nips, heated nips
Finishing operations	Sheeting, converting, packaging

objective of the stock preparation step in papermaking is to process the fibers from the pulping step and combine them with the nonfibrous materials in a manner suitable for papermaking. Stock preparation consists of the processes summarized in **Table 7**. Consistency is a measure of the solids content of a sample of pulp. It is defined as the dry mass of the solid material over the original mass. In stock preparation, consistencies typically range from 0.5% or lower (in the final feed to the papermachine itself) up to 15% for high-density storage.

Repulping

For papermaking, the pulp fibers must be dispersed in water for pumping and the papermaking process. If a mill is integrated, the fibers will remain in a high-consistency slurry from the pulp mill. However, many paper mills do not have a pulp mill associated with them. So, these mills must take market pulp, often dried to 90% solids, and redisperse the fibers in water using a repulper. Repulpers or hydrapulpers are large mixing vessels with one or more revolving agitators to provide circulation and energy sufficient to disperse the fibers in the water.

Refining

The terms refining and beating are commonly used interchangeably in the paper industry and refer to the use of mechanical energy to develop papermaking properties of fibers. As with many processes, there are tradeoffs which depend on the products being made. In general, the strength properties, such as tensile and burst strength, increase with more refining. Tear strength tends to decrease with refining. Optical properties, such as opacity, tend to

Table 4 Properties and furnishes of common grades of paper

Grade	*Fiber furnish*	*Properties*
Newsprint	TMP	Printability, optical properties, inexpensive, short life
Printing/ writing	SWK, HWK, sulfite	Printability, whiteness, optical properties, ink holdout
Grocery sack	SWK	Strength
Tissue	Sulfite, recycled	Absorbency, strength, softness
Linerboard	SWK, recycled	Strength, printability
Corrugating medium	HWK, recycled	Stiffness, conformability
Paperboard	Recycled	Bulk, stiffness
Paper toweling	Recycled	Wet strength, absorbency

TMP, thermomechanical pulp; SWK, softwood kraft; HWK, hardwood kraft.

Table 5 Characteristics of various papermaking materials

Furnish	*Characteristics*
Softwood kraft (SWK)	Strength
Hardwood kraft (HWK)	Bleachability; optical properties
Sulfite	Bleachability; softer fiber
TMP/RMP	High yield; optical properties
Groundwood	Cheap filler; optical properties
Fillers	Good optical properties; inexpensive
Recycled	Consumer demand; mixed properties
Nonwood	Specialty products
Broke	Available; needs to be used; source of fiber

TMP, thermomechanical paper; RMP, refiner mechanical pulp.

decrease with refining as the fibers become more conformable and there are fewer fiber–air interfaces to scatter light. In all cases, the rate at which water drains from the fiber decreases. Slower drainage translates to lower production on the papermachine. Thus, it is necessary to refine such an amount that the necessary strength properties are achieved, while maintaining production rates on the papermachine.

The drainage rate of the pulp is often characterized by the Canadian Standard Freeness (CSF) measurement (Tappi test method T 227). In the test, water is drained from a known sample of pulp; freeness is the volume of water that overflows a calibrated orifice at the bottom of the collection cone. The greater the overflow, the faster the pulp drains. CSF is typically used in North American paper mills. Two other freeness tests used around the world include the Schopper Reigler and Williams. Typically, chemical pulps have a typical freeness of 400–700 ml CSF depending on the degree of refining. Mechanical pulps are much slower draining with freenesses in the range 100–200 ml CSF.

A variety of equipment is used for refining (or beating) in the paper industry. Early beating was done batchwise, using a Hollander beater or similar equipment (**Figure 5**). In this batch process, the pulp at 3–6% consistency circulates in an oval tank where it passes under a roller with bars against a bedplate. However, with the increasing production rates at many mills, the batch process became too slow, and mills changed over to conical and then to disk refiners. Both types of refiners operate similarly in

Table 6 Important paper properties and testing methods (Tappi)

Property	*Test method*[a]	*Description*
Physical properties		
Grammage	T 410	Mass per unit area of paper; also known as basis weight
Thickness	T 411	Single sheet thickness (caliper) of paper
Smoothness	T 538	Measurement of air flow between the surface of the sheet and two pressurized, concentric annular rings
Moisture content	T 412	Amount of water in paper
Strength properties		
Tensile	T 494	Force per unit width required to break a specimen in tension
Tear	T 414	Force perpendicular to the plane of the paper required to tear multiple sheets through a specified distance
Fold	T 423/T 511	Measures the ability of paper to withstand repeated bending, folding, and creasing
Burst	T 403	Pressure in a rubber diaphragm required to rupture a clamped sheet of paper
Optical properties		
Brightness	T 452/T 525	Measures the reflectance of paper
Color	T 524/T 527	Measures the color of paper with tristimulus filters (red, green, blue)
Opacity	T 425/T 519	Measures the ability of a sheet to obscure printing on a backing sheet

[a] Tappi test method published by the Technical Association of the Pulp and Paper Industry, Atlanta, GA, USA.

Table 7 Operations in stock preparation

Operation	*Description*
Repulping	Dispersion of the pulp fibers in water
Refining	Modification of the fibers and fiber surfaces through mechanical action
Cleaning and screening	Mechanical separation of undesirable materials in the pulp
Blending	Mixing of fibers and fillers to achieve desired sheet properties
Chemical addition	Use of specialized chemicals to achieve desired properties or operation

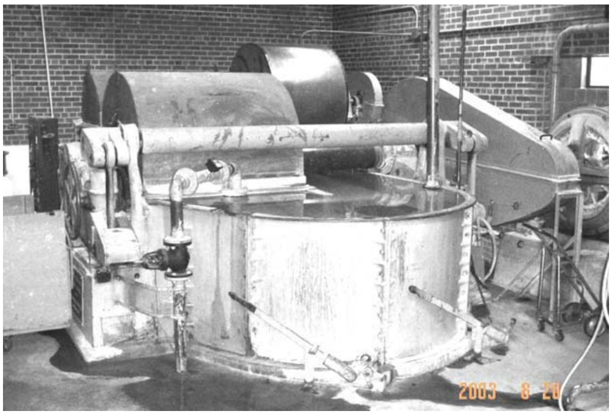

Figure 5 Jones–Bertram beater, which is similar to a Hollander beater. As the pulp circulates, it is refined in a batch process.

Figure 6 Small pilot disk refiner. Two facing rotating plates refine fibers in a continuous process.

Table 8 Effects of refining on papermaking fibers

Effect	*Description*
Fiber shortening	Cutting of fibers by the refining bars, producing shorter fibers
Fines production	Clipping and removal of fibrils from surface of fiber
External fibrillation	Increasing the fibrils on surface of fiber
Internal fibrillation	Increasing the swelling and hydration of the fiber

that the pulp passes between two surfaces that have bars over and between which the pulp must pass. In conical refiners (Jordan and Claflin refiners), the bars are on a tapered plug rotor which rotates inside the corresponding shell. In disk refiners, the pulp passes between two circular flat plates with bars. The two plates are either counterrotating or one plate is rotating while the other is fixed. Refiners operate with clearences of 0.1–1.0 mm between the bars on the two facing plates (**Figure 6**).

The passage of papermaking fibers through the close clearance of the refiners has several effects on the fibers, some beneficial to the development of the fiber properties and others that are detrimental. **Table 8** summarizes these effects on the fiber. In general, fiber cutting and fines (very short fibers) production are undesirable effects. One aspect of a fiber that determines the strength of a sheet of paper is the fiber length, especially tear strength. External fibrillation is the increase in the amount of fibrils raised from the surface. These fibrils, which look like 'hair' on the surface of the fiber, can interact and bond with similar fibrils on other fibers. The greater interaction between fibers leads to greater fiber-to-fiber bonding and greater-strength paper. Likewise, internal fibrillation, the delamination of the fiber structure, increases the flexibility of the fiber. Greater conformability also allows greater interaction between fibers and hence increased sheet strength. Refiners can be operated to favor internal and external fibrillation over fiber shortening and fines production by increasing the interaction between fibers in refining. With the greater consistency in the refiner, fibers tend to interact to a greater degree with each other rather than with the refiner plates. Gentler refining, using lower specific energies and wider plate separations, tends also to reduce the fiber cutting and fines production.

Different fibers refine at different rates. The degree of refining is typically measured through a drop in the CSF of the pulp. **Table 9** summarizes the energy needed per kilogram of pulp to drop the freeness by 100 ml CSF. Unbleached softwood kraft typically takes the most energy to refine. Bleaching the pulp weakens the fiber structure and makes it easier to refine. Hardwoods, which have shorter fibers than softwoods, also refine easier. Recycled paper, since it has already been refined at least once, also tends to require less energy to refine than the corresponding virgin fiber. Many paper grades are blends of different fibers. In the stock preparation step, it is usually necessary to refine these fibers separately as

Table 9 Energy required to change the freeness of the given furnish by 100 ml Canadian Standard Freeness (CSF)

Furnish	*Refining energy (kJ kg^{-1})*
Unbleached softwood kraft	280–360
Bleached softwood kraft	140–160
Bleached hardwood kraft	70–120
Mixed office paper	100–140
Old corrugated containers	100–180
Old newsprint	200–360

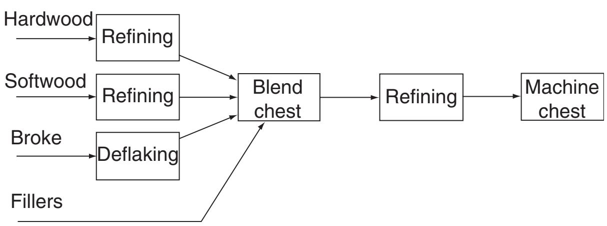

Figure 7 Overview of typical refining layout for stock preparation. Because of the different refining behavior of different fibers, they are often refined separately and then blended. A small amount of refining may be done after blending to 'fine-tune' the fiber properties.

they refine at different rates. For example, refining a blend of hardwood and softwood fibers together typically overrefines the hardwood and underrefines the softwood. As shown in **Figure 7**, the different furnishes are usually refined before blending. A small amount of refining ('tickler refining') based on feedback from the papermachine may be done after blending to meet the final requirements of the papermachine.

Cleaning and Screening

The cleanliness of the pulp going to the paper machine directly reflects on the quality of the final sheet. Most paper machines have one or more systems of screens and cleaners to remove contaminants that may affect the quality of the resulting sheet. While different fundamental processes are the basis for separation in different separation equipment, it is generally accepted that screens remove the relatively larger contaminants, while the various types of cleaners remove mid-sized contaminants. The smallest contaminants are generally removed in washing, thickening, and flotation operations, but these are not typically used on the approach flow to a papermachine.

Hydrocyclones Hydrocyclones, otherwise known as centrifugal cleaners, vortex cleaners, or centricleaners, came into widespread use in the paper industry in the 1950s. Prior to this, hydrocyclones were commonly used in the mining industry for separations. A hydrocyclone consists of a cylindrical-conical vessel with the inlet flow introduced tangentially at the top (**Figure 8**). The tangential inlet produces a helical flow of material in which centrifugal action and fluid shear force the denser material to the outside surface while the less dense material migrates to the center of the vortex. The outlet at the top of the hydrocyclone draws off the less dense material while the bottom nozzle removes the dense material that was thrown to the outside of the vortex. In the paper industry, the hydrocyclones tend to be 7.5–15 cm in diameter with the smaller-diameter cyclones developing the higher centrifugal forces.

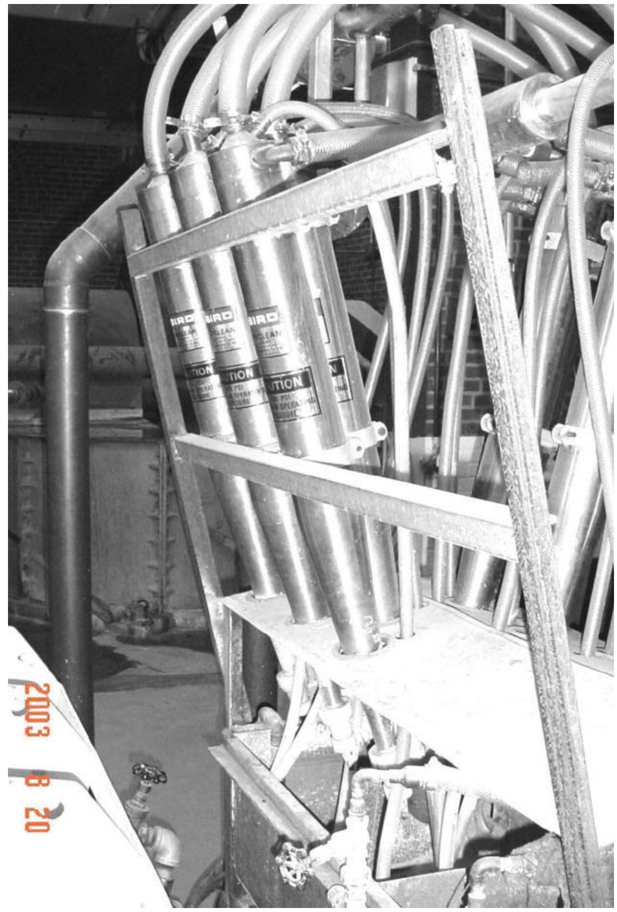

Figure 8 Pilot plant hydrocyclone cleaners manufactured by Bird. Density differences allow the removal of the heavier contaminants.

As with any separation process, it is not a perfect separation. With hydrocyclones, there is a significant amount of fibers and other papermaking material in the reject stream to be recovered. **Figure 9** shows a three-stage system in which the accepts from the secondary and tertiary stages are returned to the previous stage while the rejects from each stage go to the subsequent stage. The primary purpose of the secondary and tertiary stages is not necessarily to

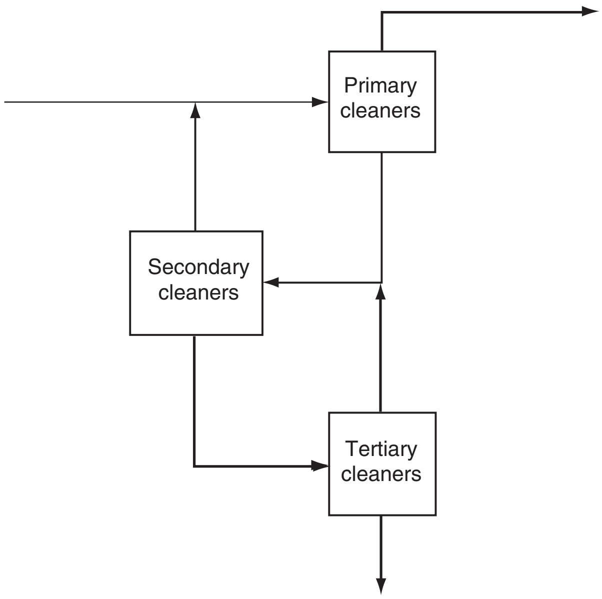

Figure 9 Three-stage cascade cleaner system. The accepts from each stage (top arrow) return to the previous stage, while the rejects (bottom arrow) go to the subsequent stage. The tertiary-stage rejects are removed from the system.

clean the pulp further. In fact, in most cases, a single stage produces cleaner pulp. However, the secondary and tertiary stages of cleaners recover usable pulp from the reject streams and return it to the primary screen. Some operations will even use four- and five-stage systems in order to recover the maximum amount of fiber.

Pressure screens Pulp is screened to remove oversized, unwanted particles before they can be incorporated in the sheet. While there are several types of screens, including vibratory and flat screens, most mills use primary pressure screens for the approach flow to a paper machine. Regardless of the type of screen, they all operate on the same principle: a barrier prevents the contaminants from passing through, while the pulp fibers and other desired papermaking materials pass through. **Figure 10** shows a pressure screen attached to a pilot paper machine. Depending on the type of contaminant that is being removed, the barrier screen can have either holes or slots. The slots in pressure screens typically have a width of 0.20–0.50 mm. As with hydrocyclones, pressure screens are usually arranged in a cascade arrangement (**Figure 9**).

Figure 10 Pilot plant pressure screen manufactured by Black Clawson. The screen uses a slotted screen to remove contaminants from the pulp slurry.

Papermachine Operations

The most common basic form of the papermachine is the Fourdrinier machine, in which the paper is initally formed on an endless moving screen called a wire. There are a number of variations of the Fourdrinier machine in use today which use two wires with the sheet formed between them. After being formed on the wire, the sheet is conveyed through a series of presses to dewater the sheet further. Finally, the sheet is dried by evaporating the remaining water in the sheet (**Figure 11**). The papermachine has two main objectives: (1) to remove the water from the pulp, which is initially at approximately 0.5% solids to approximately 95% solids; and (2) to consolidate the sheet and form bonds, such that the sheet has the desired strength, optical, and other properties.

The following sections give an overview of the numerous processes that occur on a modern papermachine. Not all machines will have all the elements described, but most have many. In addition, the description of the approach flow, headbox, and wire section pertain to the most common form of the wet end of the paper machine: the Fourdrinier machine. A different type of former, the cylinder machine, is often used for heavier-weight paperboard grades.

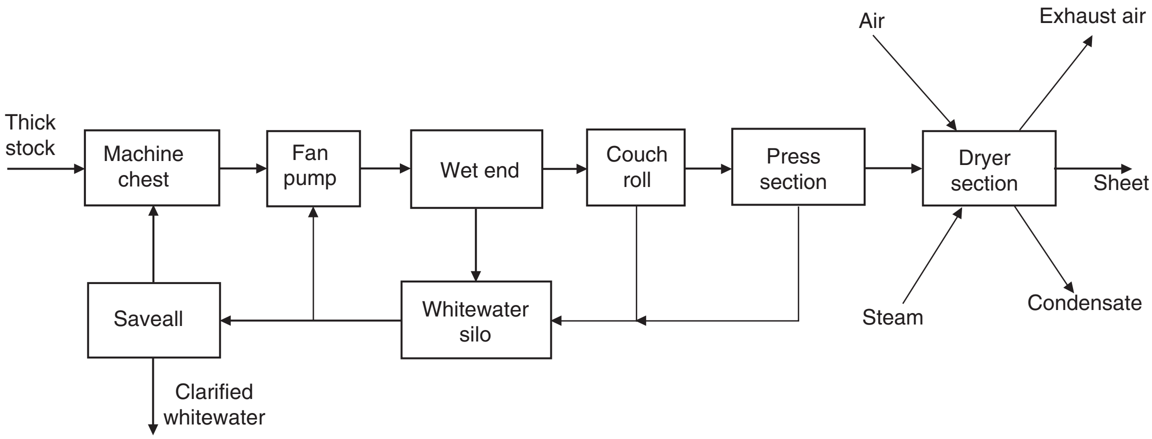

Figure 11 Flow diagram of typical papermachine. Note that the water drained from the wet end and press sections are used for dilution at the fan pump. Fiber from the excess water is recovered in the saveall.

For a description of this type of machine, the reader is directed to the further reading given at the end of the article.

Approach Flow and Headbox

The approach flow to the papermachine includes all the processes from the machine chest (where the pulp is held prior to use) to the headbox (which places the pulp suspension on to the wire). While every machine is different, most contain the hydrocyclones and screens described above, deaerators, and dilution to bring the stock to the headbox consistency. The fan pump, usually the largest pump in the papermachine, mixes the stock from the machine chest with the dilution whitewater returning from the wire, and delivers the stock to the headbox. Just prior to the headbox, the flow must be changed from a circular flow in a pipe to the flat flow evenly distributed across the machine. It is important for the uniformity of the final sheet that the pressure and flow pulsations be evened out. To accomplish this, a flow spreader, typically called a tapered header, distributes the flow evenly across the machine.

The headbox of the paper machine is the final element in the process before the pulp suspension is placed on the wire. The headbox, which can be either air-pressurized or completely hydraulic, accelerates the stock so that it hits the wire at approximately the same speed as the wire. In addition to accelerating the stock, the headbox also controls the flow rate of fiber on to the wire, thus ultimately affecting the weight of the sheet of paper. The headbox must also prevent flocculation of the fibers, which can cause nonuniformities in the final sheet. Baffles, internal mixing rolls, high stock velocities, and highly polished internal surfaces maintain the pulp dispersion.

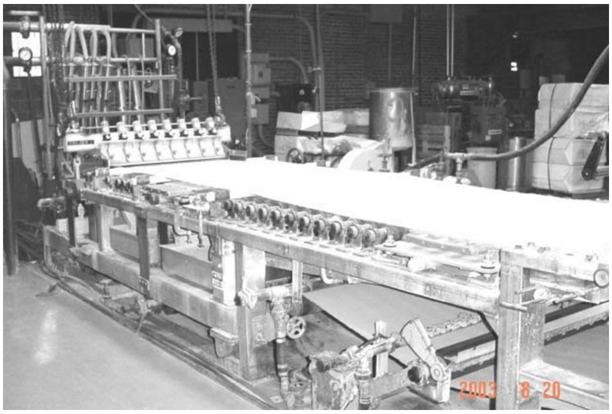

Figure 12 Wet end of the pilot papermachine at SUNY College of Environmental Science and Forestry. A hydraulic headbox is seen in the background and the forming sheet would move left to right while water drains through the wire.

Wire Section

The bulk of the water is removed at the wire section, or wet end of the papermachine (**Figure 12**). A good portion of this water is recycled for dilution of the incoming stock in the approach flow system. As the sheet moves with the wire, water is filtered through the wire, depositing the pulp fibers on the wire in a layered mat. However, as more and more fibers are deposited, the resistance to water flow is increased, thus retarding the drainage of water. With free drainage at the initial part of the wire, the only driving force of the height of the stock above the wire (on the order of 450 Pa) is quickly overwhelmed by the resistance. In some modern machines, multiple wires are used to dewater the stock from both sides of the sheet (**Figure 13**).

Table rolls and foils Table rolls and foils induce a vacuum under the wire, thus creating a greater

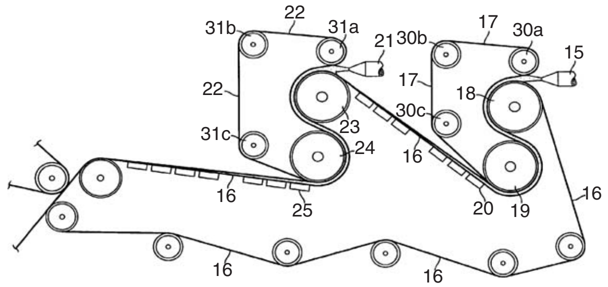

Figure 13 Patent drawing of a modern wet end of a papermachine using multiply, twin-wire forming (US patent 6,342,125). The pulp slurry is injected between two wires (15 and 21) and can be dewatered from both sides.

driving force to remove more water. Table rolls, originally used to support the wire, produce a vacuum that is proportional to the square of the velocity of the wire and related to the roll diameter and at moderate speeds on the order of 4500 Pa. Unfortunately, as speeds increased, a reverse pulse into the sheet at the front of the table rolls became too disruptive to the sheet. The foil was developed to address this drawback of the table roll. The foil is a stationary blade placed at an angle of 0.5–3° to the wire, with the larger angle causing a greater pressure drop. While the pressure driving force is approximately one-half that developed by the table roll, it does not have as great a leading pressure pulse into the sheet. Also, two to three foils can fit into the space of one table roll. However, since the foil is not rotating with the wire, they do tend to increase wear.

Vacuum boxes and vacuum couch At the final stages of the wire section, vacuum is applied to the underside of the wire to increase the driving force for water removal. As a series of vacuum boxes is often used, the vacuum level increases as one proceeds down the wire, with the highest vacuum being applied at the vacuum couch. The couch is the last roll before the sheet is removed from the wire and the wire is turned for its return. Vacuum levels can range from 20 000 to over 53 000 Pa of vacuum.

Forming fabric The fine screen on which the paper is formed is termed the wire, due to its originally being constructed of phosphor-bronze wire. Modern wires are basically a woven cloth of polyester monofilaments made into an endless loop. These fabrics are often woven into a double or triple layer construction in order to provide a wear surface on the bottom of the wire (for durability) and a smoother surface on the top on which the sheet is formed. In all cases, the wires are designed to maximize water flow from the sheet.

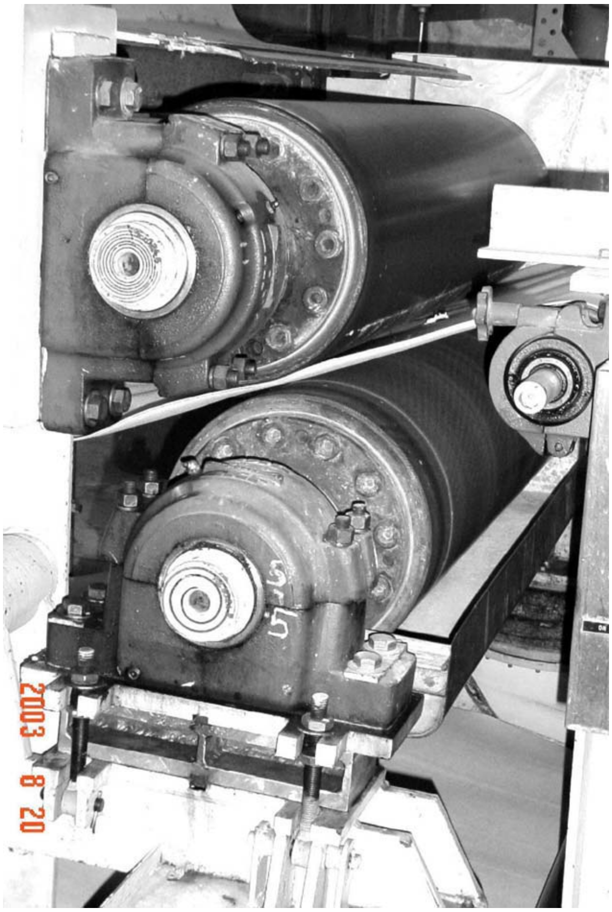

Figure 14 Press section of the pilot papermachine at SUNY College of Environmental Science and Forestry. The sheet together with its press felt would go through the nip, squeezing water from the sheet to the felt.

Press Section

The press section consists of a two to four press nips similar to the wringers on an old-fashioned washing machine (**Figure 14**). The objectives of press are to consolidate the sheet while removing water. Since the majority of the hydrogen bonding which gives paper its strength occurs at a solids content of 35–65%, pressing is key to the development of strength properties of the final sheet. Other properties that can be influenced in the press section include porosity, smoothness, and bulk. The sheet typically enters the press section at 20% solids and exits between 40 and 50%, depending on the grade of paper and pressing configuration.

In order to increase the amount of water removed, the sheet travels through the press together with a press felt, which also serves to support the weak sheet during pressing. The sheet and felt travel through the press nip in four distinct phases. In the first phase, the sheet and felt are compressed, removing air from both. When the air is removed and the sheet becomes saturated, water flows from the sheet to the felt. As the sheet passes mid-nip, the felt begins to expand and becomes unsaturated. However, hydraulic pressure still maintains water flow from the sheet to the felt. In the final phase the sheet is at maximum dryness and begins to expand and reabsorb moisture from the felt. It is important that the sheet and felt be separated as soon as possible after exiting the nip to prevent this reabsorption.

There are limits to the amount of pressure that can be applied to the sheet in the press section. In first presses in a section, the press is often 'flow-controlled.' That is, the limitation to pressing is the flow of water from the sheet to the felt. Overpressing under these conditions can lead to crushing the sheet, in which water flows backwards through the press nip, disrupting the incoming sheet. In 'compression-controlled' pressing, often found in the last press nips, the fiber web itself is the limiting factor in pressing. Under these conditions, increasing the nip pressure beyond a certain point has little effect on increasing the dewatering.

There are a number of ways of increasing the efficacy of the pressing operation; some are operational and require equipment changes. Increasing the nip pressure can increase dewatering in the early nips provided the sheet is not crushed. Double felting the nip can also increase the amount of water that can be removed. The press rolls themselves can be modified by grooving or drilling to allow water to pass through the felt. Suction press rolls can also increase water removal in the nip. Increasing the temperature of the sheet as it enters the nip reduces the viscosity of the water, making it flow easier. Finally, extending the length of the nip will increase the water removal of the nip (**Figure 15**).

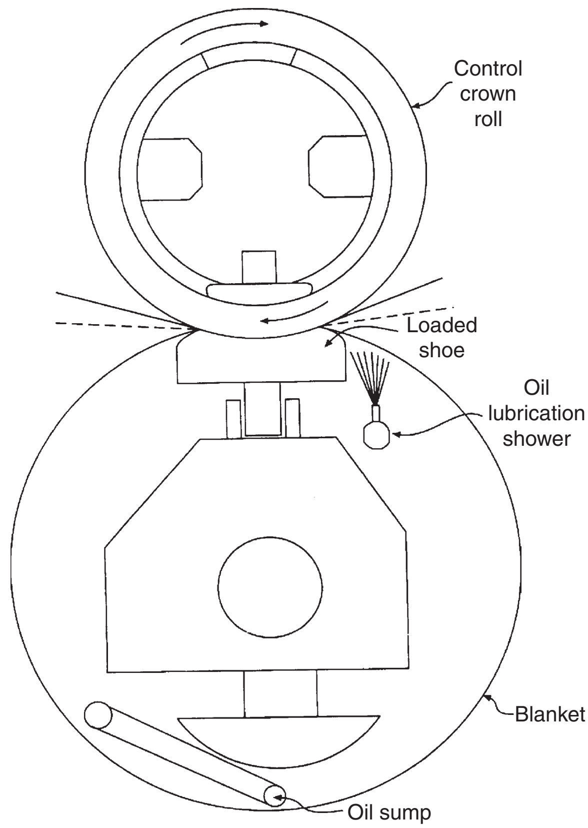

Figure 15 Patent drawing of prior art depicting shoe press used in many presses (US patent 6,458,248). Because of the loaded shoe, the sheet spends a much longer time in the press than with a nip produced by two rolls.

Dryers

The drying section is the most expensive part of the papermachine to run (**Figure 16**). About 78% of the energy used on a papermachine is used in the dryer section, with the remaining energy being split between the wet end and press sections. However, less than 1% of the water that enters with the stock at headbox is removed by drying. By contrast, pressing removes about 3% of the water, with the majority of the water being removed in the wet end. This last amount of water in the sheet is difficult to remove because of the fiber's strong affinity to water and the hydrogen bonds between cellulose and water that need to be broken. However, since this last water is so expensive to remove, small improvements in water removal at the wet end and press sections can translate into significant savings in the dryer section. Since the dryer section is also the most expensive part of the machine in terms of capital cost, paper machine production is often limited by dryer capacity.

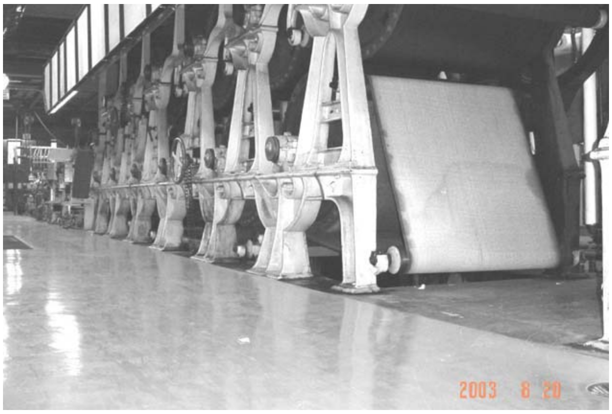

Figure 16 Dryer section of the pilot papermachine at SUNY College of Environmental Science and Forestry. The sheet passes alternately over and under steam-heated cylinders in a serpentine pattern.

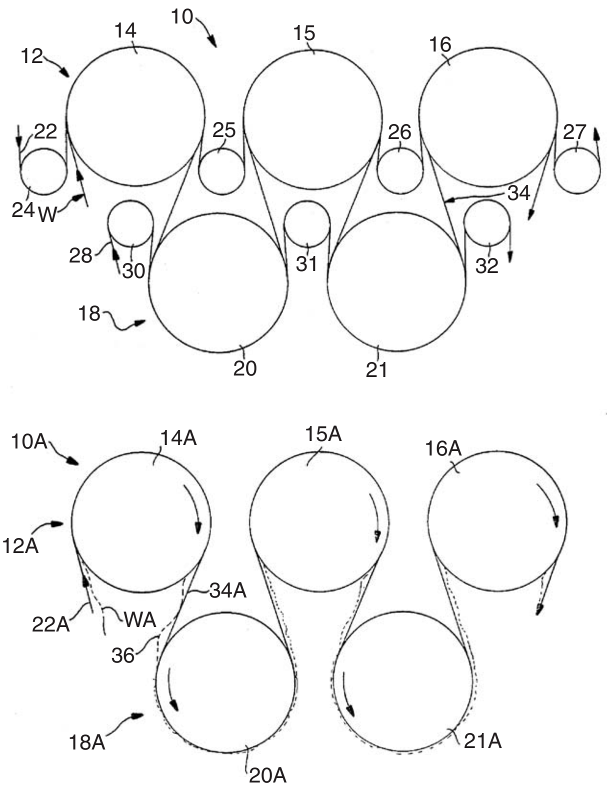

Figure 17 Patent drawing depicting prior art of dryer configuration. Top: double-felted dryer configuration; bottom: single-felted configuration (US patent 4,876,803).

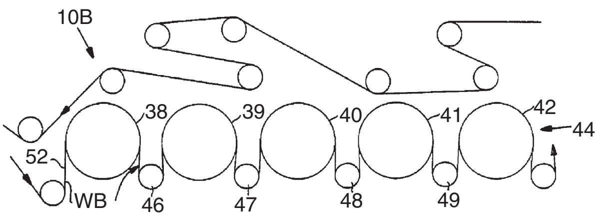

Figure 18 Patent drawing depicting modern dryer configuration. In this configuration, the sheet is completely supported by the felt through the entire run (US patent 4,876,803).

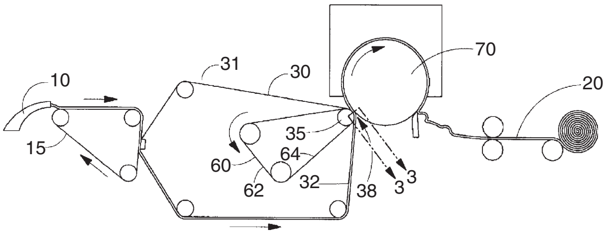

Figure 19 Patent drawing of modern tissue machine (US patent 6,447,642). Tissue machines, because of the light-weight sheet that they produce, tend to be smaller with a single, oversized dryer can (70).

The drying process consists of two main processes. First, heat is transferred from condensing steam in rotating cylinders to the paper sheet, evaporating the water in the sheet. Second, air is drawn through the dryer section to remove the evaporated moisture. The paper takes a serpentine path through the dryer section, passing alternatively over and under the steam-heated cylinders. Synthetic dryer felts hold the sheet in contact with the dryers which increases the heat transfer rate. A number of different configurations of dryers and felt are currently used in the industry. The top diagram in **Figure 17** shows the typical double-felted run in which the sheet transfers unsupported by the felt from one dryer can to the next. The bottom diagram shows a single-felted run in which the sheet is completely supported by the felt through the dryer section. However, in this case, the felt is between the sheet and the dryer can, retarding heat transfer. In **Figure 18**, the run is single-felted, so the sheet is supported and the rolls in which the felt is between the sheet and the roll have been reduced to unheated turning rolls. Tissue machines often use a single large dryer called a Yankee dryer to support and dry the sheet during the entire process (**Figure 19**).

Drying takes place in a number of stages. During the first part of drying, representing usually the first three or four dryer cans, the energy is mainly heating up the sheet. As the sheet proceeds down the machine, a constant-rate zone is entered that represents the bulk of the drying process. As the sheet nears complete dryness, the rate of drying decreases as the more difficult bound water is removed. In most paper machines, the paper is only dried to about 5% moisture, since this is the water content of paper in equilibrium with typical room air.

A size press is often located in the middle of the dryer section (**Figure 4**, item 500). The size press is used to put a surface coating or surface chemicals on to the sheet. Surface coatings can consist of clay, latex, and other materials depending on the grade of paper. Chemicals can also be added to retard moisture penetration or to provide fire resistance. After the application, which is often done as a slurry or solution, further drying is needed.

Calender

The final opportunity on the paper machine to change the paper properties is the calender stack (**Figure 20**). A calender stack consists of a loaded stack of steel rolls (or alternating steel and soft rolls) through which the paper takes a serpentine path. The paper thus passes through a number of nips depending on the number of rolls. The multiple nip passes tend to compact and densify the sheet. While some loss of strength is often evident in calendering, the process improves the smoothness and flatness of

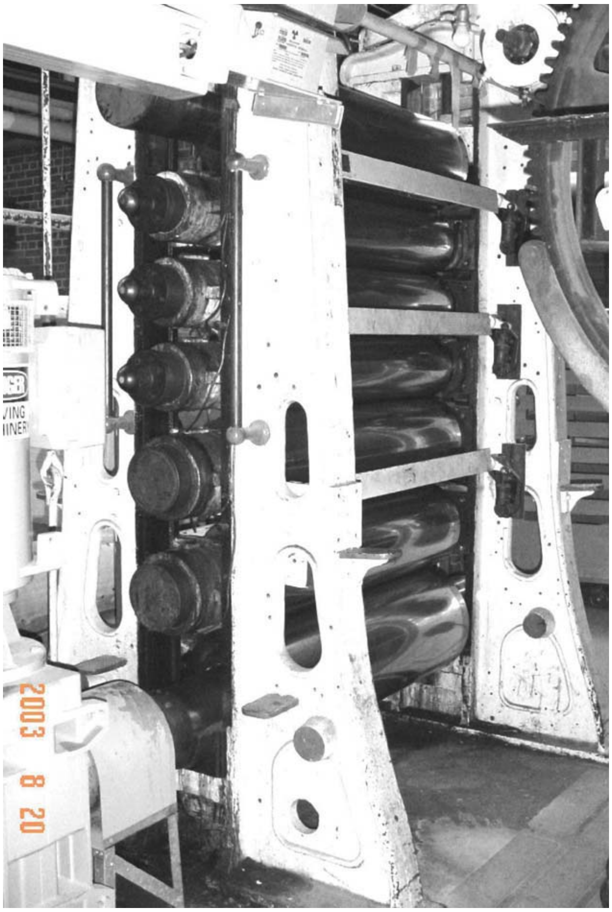

Figure 20 Calender of the pilot papermachine at SUNY College of Environmental Science and Forestry. The sheet passes through multiple nips to smooth the surface of the sheet.

the sheet and can correct some of the irregularities in the sheet. The effect of calendering on the sheet depends on a number of variables, including the sheet moisture, the type of coating applied at the size press, the calender stack loading, temperature, and number of nips.

Reel

The final step of the paper machine is to collect the paper that is produced on a reel (**Figure 4**, item 800). From here, the paper is rewound into smaller rolls needed for shipping or further processing in the finishing and converting operation. The type and amount of processing done after the reel depend on the grade of the paper and the customer specifications.

See also: **Packaging, Recycling and Printing**: Packaging Grades; **Papermaking**: Paper Grades; Paper Raw Materials and Technology; Paperboard Grades; The History of Paper and Papermaking; Tissue Grades. **Pulping**: Chemical Pulping; Mechanical Pulping.

Further Reading

Biermann CJ (1996) *Handbook of Pulping and Papermaking*. San Diego: Academic Press.

Borch J, Lyne MB, Mark RE, and Habeger Jr, CC (eds) (2002) *Handbook of Physical Testing of Paper*, vol. 2, 2nd edn. New York: Marcel Dekker.

Britt KW (1975) *Handbook of Pulp and Paper Technology*. New York: Van Nostrand Reinhold.

Clark Jd'A (1985) *Pulp Technology and Treatment for Paper*, 2nd edn. San Francisco: Miller Freeman.

Dieson M (1998) *Papermaking Science and Technology*. Atlanta, GA: Tappi Press.

Gavelin G (1998) *Paper Machine Design and Operation*. Vancouver, BC: Angus Wilde.

Hunter D (1978) *Papermaking: The History and Technique of an Ancient Craft*. New York: Dover Publications.

Karlsson M (2000) *Papermaking*, Part 2, *Drying*. Atlanta, GA: Tappi Press.

Kline JE (1991) *Paper and Paperboard: Manufacturing and Converting Fundamentals*. San Francisco: Miller Freeman.

Kojio M (1999) *Papermaking: Finishing*. Atlanta, GA: Tappi Press.

Levlin J-E and Söderhelm L (1999) *Pulp and Paper Testing*. Atlanta, GA: Tappi Press.

Mark RE, Habeger Jr, CC, Borch J, and Lyne MB (eds) (2002) *Handbook of Physical Testing of Paper*, vol. 1, 2nd edn. New York: Marcel Dekker.

Patrick KL (1999) *Primer of Pulping and Paper Making: Technologies and Production Practices*. San Francisco, CA: Miller Freeman Books.

Paulapuro H (2000) *Papermaking* Part *1: Stock Preparation and Wet End*. Atlanta, GA: Tappi Press.

Savolainen A (1998) *Paper and Paperboard Converting: Papermaking Science and Technology*. Atlanta, GA: Tappi Press.

Smook GA (1982) *Handbook for Pulp and Paper Technologists*, 3rd edn. Vancouver, BC: Angus Wilde.

Smook GA (1992) *Handbook of Pulp and Paper Terminology: A Guide to Industrial and Technical Usage*, 2nd edn. Vancouver, BC: Angus Wilde.

Thorp BA (ed.) (1991) *Pulp and Paper Manufacture*, vol. 7. *Paper Machine Operations*. Atlanta, GA: Tappi Press.

Paper Grades

G J F Ring, University of Wisconsin–Stevens Point, Stevens Point, WI, USA

Introduction

Paper is a sheet of dried cellulosic fibers and noncellulosic components formed from an aqueous suspension on a fine mesh screen. The ideal forming