COTTON

1. Introduction

The use of cotton predates recorded history. Although the actual origin of cotton is still unknown, archaeological findings indicate its use in cloth in 3000 BC. Early explorers in Peru found cotton cloth on exhumed mummies that dated to 200 BC. The first cotton mill was built in Beverly, Massachusetts in ~1790, and in 1794 Eli Whitney was granted a patent for the invention of the cotton gin, the "engine" that separates the cotton from the seed.

Cotton culture has evolved from gathering of the lint and seed from wild plants by indigenous people to the domestication and cultivation of selected species. Cotton is both a fiber (lint) and food (cottonseed) crop. For each 45.36 kg (100 lb) of fiber produced, the plant also produces ~68.04 kg (150 lb) of cottonseed. Cotton, which only has value once the fiber and seed are separated at the gin, is perishable and must be harvested in a timely manner or the fiber and seed can deteriorate in quality and value.

Cotton fiber (see FIBERS, VEGETABLE) is the most important natural vegetable textile fiber used in spinning to produce apparel, home furnishings and industrial poducts (1). In 2001, worldwide ~37% of the textile fiber consumed was cotton (*World Synthetic Fibres Supply/Demand Report 2001*). In its marketed form, raw cotton consists of masses of fibers packaged in bales of ~85–230 kg (187–507 lb). A single kilogram (2.2 lb) of cotton may contain 200 million or more individual fibers.

Cottonseed [world's No. 3 oilseed; 26,665 thousand metric tons (*Oil World Annual 2000*)] can be fed as whole seed (16% oil, ~45% protein) to dairy cattle or crushed at a cottonseed oil mill to obtain oil [160 kg/tonne (320 lb/t)], hulls [260 kg/tonne (540 lb/t)], meal [455 kg/tonne (910 lb/t)], linters [fuzz fibers

$\leq$0.33 mm long; 83.5 kg/ton (167 lb/t)] and manufacturing loss [31.5 kg/ton (63 lb/t)] (2). The oil is used for human consumption; the hulls and meal are sources of vegetable protein feed for animals; and the linters are used as a chemical cellulose source and in batting for upholstered furniture and mattresses as well as for high quality paper.

The origin, development, biology/breeding, production, morphology, chemistry, physics, and utilization of cotton have been discussed in many publications (1–7).

Cotton fibers are seed hairs from plants of the *Malvaceae* family, the tribe *Gossypieae*, and the genus *Gossypium*. It is a warm-weather shrub or tree that grows naturally as a perennial but for commercial purposes is grown as an annual. Botanically, cotton is a fruit. The principal domesticated species of cotton of commercial importance are *hirsutum, barbadense, arboreum*, and *herbaceum*. Many different varieties of these species have been developed through breeding to produce cotton plants with improved agronomic properties and cotton fibers with improved length, strength, and uniformity. In addition to conventional breeding methods, genetic engineering is being used to produce transgenic cottons with insect resistance (eg, Bollgard; “Bt cottons” incorporting genes from *Bacillus thuringiensis* for boll worm/bud worm resistance) and herbicide tolerance [eg, bromoxynil (Buctril; “BXN cotton”) and glyphosate (Roundup; “Roundup Ready cottons”) tolerant cottons, which enable reduced use of herbicides] (8). In 2002, transgenic cotton varieties are ~25 to 30% of the cotton grown in the world and are being grown in the United States, China, Australia, South Africa, Argentina, Mexico, India, and Indonesia. Research is underway to produce transgenic cottons with other improved agronomic traits as well as improved fiber quality properties.

Gossypium hirsutum, developed in the United States from cottons that originated in Central America and Mexico, includes all of the many varieties of American Upland cotton. Upland cottons now provide <90% of the world’s production of raw cotton fiber and vary in length from ~22–36 mm ($\frac{7}{8}$ to $1\frac{1}{2}$ in.) with micronaire scale [numerical values are roughly the equivalent of linear density (expressed in micrograms weight per inch of length); represents fiber surface area, used as an indicator of fiber fineness (http://www.uster.com/en/prod/main_2_0_4.htm)] ranging from 3.8 to 5.0. *G. hirsutum* is a shrubby plant that reaches a maximum height of 1.8 m (5.9 ft). *G. hirsutum* is used in apparel, home furnishings, and industrial products.

Gossypium barbadense, originally of early South American origin, has the longest staple length and is commonly refered to as “extra long staple” (ELS) cotton. It includes Sea Island, Egyptian Giza strains, American Pima, and Tanguis cottons. Sea Island is the longest and silkiest of the commercial cottons. *G. barbadense* accounts for ~8% of current world production. ELS cotton fiber is long and fine with a staple length usually greater than 35 mm ($1\frac{3}{8}$ in.) and a micronaire <4.0. The plant grows from black usually linter-less seeds and reaches a height of 1.8–4.5 m (5.9–14.8 ft). Egypt is the major producer of ELS cotton today. Pima, an ELS, is a complex cross of Egyptian and American Upland strains and is grown in the western United States as well as South America. *G. barbadense* is used in high quality apparel, speciality yarns for lace and knitted goods, and sewing thread.

Gossypium arboreum and *Gossypium herbaceum*, known collectively as "Desi" cottons, are the other commercial species. They are the Asiatic or Old World short staple cottons. Both are of minor commercial importance but are grown in India and Pakistan. *G. herbaceum* is also grown in China. These cottons are the shortest and coarsest cottons cultivated, ranging from 9.5 to 19 mm ($\frac{3}{8}$ to $\frac{3}{4}$ in.) and micronaire >6.0. *G. arboreum*, the tree wool of India, grows as tall as 4.5–6.0 m (14.8–19.7 ft) and includes both Indian and Asiatic varieties. Its seeds are covered with greenish gray fuzz fibers below the white lint fibers. *G. herbaceum*, the original cotton of India, averages 1.2–1.8 m (3.9–5.9 ft) in height. The fiber is grayish white and grows from a seed encased in gray fuzz fibers.

Commercial cottons are almost all white but recently there has been a renewed interest in naturally colored cottons. They have existed for >5000 years (9,10). The availability of synthetic dyes and the need for high quality, higher yielding cottons caused these cottons that are short, weak, and low yielding to almost disappear. Naturally colored cottons available today are usually shorter, weaker, and finer than regular upland cottons, but can be spun into ring and rotor yarns for some applications alone or when blended with normal white fiber (11). The color can intensify with washing and colors can vary somewhat from batch to batch (11) . Colored cottons are being grown presently in the United States, Peru, China, and Australia. The amount available is very small. Shades of brown and green are the main colors available. Other colors (mauve, red) are available in Peru and some other colors are being researched. The color for brown and red-brown cotton appears to be in material bodies in the lumen. The different colors of brown and red-brown are due most likely to tannins derived from (+)-catechin (12) and some may be protein–tannin polymers. The color in green cottons is due to a lipid biopolymer (suberin) deposited between the cellulose microfibrils in the secondary wall. The brown cotton fibers (and white lint cultivars) do not contain suberin like the green cotton fibers. Green cotton fibers are chacterized by a high wax content of 14–17% of their dry weight, whereas white and brown fibers contain only 0.4–0.7% wax (12,13).

At present, cotton is grown in evironments that range from arid to tropical, with long to very short growing seasons. Cotton typically requires a growing season of at least 160 days when minimum temperatures are >15°C (60°F) (5). Fairly moist and loamy soil produces the highest yields. Under normal climatic conditions, cotton seeds germinate and seedlings emerge in 7–10 days after planting. Flower buds (known as squares) appear 35–45 days later followed by open white (Upland cotton) or creamy to dark-yellow (Pima cotton) flowers 21–25 days later. One day after the flower opens the cotton boll begins to grow rapidly, if the flower has been fertilized. Mature bolls open 40–80 days after flowering, depending on variety and environmental conditions. Within the boll are three to five divisions called locks or locules, each of which normally has seven to nine seeds that are covered with both lint and linters (Fig. 1). The linters form a short, shrubby undergrowth beneath the lint hairs on the seed. At least 13,000–21,000 fibers are attached to each seed and there are close to 500,000 fibers in each boll.

Each cotton fiber is a single cell that originates in the epidermis of the seed coat at about the time the flower opens. The fibers first emerge on the broad, or

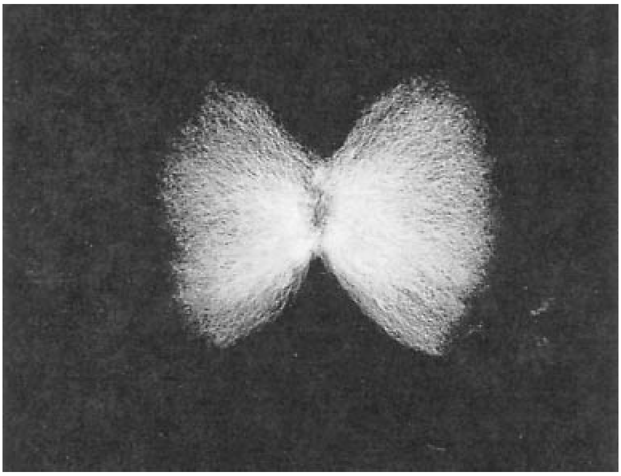


Fig. 1. Cotton butterfly with lint and linters (fuzz fibers).

chalazal, end of the seed and progress by degrees to the sharp, or micropylar, end. As the boll matures, the fiber grows until it attains its maximum length, which averages ∼2500 times its diameter (Fig. 2). During the first 3 weeks, the cell is composed of a thin wall (primary wall) that is covered with a waxy,

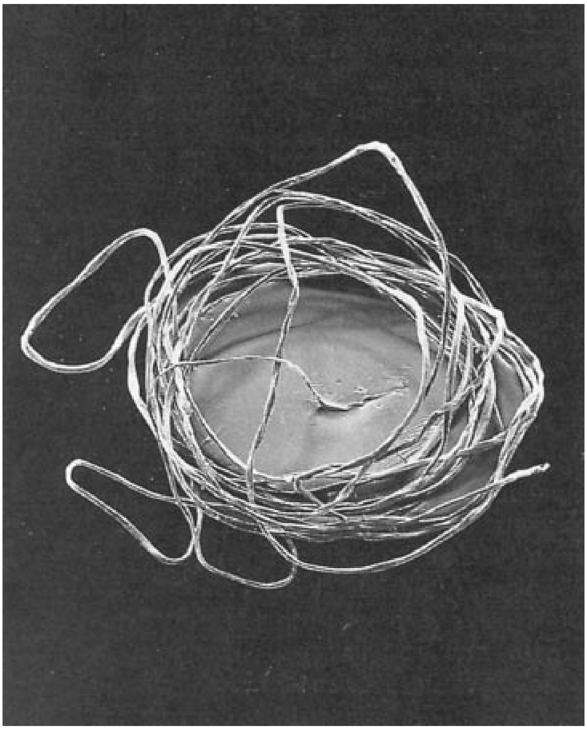


Fig. 2. Single cotton fibers, showing ratio of length to diameter.

pectinaceous material, which encloses the protoplasm or plant juices. The primary wall also contains protein, cellulose and Hemicellulose. In ∼17–25 days after flowering (postanthesis), when the boll is half-mature, each fiber virtually attains its full length. Then layers of cellulose (qv) are deposited on the inside of the thin casing, or primary wall. The pattern of deposition is such that one layer of cellulose is formed each day in a centripetal manner until the mature fiber has developed a thick secondary wall of cellulose from the primary wall to the lumen, or central canal. The fiber now consists of three main parts: primary wall, secondary wall, and lumen. At the end of the growing period when the boll opens, the fibers dry out. The mature cotton fiber is a dead, hollow dried cell wall tubular structure, which is collapsed, shriveled, and twisted, giving the cotton fiber convolutions. The convolutions differentiate cotton fibers from all other forms of seed hairs and are partially responsible for many of the unique characteristics of cotton.

The seed hairs of cultivated cottons are divided into two groups (fuzz fibers or linters and lint) that differ in length, width, pigmentation, and strength of adherence to the seed. The growth of linters is much the same as that of lint, but elongation is initiated about 4 days after flowering. They are usually ∼0.33 cm (1.3 in.) long compared with the 2.5 cm (1 in.) average length of lint fibers and are twice as thick, or ∼32 μm (Fig. 3). Their color is usually greenish brown to gray. After lint fibers have been ginned off the seed, the linters remain. Removal of linters is usually done at the cottonseed oil mill and requires a machine similar to that used at the saw cotton gin to remove the fiber from the seed.

2. Cotton Fiber Biosynthesis

During the cell elongation stage of fiber development, a primary cell wall envelopes the growing fiber. The principal components of fiber primary cell walls are pectins, hemicelluloses, cellulose, and proteins. Relatively few studies on the chemical identity and structure of fiber primary cell wall components have been conducted (14–16). In higher plants, pectins and hemicelluloses are produced in Golgi bodies and are deposited in the wall by fusion of Golgi-derived vesicles with the cell membrane. Cell wall proteins are synthesized in association with the endoplasmic reticulum and may be glycosylated in the Golgi. In contrast, the enzyme complex responsible for cellulose biosynthesis is associated with the cell membrane in structures known as rosettes.

Cellulose biosynthesis has been extremely difficult to characterize biochemically. At maturity, cotton fibers are nearly pure cellulose and should be a rich source of the enzyme cellulose synthase. Unfortunately, it has been difficult to separate a β-1,4-glucan (cellulose) producing activity from a large background of β-1,3-glucan (callose) synthesis. Progress in separating the two enzyme activities from cotton fiber has been reported recently (17), however detailed structural information comparing the two enzymes is still lacking. With the advent of molecular genetic approaches to study genes expressed during cotton fiber development, a break-through has been achieved. By determining the sequence of many messenger RNA (m RNA) molecules produced by immature cotton fibers,

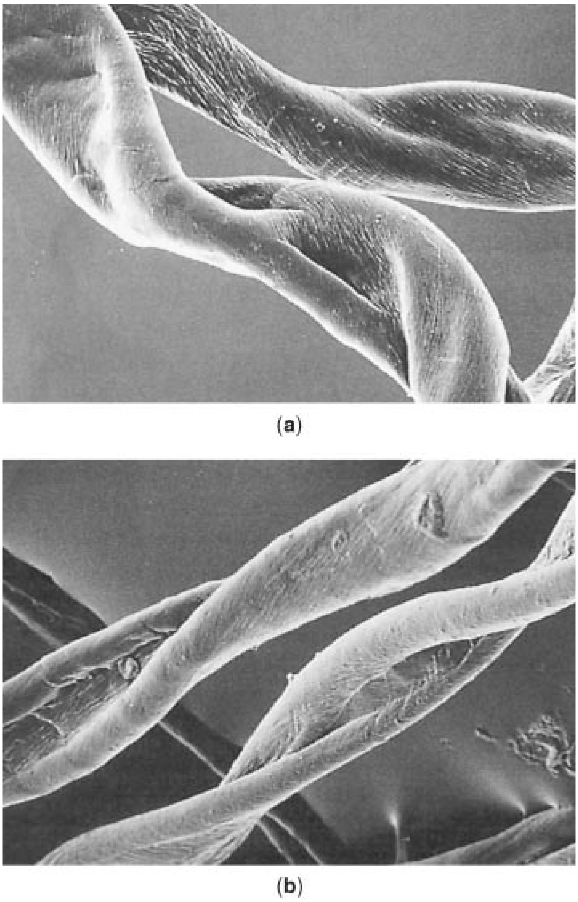


Fig. 3. Longitudinal view of fuzz (**a**) and lint (**b**) fibers.

two gene transcripts with regions similar to those found in bacterial cellulose synthases were discovered (18). These subunits of the cellulose synthase complex were named CesA1 and Ces A2 and are produced concomitantly with the initiation of secondary cell wall biosynthesis in fiber (18). A third CesA gene from cotton has also been described and is expressed both during the cell elongation and secondary wall thickening stages (19). The CesA subunit alone will not produce cellulose, but genetic experiments in the model plant *Arabidopsis* link the CesA gene to cellulose biosynthesis (20). In addition, a membrane-associated cellulase gene has also been implicated in cellulose biosynthesis by induced mutations in *Arabidopsis* (21,22). It seems paradoxical that cellulase, an enzyme capable of degrading cellulose, is involved in cellulose biosynthesis. Initiation of cellulose biosynthesis in cotton fiber has been found to require sitosterol-β-glucoside as a primer (23). It has been suggested that the cellulase activity is required for cleaving the primer from the growing glucan chain. Another enzyme, sucrose synthase, colocalizes with sites of cellulose biosynthesis in cotton fiber membranes, and may function to partition substrate to the cellulose biosynthetic complex (24).

3. Production

About 80 countries in the world grow cotton. Planting time for cotton varies by locality, varying from February to June in the northern hemisphere; harvest time is in the late summer or early/late fall. In the western hemisphere, cotton is cultivated between about 37° N and 32° S latitude and in the eastern hemisphere, between $\sim 47^\circ$ N and 30° S.

Cultivation of cotton differs markedly from one country to another, depending upon the degree of mechanization (5). When cotton is grown and processed in a responsible manner , it does not have adverse effects on the environment, the workplace, or the consumer (1,25). In the United States cotton-breeding research, and management and harvesting practices have increased the yields so $<30\%$ as much land is needed today to produce the same amount of cotton as in 1930. Through conventional cotton-breeding research, many fine-quality cotton varieties have been developed (26).

3.1. Field Preparation. Field preparation practices reflect the varied environments and production systems encountered in the various cotton growing regions. In the United States, some form of conventional or clean tillage dominates in regions not subject to erosion. This includes incorporation of plant residues in the fall to minimize overwintering insects and food sources for disease organisms; deep tillage in either fall or spring to improve root penetration, water availability and crop performance; ridges or beds may be formed following tillage to facilitate surface drainage, irrigation and aeration and speed soil warming; and shallow tillage completes field preparation to enhance soil tilth and seedling growth.

Conservation tillage systems are gaining in popularity in areas subject to soil erosion. Conservation tillage, which includes minimum till, no till and other forms of maintaining residue on the soil surface, has enabled farmers to increase their production options in response to their specific challenges. These systems became feasible with the advent of specialized equipment and new herbicide chemistry that reduce or eliminate the need for extensive tillage.

3.2. Planting. Less than 5% of the cottonseed produced is used for planting seed. Advances in equipment design and engineering have vastly improved the precision of the planting operation. Seed depth and spacing can be adjusted in response to soil, weather, geographical and seasonal requirements. When coupled with high quality seed and state- of-the art weather forecasts, seeding rates can closely approximate final stand density.

3.3. Irrigation. Approximately 70% of the U.S. cotton is rain grown, but western states (Arizona, California, and New Mexico) grow only irrigated cotton. The use of supplemental irrigation is increasing in some rain grown areas of Texas, New Mexico, and the mid-south states, so that presently $\sim 70-80\%$ of U.S. cotton uses some form of supplemental irrigation. Whether applied down the furrow via ditches, overhead with moving pipes or below the surface in drip systems, irrigation requires close producer attention. Water demand by the crop is monitored with soil or plant-based instrumentation including calculated evapotranspiration, soil tensiometers, gypsum blocks and neutron probes, leaf pressure chambers, and infrared (ir) thermometers that measure canopy temperature. The specific technique selected reflects the production region, soil characteristics, irrigation capabilities, and management style of the individual producer. Whatever technique is employed, irrigation decisions are made to maximize production efficiency and eliminates waste.

3.4. Fertilization. Cotton normally is grown under intense production systems; many fields are planted in cotton year after year. However, in the United States in 2002 ~55% to 100% of cotton farmers, depending on the state, also grow other crops and have the potential for crop rotation (personal communication from D. K. Lanclos, National Cotton Council, based on a 2002 planting intentions survey). On average, U.S. cotton is fertilized with 31 kg (68.3 lb) of nitrogen, 10 kg (22 lb) of P_2O_5, and 6.8 kg (15 lb) of K_2O (27). The type and concentration of fertilizer required for high yield depends on many factors such as soil type, previous fertilization rate, cropping system, and irrigation. Therefore, an efficient fertilization program must be based on results of soil and tissue tests and the yield desired from the crop.

Supplying nutrients according to crop demands has replaced traditional methods, as soil and tissue testing have become widespread. Nitrogen can now be metered out on an "as-needed" basis through the use of rapid and reliable soil and tissue testing methods. Unnecessary and undesirable applications are, therefore, avoided, reducing the risk of off-site discharge of nitrates. Potassium fertilization has undergone a similar evolution as application strategies are modified in light of sod characteristics and yield expectations. Soil and tissue testing, coupled with soil or foliar-applied potassium, enables growers to respond rather than anticipate crop needs. Other macronutrients, such as phosphorous, or micronutrients, such as boron, can be applied in a manner consistent with producer philosophy without compromising environmental quality.

Throughout the cotton-growing regions of the United States, the method of applying fertilizer must be tailored to the crop needs and the characteristics of the cropping system. In some production systems, fertilizer is applied during the seedbed preparation, whereas in other systems it may be applied at planting or after emergence. Combinations of preplant and postemergence applications are common, especially for nitrogen. Foliar application is relatively new. Dilute nitrogen and phosphorus solutions are sprayed on the foliage of the plant at various times during the season, which is an attempt to match fertilizer application to the weekly needs of the plant more closely (see FERTILIZERS).

3.5. Crop Protection. Cotton can be affected by insects (28), weeds, diseases (29), nematodes, and mycotoxins. About 90% of the U. S. cotton uses Integrated Pest Management (IPM) practices. This approach optimizes the total pest management system by utilizing all available tools, including rotation, crop residue destruction, maximum crop competitiveness, earliness, pest scouting, action thresholds, releases of beneficial insects, sterile insect releases and selective crop protection chemistry.

New plant protection options including new chemical, biological, and transgenic technologies coupled with good IPM schemes are helping to reduce use of broad spectrum pesticides favored in the past. Weed management (*Weeds of Cotton: Chacterization and Control*, The Cotton Foundation Reference Book Series, Number Two) is a particularly exciting area as genetically engineered transgenic cotton varieties and less persistent herbicides become available. Diseases (29) and nematode pests (*Cotton Nematodes, You Hidden Enemies: Identification* *and Control*, The Cotton Foundation, National Cotton Council, and Aventis CropScience, 2002) are managed by selecting tolerant or resistant cultivars and adopting specific agronomic practices that minimize their impact on cotton performance. Aflatoxin, a mycotoxin by-product (secondary metabolite) of the naturally occurring fungi, *Aspergillus flavus and parasiticus*, can be a serious food safety hazard, if it occurs on cottonseed. A potential biocontrol (competitive exclusion) method (30) for managing aflatoxin in cotton is being evaluated and developed in Arizona. Also ammoniation of the cottonseed is an effective way to eliminate the aflatoxin in seeds used for feeding (31).

Insect management (28) continues to evolve as more selective chemistry reaches commercialization, as insect resistant trangenic cottons are introduced, sterile insect technology evolves and cultural practices are refined. Historically, the most destructive pests of the cotton plant in the United States are the boll weevil (32) and the bollworm/budworm complex. Insects are serious threats to the cotton industry in countries around the world. The boll weevil migrated into the United States from Mexico ~1892 and spread over the entire cottonbelt within 30 years (32). An organized effort to eradicate the boll weevil began in the United states in 1978. Using phermone technology for trapping and detection, insect diapause control to disrupt reproduction and hibernation, and chemical control technology, the weevil is being systematically eliminated from the United States. Before the boll weevil eradication program started, the domestic cotton crop lost to the weevil was ~$200 million a year and ~$75 million a year was spent for pesticides to control this destructive pest (33). Because of the boll weevil eradication program, this pest is on the way to being eliminated in the United States. About 33% of cotton-growing states have completed elimination of the boll weevil and ~65% are nearing completion (34).

A serious cotton insect pest in Arizona, Calforinia, New Mexico, far western Texas, and northwestern Mexico is the pink bollworm, which overwinters as diapausing (hibernating) larvae in the soil. After feeding on the late-blooming bolls, the larvae drop to the ground and hibernate for the winter, emerging as adults in the spring to lay eggs on the early cotton blooms. The eggs hatch and the new larvae bore into the fresh cotton bolls, go through molting stages, bore their way out, and drop to the ground. Throughout the growing season, the cycle repeats itself, rendering useless vast numbers of cotton plants in a single field.

For >25 years, the San Joaquin Valley of California has been protected from pink bollworm through use of a monitioring and sterile insect release program. Moths are mass-reared, irradiated to render them sexually sterile and released onto fields where traps indicate a potential reproducing population. Chemical treatments also are effective along with other practices that include early stalk shredding, early and deep tillage, and winter irrigation that drowns diapausing larvae (35). Insect resistant transgenic cottons are particularly effective in controling the pink bollworm. Presently pink bollworm eradication efforts (*Pink Bollworm Eradication*, National Cotton Council, August 2001) are underway in parts of the United States and northweastern Mexico.

Other insects injurious to the cotton plant include aphids, leafhoppers, lygus bugs, mites, whiteflies, fleahoppers, thrips, cutworms, and leaf miners (28). As boll weevils are being eliminated and transgenic insect protectant plants are reducing damage from bollworms, pests, which traditionally were considered secondary, are now gaining in prominance.

4. Harvesting

Except for the cotton gin, the introduction of the mechanical harvester has probably had a greater effect on cotton production than any other single event. Commercial mechanical harvesters were introduced into the United States after World War II and by 1955, ~23% of the U.S. cotton was mechanically harvested. Presently >99% of the U.S. cotton crop is mechanically harvested, but ~75% of the cotton produced in the world is still hand harvested one boll at a time (36).

When the cotton boll reaches full maturity, it begins to lose moisture and opens. As the boll opens, the drying fiber fluffs or expands outward. After the seed cotton (linters and lint) has dropped to a moisture content of ~12% it is ready for harvest. If the cotton is to be mechanically harvested, the plant is usually treated with a harvest-aid chemical (ie, a defoliant or desiccant) (36) (Table 3). A defoliant induces abscission (shedding) of foliage. The removal of leaves helps to minimize the trash harvested with the mechanical harvester and promotes faster drying of early morning dew on the lint. Defoliants should not be applied until ~60% of the bolls are open and harvest should be delayed for 7–14 days after application. Desiccants (qv) are chemicals that induce rapid loss of water from the plant tissue and subsequent death of the tissue. The dead foliage remains attached to the plant. Harvest can begin in 3–5 days after application.

Once the plant is ready, the cotton is mechanically harvested with either a spindle picker or cotton stripper. The spindle picker selectively harvests seed cotton from open bolls. The unopened bolls are left on the plant and can be picked at a later date. The spindle picker uses a rotating tapered barbed spindle to remove the cotton from the bur (seed case). The seed cotton is wrapped around the spindle, pulled from the bur, removed from the spindle with a rubber doffer, and then transferred to a basket. Two types of cotton strippers are currently in use in the United States. The finger-type stripper uses multiple fingers made from metal angles with the vee turned up and operating at a 15–20° approach angle with the ground. The roll-type stripper uses two 7-in.-diameter (17.8-cm diameter) stripper rolls angled 30° with the ground and rotating in opposite directions. Each roll consists of three brushes and three paddles mounted in alternating sequence.

Strippers are efficient and can harvest up to 99% of the cotton from the plant. They are nonselective and remove not only the seed cotton but also the cracked and unopened bolls, the burs, and other foreign matter. The extra foreign matter requires additional cleaning at the gin.

After harvesting the seed cotton is transported to the gin where the fiber is separated from the seed. Because the gin capacity is usually not sufficient to keep up with the harvesters, the harvested cotton is often stored in a compacted module and ginned at a later date. The type of storage or seed cotton processing may place additional constraints on the harvest process. If the seed cotton is to be placed in module storage, the cotton should not be harvested until the moisture content is 12% or less and the harvested seed cotton should be free of green plant material, such as leaves and grass.

5. Ginning

Gin equipment is designed to remove foreign matter, moisture, and cottonseed from raw seed cotton (37). Two types of gins are in common use—the saw gin and the roller gin. Saw gins are normally used for Upland cottons, whereas roller gins are used for the ELS (Pima) cottons. In a saw gin, the cotton enters the saw gin stand through a huller front and the saws grasp the seed cotton and draws it through widely spaced ribs. The ginning action is caused by a set of saws rotating between a second set of narrowly spaced ginning ribs. The saw teeth pass between the ribs pulling the fiber through at the ginning point. The space is too narrow for the seed to pass and so the fiber is pulled from the seed. A roller gin consists of a ginning roll (covered with a compound cotton and rubber material), a stationary knife held against the roll and a rotary knife. The rotating roll pulls the fiber under the stationary knife. The seeds can not pass under the stationary knife and are separated from the fiber. The rotary knife then pushes the ginned seed away from the ginning point allowing room for more seed cotton to be ginned.

Typical types of gin equipment are cylinder cleaners, stick machines, and lint cleaners for cleaning; hot air driers for removing moisture; and gin stands for separating the fiber from the cottonseed; and the bale press for packaging the lint (37). The gin stand (Fig. 4) is actually the only item of equipment required to gin cotton, the other equipment is for trash removal and drying.

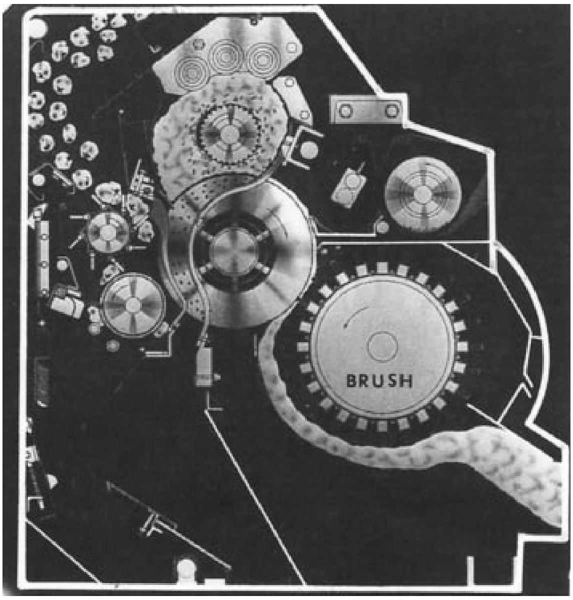


Fig. 4. A modern gin stand that separates fiber from cottonseed.

About 636 kg of seed cotton is required to produce a bale (~227 kg; 500 lb) of lint cotton from spindle harvested cotton. The remainder consists of about 354-kg seed and 55-kg trash and moisture. Typical gins contain one to four individual gin stands, each rated at 6–15 bales/h. However, a few gins contain as many as eight gin stands and produce up to 100 bales/h. The greatest number (30,498) of gins existed in the United States in 1902. The majority were on plantations, and they processed 10.6 million bales (2.3×10^9 kg) of cotton (38). Since then the number of gins has declined, and the average number of bales processed per gin has increased. In 2000, a total of ~1018 active gins handled a crop of 16,742,000 bales (~3.65×10^9 kg) for an average of 16,446 bales (3.58×10^6 kg) per gin plant (39). The number of bales produced in the United States varies substantially from year to year, which places a severe financial burden on the ginning industry.

Mechanical harvesting systems were made possible by the invention of saw-type lint-cleaning systems in the early 1950's. Lint cleaners enabled gins to remove from the cotton the additional trash that resulted from mechanical harvesting. The mechanical systems reduced the harvesting period from 4 to 5 months to ~6 to 8 weeks of intensive operation. Severe congestion problems at the gin were eased with the storage of seed cotton in 8- to 15-bale, freestanding modules. Modules avoided the massive need for wheeled trailers during the compressed harvest season. Storage of seed cotton in modules increased rapidly from the 1970's on, accounting for >90% of the crop in 2000. At present, the average U.S. cotton ginning capacity is ~30 bales/h. A few gins process in excess of 100 bales/h (40).

Most of the U.S. gins are now operated as cooperatives or as corporations serving many cotton producers. Automatic devices do the work faster, more efficiently, and more economically than hand labor. High volume bulk seed cotton handling systems and hydraulic suction systems to remove cotton from modules, high volume trailers to get cotton into the gin, larger trailers and modules, increased processing rates for gin equipment, automatic controls, automated bale packaging and handling devices, and improved management have all increased efficiency.

After ginning, baled cotton is sampled so that grade and quality parameters can be determined (classification). The fiber quality/physical attributes affect the textile manufacturing efficiency and the quality of the finished product. Cotton bales are normally stored in warehouses in the form of highly compressed bales. The International Organization for Standardization (ISO) specifies that bale dimensions should be of length 140 cm (55 in.), width 53.3 cm (21 in.), height 70–90 cm (27.6–35.4 in.) and density of 360–450 kg/m^3 (22.4–28 lb/ft^3) (41). Bales of cotton produced in the United States meet these dimensional standards. Bales of cotton packaged in accordance with these dimensions (ISO 8115) are not considered a flammable solid by the International Maritime Organization and the U.S. Department of Transportation for transportation purposes for vessel and other types of shipment (42) and are considered to present no measurable pest risk to the importing country.

Baled cotton fiber is merchandized and shipped by the merchant to the textile mill for manufacturing into products for the consumer. The seed is shipped directly for feeding to dairy cattle or to a cottonseed oil mill for crushing (43,44).

6. Classification/ Measurement of Fiber Quality

Classification is a standardized set of procedures for measuring the quality/ physical attributes of raw cotton fiber that affect the quality of finished products and/or manufacturing efficiency (45).

6.1. Classing U.S. Upland Cotton. In the United States, the quality of cotton is described (classed) in terms of color, leaf, extraneous matter, fiber length, length uniformity, strength, and micronaire according to the Official Cotton Standards (also called "universal standards") (45). Research to rapidly measure other important fiber chacteristics, such as maturity, stickiness, and short fiber content, continues. The transition to all-instrument classification will be completed as soon as the technology can be developed and instruments are sufficiently refined. Practically all cotton grown in the United States is classed by the Cotton Program, AMS, U. S. Department of Agriculture (USDA), on a fee basis at the request of producers. Measurements for fiber length, length uniformity, fiber strength, micronaire (fineness), color grade, and trash are performed by precise high volume instruments (commonly referred to as "HVI" classification, see below). There are 25 official color grades (15 physical standards and 10 descriptive) for American Upland cotton, plus 5 categories of below-grade. Micronaire reading is determined by an airflow measurement. (Micronaire is often associated with maturity since usually the more mature the fiber, the larger the diameter. Such association is a gross estimation and often unreliable measure of maturity.) Classification for leaf grade, preparation, and extraneous matter are still based on subjective (classer) determinations performed by visual observation.

6.2. Classing U.S. Long Staple (Pima). Pima (ELS cotton) and Upland cotton grade standards differ (45). The most significant difference is that the American Upland color grade is determined by instrument measurement and the American Pima color grade by trained cotton classers. Pima is naturally of a deeper yellow color than Upland cotton. The leaf content of Pima standards are peculiar to this cotton and do not match Upland standards. Because it is roller ginned, Pima cotton's appearance is not as smooth (ie, more stringy and lumpy) as that obtained with the saw gin process. There are six official cotton grades for American Pima color and six for leaf, ranging from grade 1 (highest) to 6 (lowest). All are represented by physical standards and a descriptive standard for cotton, which is below grade.

6.3. Classing in Other Countries. The measurement of fiber quality/ classing in countries other than the United States can be based on variety and growing area; appearance and visual observation; visual class and length; or classed as seed cotton, ginned by class of seed cotton, and reclassed after ginning. At present more countries are moving to some type of automated testing system like the HVI. Differences between the U.S. classing system and those of other countries are described in the literature (1).

6.4. High Volume Instrument (HVI) Systems. Instruments to measure fiber properties have been used for a number of years, but until recently high costs and the length of time required for the tests have limited their use. However, in the mid-1960's, a cooperative effort between the USDA and instrument manufacturers began what was aimed at developing instruments that are fast enough for classification of the millions of bales of cotton produced each year.

This led to the development of HVI systems. Modern HVI systems make use of the latest advances in electronic instrumentation and space-age technology to rapidly and inexpensively measure the more important fiber properties, including length, length uniformity, strength, fineness, color (including color grade), and trash.

At present, the Switzerland based Zellweger Uster Corp. is the major HVI system manufacturer on the market. Zellweger Uster continues to advance the utilization of its cotton fiber testing technology through measurement systems specifically adapted for utilization in classing offices, gins, and mills. In recent years, other HVI system manufacturers have come into the market providing competing technologies and choices for HVI users. Schaffner Technologies of Knoxville, Tennessee, Lintronics Ltd. of Arad, Israel and Premier Polytronics Ltd. of Coimbatore, India are offering HVI systems at various stages of development targeted for use in gins, mills and classification. At the end of 2001, there were some 1450 HVI systems in 70 countries.

Currently, HVI systems are providing reliable information on six characteristics of quality from a cotton sample in ~30 s. that are highly related to the spinning quality and market value of the cotton. Starting with the 1991 crop year, cotton has been required to be tested by HVI to be eligible for price supports in the United States. Information on every bale of cotton greatly improves the marketing of cotton and encourages the production of cotton with fiber properties desired by users.

6.5. Advanced Fiber Information System.

The Advanced Fiber Information System (AFIS) (46–48) is a recent development that incorporates several fundamental measures into one system. AFIS measures several fiber properties that are key to predicting the ease of spinning and quality of finished product, including fiber neps (small tangles of fiber), dust, trash, fiber length, short fiber, and maturity. The measurements are unique in that individual fibers and particles (neps and dust) are automatically counted and sized. The principle of operation is that a fiber individualizer aeromechanically opens and separates the sample into single fibers that are injected into an airstream. Dust and trash particles are diverted to a filter while the airstream transports the fibers and neps past an electrooptical sensor that is calibrated to measure the specific size characteristics of the fibers and neps. The AFIS determines the average size and size distribution of neps. Measurements of dust and trash include their particle size distributions, the number of dust and trash particles per gram, and the average size of trash particles.

AFIS length measurements include: percentage of short fiber content (<12.7mm/ 0.50 in.) by number and by weight; average length by number and by weight; coefficient of variation of fiber length by number and by weight; upper quartile length (75% of fibers shorter than) by weight; and the 5.0% length by number (95% of the fibers shorter than). Fiber maturity measurements include fiber fineness (linear density measured in millitex), the immature fiber content (% of immature fibers by number), and the average maturity ratio.

7. Physical Properties

Fiber length is universally accepted as the most important fiber property, because it greatly affects processing efficiency and yarn quality. The recognized reference machine method for fiber length information is the Suter–Webb Comb Sorter (49). Fibers are sorted and separated by a series of combs into length increments of 1.6 mm (0.063 in.). Each group is then weighed to determine the weight–length distribution parameters, which include the mean length of the longest half (upper-half mean) of the fibers by weight, the mean length, the percentage of the fibers <12.7 mm (0.5 in.) and the coefficient of length variation. Variations of length are unique to specific varieties of cotton and range from <2.5 cm (1 in.) for short-staple Upland varieties to 2.6–2.8 cm (1.02–1.10 in.) for medium-staple Uplands, to >2.85 cm (1.12 in.) for long-staple varieties (Pima, Egyptian, and Sea Island) (45,50).

Next to length, *fiber strength* is the most important physical property that relates to fiber and yarn quality. The recognized reference method for fiber strength is based on measurements made on bundles of parallel fibers (51). One suitable instrument, the Pressley tester, consists of a set of jaws and an inclined lever system in which an ever-increasing load is applied to the specimen until the bundle breaks. The position of the load when the bundle breaks is read from the scale and used, together with the bundle weight, to calculate bundle strength. An alternate approach to bundle measurements is the Stelometer tester, which uses a somewhat different loading concept but still requires clamped and weighed bundles very much like the Pressley. In this case, the clamp jaws are separated by 3.2 mm (gauge length), a convention that has proven the method to be highly related to yarn strength and processing parameters. Fiber strength is expressed as breaking stress or force to break per linear density of the bundle. These units are newtons [or gram force (gf)] per linear density (tex), where 1.0 tex = 1 g/1000 m. Variations in fiber strength are also unique to specific varieties of cotton and range from 0.176 to 0.216 N/tex (18 to 22 gf/tex) for short-staple Upland varieties to 0.235–0.275 N/tex (24–28 gf/tex) for some medium-staple Uplands to 0.314–0.373 N/tex (32–38 gf/tex) for long-staple varieties (Pima, Egyptian, and Sea Island) (52).

Another important characteristic property of cotton is its *fineness*, or *linear density*, or weight per unit length. The normal units for cotton fineness are millitex (the units of tex are g/km). Fineness is directly related to the amount of cellulose in the fiber, which is a function of the fiber wall area, excluding the hollow center (lumen), and the fiber length. Variations in fiber fineness range from ~100 mtex for fine Sea Island cotton to ~180 mtex for a typical United States Upland variety to in excess of 300 mtex for a coarse Asian cotton (53). The term *fiber maturity* relates to the degree of development or thickening of the fiber wall relative to its outer perimeter. Recent developments in techniques for preparing excellent thin cross-sections of cotton coupled with advances in computerized microscopic image analysis allow for rapid and accurate measurements of fiber wall area and perimeter (54,55). An acceptable range of maturity for mill usage is from 75 to 80%. The most commonly used measure/indicator of fiber fineness is the Micronaire reading, an airflow measurement performed on a 3.25-g test specimen, which is compressed to a specific volume in a porous chamber. Air is forced through the specimen and the resistance to the airflow is proportional to the linear density. The Micronaire reading is affected by a combination of both fiber fineness and maturity to the extent that for the same genetic variety with a constant perimeter, the Micronaire will correspond to maturity. Depending on acceptable maturity, a good range of Micronaire is between ~3.5 and 4.8 (56).

In addition to fiber length, strength, and fineness, two other properties that have significant bearing on fiber and yarn properties are *color* and *trash* measurements, which are measured by instrumentation such as the Nickerson-Hunter Colorimeter (57) and the Shirley Non-Lint Analyzer (58).

8. Textile Processing

8.1. Yarn Manufacturing. Cotton is received by the textile mill in the form of highly compressed bales ($\sim$450 kg/m^3), weighing $\sim$227 kg (480 lb). Although the seed and a large portion of the plant trash are removed at the gin, baled cotton still contains various forms of trash, including stem, leaf, and seed coat fragments that must be removed in the manufacturing process.

The first step in textile mill processing is opening and blending (59). Cotton properties vary considerably from bale to bale, therefore to ensure consistency in processing efficiency and product quality, it is important that many bales be blended to produce a homogeneous mix. To do this, bales of cotton are arranged in a “lay-down” so that sophisticated blending equipment can continuously remove some cotton from $>$100 bales of cotton at a time, thereby ensuring consistency of fiber properties along the length of the yarn.

After blending, the cotton is fed through a series of opening and cleaning machines containing various types of revolving beaters and sawtooth cylinders that reduce the cotton into smaller masses of less compacted tufts. Most of the dirt and heavier trash is removed through screens or grids as the cotton is tumbled, beaten, shaken, or otherwise manipulated.

The next step is carding, where the cotton is passed between two surfaces set in close proximity to each other and covered with fine brush-like wires. The surfaces move in opposite directions or in the same direction at different speeds, resulting in a combing action that separates the fibers into a fine web. Getting the cotton to this opened condition causes most of the remaining finer trash to be removed. The fine web of fibers delivered from the card is condensed into a ropelike strand called card sliver and coiled into large cans.

Fibers in card sliver are held together by the natural cohesiveness of the cotton. The fibers must now be further aligned and straightened. In a process called drawing, several strands of card sliver (usually eight) are combined to produce a single sliver of improved uniformity and fiber orientation. The drawing frame contains four or five sets of drafting rolls rotating at progressively higher speeds, that attenuate or draft the material down to approximately the original size of the card sliver. The cotton sliver is generally processed through two or three drawings to obtain maximum uniformity and parallelization of individual fibers.

Cotton is combed to produce finer, higher quality yarns and fabrics. In 1990, $\sim$12% of the cotton processed in the United States was combed. Combing mechanically removes as much as 10–15% of the cotton as short fiber. These fibers are used in the production of lower grades of fabric. Yarns not spun from combed cotton are referred to as carded yarns. Because many of the short fibers have been removed, combed yarns are stronger and more uniform than carded yarns. However, the combing process is expensive and adds considerably to yarn costs.

The next process, roving, is an intermediate step in the preparation of the cotton exclusively for ring spinning. On the roving frame, the sliver is attenuated several times by a series of drafting rollers and a small amount of twist is added to hold the smaller mass of stock together. The product, also called roving, is then wound on a special bobbin to accommodate the creel on a ring-spinning frame.

The final process in the yarn manufacturing operation is spinning. Ring spinning is the mainstay of the textile industry and accounts for >50% of all cotton yarn produced in the United States. In ring spinning, the roving is first attenuated to the desired size through a series of drafting rollers. The strand of drafted fibers passes through a metal guide, or traveler, which revolves rapidly around a circular track, or ring, which in turn surrounds a rotating spindle and bobbin. Sufficient twist to obtain the required tensile strength is inserted by the rotation of the spindle and bobbin at speeds of up to ~20,000 rpm. Yarn is wound on the bobbin spinning tube by an up and down traversing of the ring. Average production rates for ring-spun yarns range from 18 to 27 m (20 to 30 yd)/min.

The newer spinning methods produce yarn directly from drawing sliver, such yarns rarely, if even, achieving the overall quality of ring, spun yarns. Rotor, or open-end spinning is a method of yarn formation that can produce coarser yarns at three to five times the rate of ring spinning. Sliver is fed to a pinned or sawtooth-covered opening roller that rotates at a relatively high speed and individualizes the fibers. The opened fibers are then drawn via suction through a conical shaped duct and then aligned and deposited on the inside of a rapidly revolving rotor (up to 150,000 rpm) from which they are twisted into yarn. Twist is inserted by rotation of the rotor, and the yarn is removed through a tube and wound onto a package. Rotor-spun yarns are more uniform but weaker than ring-spun yarns.

Air-jet spinning is one of the newest yarn formation techniques and can spin yarns at speeds of up to 183 m (200 yd)/min. A conventional roller drafting system is used to reduce drawing sliver to the proper size. The drafted ribbon of fibers is then opened, twisted, and entangled by jets of compressed air as they pass through nozzle assemblies. Air-jet spun yarns tend to be weaker and harsher than those produced by ring or rotor spinning. Another new method of yarn production in limited use is friction spinning. In this process, the yarn is formed by frictional contact of the fibers with a pair of rotating perforated drums. The rotation of the drums causes the fibers to be rolled into a thread, which is then drawn off axially from the drums as a finished yarn. Production rates for this equipment can exceed 229 m (250 yd)/min.

8.2. Fabric Manufacturing (Weaving and Knitting). Yarns manufactured in the spinning process are used to make woven or knitted fabrics. Weaving and knitting are the two pimary textile processes for manufacturing fabrics. In the modern textile industry, these processes take place on electrically powered automated machines, and the resulting fabrics go into a wide range of end-uses, including apparel, home furnishings, and industrial (60). Most woven and knitted cotton fabrics are produced from single yarns. However, for the manufacture of industrial fabrics such as canvas, it is necessary to combine, or ply twist, several strands of single yarns together to obtain increased strength and resilience. Sewing thread and cordage are also produced from multiple plies of single yarns twisted together.

The weaving process consists of interlacing straight yarns at right angles to one another. Warp yarns are supplied from a large reel, called a warp beam, mounted at the back of the weaving machine. Each warp yarn-end is threaded through a heddles harness, which is used to lift or depress the warp yarns to allow the weaving to be done.

The machine knitting process consists of interlocking loops of yarn on powered automated machines that are equipped with rows of small, hooked needles which draw formed yarn loops through previously formed loops. The hooked needles have a unique latch feature that closes the hook to easily allow the loop drawing, then opening to allow the yarn loop to slide off the needle.There are circular-knitting, flat-knitting, and warp-knitting machines.

8.3. Nonwoven Manufacturing.

Cotton staple is readily processed to form carded, air laid, or carded/crossed-lapped webs that can be bonded by various techniques to form useful nonwoven materials, eg, needlepunched, spunlaced (hydroentangled), and stitchbonded nonwovens and resin bonded and thermal bonded carded fabrics (*Cotton Nonwovens: A Tecnnical Guide*, Cotton Incorporated, 1997). Many times a combination of these processes is used to produce hybrid structures and other products. Cotton's share of the nonwovens market in 2002 is 7.8% globally and 2.8% in North America (*Cotton Nonwovens: Innovations & Solutions*, Cotton Incorporated, 2002). In 2000–2001 ~32–36 million kg (70–80 million lb) of cotton was used in North America to produce the following nonwovens: [in millions of kg (millions of lb)] swabs [6.4–7.3 (14–16)], bandages [1.8–2.3 (4–5)], cosmetic pads [5.9–6.8 (13–15)], tampons/feminine pads [6.8–7.7 (15–17)], spunlaced wipes [1.4 (3)], surgical sponges [0.9–1.4 (2–3)], shoulder pads/glove padding [0.9–1.4 (2–3)], jewery box pads [0.9–1.8 (2–4)], quilt bedding [0.9–1.4 (2–3)] and diapers.

9. Chemical Composition and Morphology

The cotton fiber is a single biological cell, 15–24 μm in width and 12–60 mm (4.7–23.6 in.) long. It has a central canal, or lumen, down its length except at the tip (61). It is tapered for a short length at the tip, and along its entire length the dried fiber is twisted frequently and the direction of twist reverses occasionally (62). These twists (referred to as convolutions) are important in spinning because they contribute to the natural interlocking of fibers in a yarn (see Fig. 5).

Raw cotton fiber after ginning and mechanical cleaning is essentially 95% cellulose [9004-34-6] (61,62) (Table 1). The noncellulose materials, consisting mostly of waxes, pectinaceous substances, and nitrogenous matter (mainly protein), are located to a large extent in the primary wall, with small amounts in the lumen (63). Analysis of the fiber for metal content (64–66 is given in Table 2. Potassium, magnesium, calcium, sodium, iron, and phosphorous are the most abundant elements; silicon, chlorine, sulfur, and boron are some times detected in trace amounts (64); lead and cadmiun are not detected (64); and arsenic levels in untreated cotton is usually <1 ppm (65). Knowledge of the content of metals

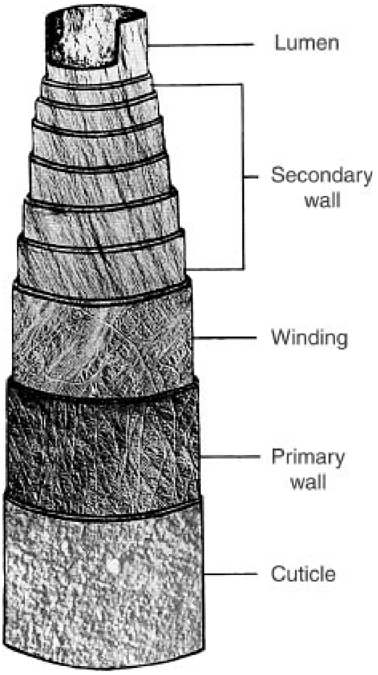


Fig. 5. Schematic diagram of cotton fiber.

is important to processors, because metals can contribute to problems in yarn manufacturing, bleaching, and dyeing (1).

Of the noncellulose constitutents, nitrogen-containing compounds (mostly protein) normally occur in the largest amounts, almost entirely in the lumen, and are most likely protoplasmic residue left behind after the gradual drying up of the living cell. Most of the pectin in the cotton fiber is in the primary wall. Removal of the pectic substances is accomplished by scouring, which does not change the properties of the cotton greatly.

Table 1. **Composition of Typical Cotton Fibers**

	Composition, percent of dry weight	
Constituent	Typical	Range
cellulose	94.0	88.0–96.0
protein (%N × 6.25)[a]	1.3	1.1–1.9
pectic substances	1.2	0.7–1.2
ash	1.2	0.7–1.6
wax	0.6	0.4–1.0
total sugars	0.3	
pigment	trace	
others	1.4	

[a] Standard method of estimating percent protein from nitrogen content (% N).

Table 2. **Metal Content of Cotton**[a]

Metal	ppm
potassium	2000–6500
magnesium	400–1200
calcium	400–1200
sodium	100–300
iron	30–90
manganese	1–10
copper	1–10
zinc	1–10
lead	n.d.[b]
cadmium	n.d.
arsenic	trace (<1)[c]
phosphorous	180–1000[d]

[a] Ref. 64.

[b] n.d. = not detected.

[c] Ref. 65.

[d] Ref. 66.

The wax of most cottons is located principally on the fiber surface in the primary wall of the fiber and is a complex mixture of higher molecular weight lipids (1); there are some differences among varieties. The green lint cotton, as discussed earlier, contains ~14–17% wax of high melting point. Because the wax becomes established in fibers, largely if not wholly, during the first phase of development, the wax content as a percentage of the whole fiber mass decreases as the fiber maturity or degree of wall thickening increases; the finer cottons tend to have a larger percentage of wax. Wax serves as a lubricant and is essential for proper spinning of the fiber into yarn. After spinning and weaving or knitting, the wax is removed by scouring and bleaching in preparation for dyeing and finishing.

The mature cotton fiber has a primary and secondary wall, and a lumen. It also has a cuticle and a winding layer between the primary walls (Fig. 5). The cellulose of the primary wall exists as a randomly woven network of microfibrils in and on which are deposited noncellulose materials that form the primary wall. Just beneath the primary wall is the winding layer, which is also the first layer of the secondary wall. The winding layer appears to be made up of a single layer of fibrillar bundles composed of highly oriented cellulose microfibrils and oriented at an angle to the fiber axis. The main body of the fiber consists of cellulose fibrils packed tightly in a solid cylinder, which, under certain conditions of chemical swelling, can be induced to separate into more or less concentric layers. These layers seem to have a finer and more regular structure than does the winding layer, because the 20–50 secondary wall layers have cellulose microfibrils compactly aligned along the axis of the fiber (see CELLULOSE).

The gross morphology of cotton, which refers to the relatively large structural elements above, is visible in the electron microscope. The microfibrillate structure includes pores, channels, and cavities that play an important role in the chemical modification of cotton. The fibrils follow a spiral pattern and at times reverse; it is believed that regions of low strength along the length of the fiber occur close to the reversal zones. Microfibrils of the secondary wall are 10–40 nm wide, and these in turn are composed of elementary fibrils (crystallites) 3–6 nm wide.

Chemical modification of the cotton fiber must be achieved within the physical framework of this rather complicated architecture. Uniformity of reaction and distribution of reaction products are inevitably influenced by rates of diffusion, swelling, and shrinking of the whole fiber, and by distension or contraction of the fiber's individual structural elements during finishing processes.

10. Structure and Reactivity

10.1. Chemical Structure. The raw cotton fiber produced in the bolls of the cotton plant is composed almost entirely of the polysaccharide (see CARBOHYDRATES) cellulose (see CELLULOSE). Evidence from degradation of cellulose by hydrolysis, oxidation, and other chemical reactions shows that it is a 1 → 4 linked linear polymer of β-D-glucopyranose (Fig. 6). If degradation is extensive, cellobiose (the dimer) or glucose is produced.

The molecular cellulose chains have varying lengths. Measurements of the chain length require that cotton be in solution. Solvents for this purpose include cuprammonium hydroxide solution, phosphoric acid [7664-38-2], nitric acid [7697-37-2], quaternary ammonium bases, cadmium ethylenediamine hydroxide [14874-24-9], cupriethylenediamine hydroxide [111274-71-6] (67),*N,N*-dimethylacetamide [127-19-5]–lithium chloride [7447-41-8] (DMAC–LiCl), and 1,3-dimethyl-2-imidazolidinone [80-73-9] (DMI) and lithium chloride (68). DMAC/LiCl (25,26), when used in conjunction with gel permeation chromatography (gpc) (69,70), provides both the weight (M_w) and number average (M_n) molecular weight of cellulose in a nondegrading solvent without derivatization. Many researchers have reported weight average molecular weights for cotton cellulose ranging from 800,000 to 900,000 (∼6000 glucose residues) but results vary widely. Those reported for DMAC/LiCl (25,26) are very high (∼1,500,000), which may be due to incomplete dissolution of the cotton fibers in this solvent. Cotton cellulose generally has a higher molecular weight than wood cellulose.

10.2. Molecular and Supramolecular Physical Structure. The chains of cellulose molecules associate with each other by forming intermolecular hydrogen bonds and hydrophobic bonds. They coalesce to form microfibrils also called crystallites. In cotton, the microfibrils can organize into macrofibrils 60–300 nm wide. The macrofibrils are organized into fibers. Cotton fibers have a complex, reversing, helical arrangement of macrofibrils. There are several different forms or polymorphs [cellulose I to IV and X with recent subclasses Iα and Iβ (71,72)], depending on the source and treatment. There are both different unit

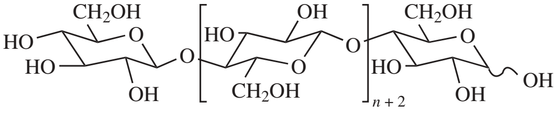


Fig. 6. Chemical structure of cellulose.

cells and different packing arrangements in the unit cell. Native cotton is cellulose I. It has been proposed that cotton and other commercial cellulose, such as wood and ramie, are mostly cellulose Iβ (73). The crystal structure of cellulose Iβ is fairly well understood (74). Despite this, research continues on the crystal structures of it (75) and cellulose II (76) (see CELLULOSE).

Typical one-step commercial mercerization of cotton yarn with caustic or liquid ammonia causes only partial conversion to cellulose II or cellulose III. Cotton cellulose is partially converted to cellulose II by repeated mercerization, the swelling of cellulose in strong alkali (eg, 23% NaOH), followed by rinsing and drying. Cellulose III results from treatment of cellulose with liquid ammonia (ammonia mercerization) or amines. Cellulose III can be made from either cellulose I or II. When treated with water, cellulose III can revert to its parent structure. Cellulose IV can be prepared by treating cellulose I, II, or III in glycerol at temperatures $\sim$260°C. Conversion of the crystal form in cotton fibers to cellulose IV can be effected by heat treatment of ethylamine-treated cotton cellulose in either saturated steam or formamide with minimal fiber degradation (77). Like cellulose III, cellulose IV preparations can revert to their parent structures.

Conversion to cellulose II and cellulose III via caustic mercerization and liquid ammonia treatment are commercial textile processes that are discussed later. Figure 7 shows the characteristic diffractograms (CuKα radiation) of native cellulose, cellulose mercerized with sodium hydroxide, and cellulose treated with liquid ammonia.

10.3. Pore Structure and Affinity for Water. The cotton fiber is a porous, hydrophilic material that accounts for the comfort of cotton clothing. Moisture is retained tenaciously in cotton. The moisture absorbed from the atmosphere and held under ambient conditions is expressed either as moisture content (amount of moisture as the percentage over the oven-dried weight) or more commonly as moisture regain (amount of moisture as a percentage of the oven-dry sample). Under ordinary atmospheric conditions, moisture regain is 7–11%. Upon immersion in liquid water the cotton fiber swells and its internal pores fill with water. Pure cotton holds a substantial percentage of its dry weight in water under conditions of centrifugation. Values for the liquid water held depend on the test used. The values are $\sim$30% for water of imbibition (78) and 50% for the water retention (79). Centrifugation conditions are less severe in the latter case.

Pores accessible to water molecules are not necessarily accessible to chemical agents. Many uses of cotton, eg, easy care fabric, depend on chemical modification to impart the desired properties. Knowledge of accessibility to dyes and other chemical agents of various sizes under water-swollen conditions is required for better control of the various chemical treatments applied to cotton textiles. The principle of molecular exclusion by gpc (80) has been used to assess the pore size distribution in cottons after various chemical treatments. Trends for accessibility to sugars of increasing size are depicted in Figure 8. These probes cover the range of molecular sizes of reagents generally used to modify cotton chemically.

Scouring and bleaching slightly increase the accessible internal volume, liquid ammonia treatment of the scoured–bleached cotton decreases it slightly, caustic mercerization substantially enhances accessibility, and cross-linking to

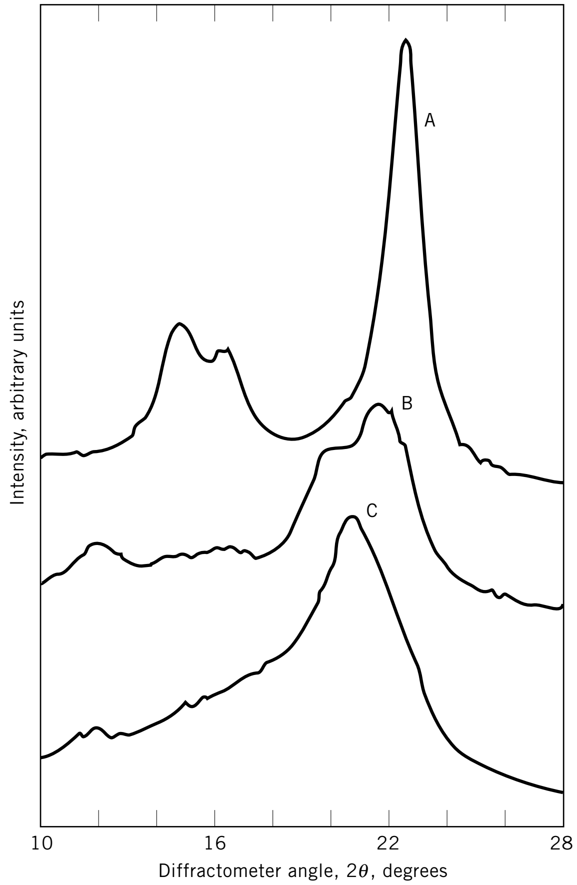


Fig. 7. X-ray diffractograms. A, native; B, NaOH mercerized; C, NH_3 treated.

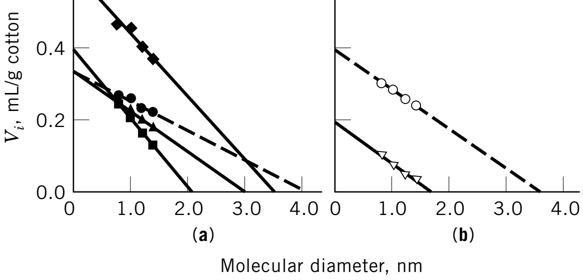


Fig. 8. Internal volume (V_i) that is accessible to sugars as functions of the cotton molecular diameters (80). (**a**) Batting: ▲ greige; •, scoured–bleached; ◆, caustic mercerized; ■, liquid ammonia treated. (**b**) Fabric: ○, scoured–bleached; ▼, cross-linked.

Table 3. **Relative Availabilities of Hydroxyl Groups of Cotton Cellulose throughout Growth and Weathering**[a]

Days postanthesis[b]	Period	3-OH/2-OH	6-OH/2-OH
20	growth/closed boll	0.12	0.49
27		0.05	0.59
34		0.05	0.58
41		0.05	0.59
48		0.06	0.59
62	field weathering/open boll	0.24	0.68
83		0.30	0.75
104		0.31	0.74

[a] Ref. 36.

[b] Bolls open shortly after 48 days postanthesis.

impart durable press properties reduces the accessible internal pore volume substantially.

10.4. Availability of Hydroxyl Groups.

The chemical structure given in Figure 6 shows the 2-OH, 3-OH, and 6-OH groups that are potential sites for the same chemical reactions that occur with common alcohols. However, the regular occurrences of intermolecular and intramolecular hydrogen bonds in the crystalline regions of cotton cellulose render the involved hydroxyl groups unavailable to chemical agents under mild reaction conditions. Chemical agents that have access to the interior pores of the cotton fiber thus find potential reactive sites unavailable for reaction. Direct information on the availabilities of 2-OH, 3-OH, and 6-OH on accessible surfaces has been obtained from chemical measurements based on the reaction of the cellulose with diethylaminoethyl chloride [2210-36-8] under mild conditions (81,82). The order of decreasing availability of hydroxyl groups in cotton is 2-OH $>$ 6-OH $\gg$ 3-OH. Specific values for the relative availability of the 3-OH and 6-OH to the 2-OH depend on the growth (83) and processing (37) history of the fiber. Data on growth and weathering are given in Table 3. Values for relative availability of hydroxyls are maintained throughout the ginning procedure but gradually increase (to ~0.40 and ~0.80 for 3-OH/2-OH and 6-OH/2-OH, respectively) as the fibers are subjected to the stress of processing in the greige mill (84).

11. Reactions for Practical Objectives

Chemical modification has assisted in building cotton's position in the market place despite the advent of synthetic fibers.

11.1. Mercerization.

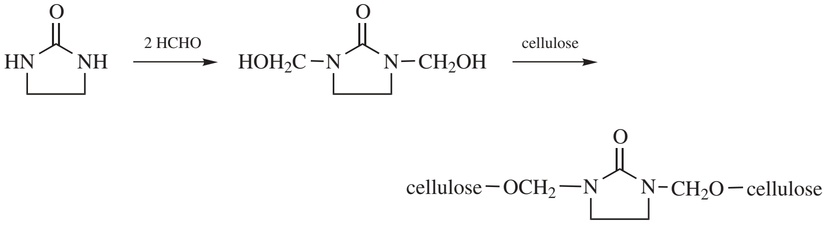
One of the earliest known modifications of cotton that had commercial potential was mercerization. Traditionally, the process employed a cold concentrated sodium hydroxide (caustic soda) treatment of yarn or woven fabric followed by washing and a mild acetic acid neutralization. Maintaining the fabric under tension during the entire procedure was integral to achieving the desired properties. The resultant mercerized cotton has improved luster and dyeability and strength. A variation of this procedure substitutes hot sodium hydroxide that is allowed to cool while the cotton remains immersed in the caustic solution. More thorough initial penetration increases the efficiency of the mercerizing process. If the cotton is allowed to shrink freely during contact with mercerizing caustic, slack mercerization takes place; this technique produces a product with greatly increased stretch (stretch cotton) that has found application in both medical and apparel fields. Effects similar to those from sodium hydroxide mercerization have been produced by exposure of the cotton to volatile primary amines or to ammonia. A procedure that uses liquid ammonia has found commercial adaptation (85). Improvements in luster and strength are similar to those achieved with sodium hydroxide mercerization, but dyeability is not enhanced. A distinct structural difference exists chemically between cotton mercerized in sodium hydroxide and that treated in liquid ammonia, particularly after nonaqueous quenching (86). With both treatments, there is increased accessibility, but differences in dye receptivity presumably result from differences in swelling loci between sodium hydroxide and liquid ammonia treatments.

11.2. Etherification.

The accessible, available hydroxyl groups on the 2, 3, and 6 positions of the anhydroglucose residue are quite reactive (87) and provide sites for much of the current modification of cotton cellulose to impart special or value-added properties. The two most common classes into which modifications fall, include etherification and esterification of the cotton cellulose hydroxyls as well as addition reactions with certain unsaturated compounds to produce cellulose ethers (see CELLULOSE ETHERS). One large class of cellulose-reactive dyestuffs in commercial use attaches to the cellulose through an alkali-catalyzed etherification by nucleophilic attack of the chlorotriazine moiety of the dyestuff:

$$\text{cellulose}\text{—}O^- + \text{Cl}\text{—}\text{dyestuff} \longrightarrow \text{cellulose}\text{—}O\text{—}\text{dyestuff} + \text{Cl}^-$$

Cross-Linking. By far, the most important commercial modifications of cotton cellulose are those that occur through etherification. For example, commercial modification of cotton to impart durable-press, smooth drying, or shrinkage resistance properties involves cross-linking adjacent cellulose chains through amidomethyl ether linkages. This cross-linking is commonly achieved by immersing the fabric in a solution of the agent and an appropriate catalyst, removing the excess liquid by passing the fabric through squeeze rolls (pad), drying in an oven to remove the remaining water, and heating to a high temperature to effect covalent bond formation to cellulose. This sequence is called a pad-bake process. Methylene, or oligomeric, cross-links from a pad-bake formaldehyde treatment result in severe fabric strength loss. There is, however, a process for cross-linking cotton-containing garments with formaldehyde in the vapor phase that has found commercial acceptance in the uniform-rental garment market. Most reagents for cross-linking cotton cellulose are difunctional or polyfunctional amidomethylol compounds or amido compounds that have pendent hydroxyls on carbons alpha to the amido nitrogen (see AMINO RESINS). The methyol compound is generated by reaction of the amido compound with formaldehyde [50-00-0]. For example, ethyleneurea [120-93-4] reacts as follows (88).



Commercially available cross-linking agents include dimethylolurea [140-95-4], dimethylolethyleneurea [136-84-5], dimethyloldihydroxyethyleneurea [1854-26-8], dimethylolpropyleneurea [3270-74-4], dimethylolalkyl carbamate, tetramethylolacetylenediurea [5395-50-6], methylolated melamine, dimethylolalkyltriazone, dimethoxymethyluron [7327-69-7], dihydroxydimethylethyleneurea [3923-79-3] (dimethylurea–glyoxal adduct), and ethyleneurea–glyoxal [107-22-2] adducts. The cross-linking proceeds via either Lewis or Brønsted acid catalysis (89) by a carbocation mechanism. Gross effects of the cross-linking are increased resiliency (manifested in wrinkle resistance, smooth drying properties, dimensional stability, and greater shape-holding properties) as well as, reduced extensibility, strength, and moisture regain. These effects are observed with one cross-link per 20–25 anhydroglucose residues (90). Liquid ammonia treatment of cotton fabric, followed by cross-linking, attenuates the strength loss as well as an accompanying loss in abrasion resistance. This combination contributed to a reappearance of all-cotton fabrics in the woven shirting/sheeting market in the 1970s (91).

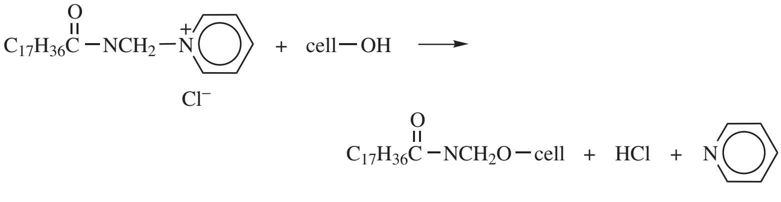
Resiliency. Base-catalyzed reactions of cotton cellulose with either monoepoxides or diepoxides to form cellulose ethers also result in fabrics with increased resiliency. Monoepoxides, believed to result only in cellulose hydroxyalkyl ethers or linear graft polymers (92), produce marked improvement in resiliency under wet conditions, but little improvement under ambient conditions. Difunctional epoxides, which are capable of cross-linking cellulose, can be used to impart increased resiliency to cotton textiles under both wet and ambient conditions (93). Besides imparting resiliency through epoxide etherification, oil and water repellency can be imparted by reactions of monomeric perfluoro epoxides with cotton. Epoxide reacted cotton also accept dyes not traditionally used for cotton. Etherification of cotton with ethyleneimine [2734-98-8] provides a means for imparting special properties to cotton; the end product depends on the attached group. The cross-linking reaction between bis(hydroxyethyl) sulfone and cellulose is another base-catalyzed etherification that produces fabrics possessing increased resiliency under both wet and ambient conditions. The earliest application of sulfone cross-links to cotton textiles was the reaction of divinyl sulfone under alkaline conditions (94). However, the hazard of working with the vinyl compound led to modifications of the sulfone agent. Vinyl groups were replaced with more stable precursors such as the β-thiosulfatoethyl, β-sulfatoethyl (95), or β-hydroxyethyl groups (96). Etherification of cotton by divinyl sulfone [77-77-0] and its precursors also forms the basis for a large class of fiber-reactive dyes with the general formula of dye-$SO_2CH{=}CH_2$ (97) (see Dyes, reactive).

Other Cellulose Ethers. Other cotton cellulose ethers include carboxymethyl, carboxyethyl, hydroxyethyl, carbamoylethyl , cyanoethyl, sulfoethyl, and aminoethyl (aminized cotton) products. Most, with the exception of cyanoethylated and aminized cotton, are of interest in applications requiring solubility or swellability in water or alkali (98). In addition, ethers with pendent acid or basic groups have ion-exchange properties (99). Aminized cotton is of interest because it introduces basic groups onto the cotton that provide sites for attachment of acid dyes. Simultaneous aminization of cotton and dyeing with an acid dyestuff marked the first successful attempt at dye attachment to cellulose through an ether linkage (100).

Flame Resistance. The chemical treatment of cotton with fire retardants to make it flame resistant is discussed elsewhere (see Flame retardants for textiles). Numerous end uses for cotton require it to be flame resistant. The major factors that influence ignition of cotton materials are airflow, relative humidity of the fabric, the amount of oxygen available, physical factors (geometry, density, thickness, etc), chemical factors (eg, inorganic impurities), heat source and rate of heating. Thermal analysis studies in air and in 8.4% oxygen indicate that cotton ignites at ~360–425°C (101,102).

Although certain cellulose esters, such as the ammonium salt of phosphorylated cotton and cellulose phosphate [9015-14-9], are flame resistant, the attachment of most currently used durable polymeric flame retardants for cotton is through ether linkage to the cellulose at a relatively low degree of substitution (DS). Nondurable flame retardants based on liquid-or vapor-phase applications of boric acid [10043-35-3] or methyl borate [121-43-7] are used in treatment of cotton batting for upholstery, bedding, and automotive cushions (103–105). Cotton carpet materials will pass the U.S. Consumer Product Safety Commission (CPSC) federal flammability test for carpets (16 CFR 1630) when crosslinked with polycarboxylic acids such as 1,2,3,4-butanetetracarboxylic acid or citric acid with sodium phosphate, sodium hypophosphite, sodium bicarbonate, or sodium carbonate catalysis (106).

Water Repellency. The development of water-repellent cellulose ethers has been reviewed (107) (see Waterproofing). A typical example of a commercial etherification for waterproofing cotton is with stearamidomethylpyridinium chloride:



N-substituted, long-chain alkyl monomethylol cyclic ureas have also been used to waterproof cotton through etherification. Other water repellent finishes for cotton are produced by cross-linked silicone films (108). In addition to the polymerization of the phosphorus-containing polymers on cotton to impart flame retardancy and of silicone to impart water repellency, polyfluorinated polymers have been successfully applied to cotton to impart oil repellency. Chemical attachment to the cotton is not necessary for durability; oil repellency occurs because of the low surface energy of the fluorinated surface (109).

Cyanoethylation. One of the earliest examples of etherification of cellulose by an unsaturated compound through vinyl addition is the cyanoethylation of cotton (110). This base-catalyzed reaction with acrylonitrile [107-13-1], a Michael addition, proceeds as follows:

$$CH_2{=\!=}CHCN + cell{-\!-}OH \longrightarrow cell{-\!-}OCH_2CH_2CN$$

For most textile uses, a DS <1 is desirable. Cyanoethylation can impart a wide variety of properties to the cotton fabric, such as rot resistance, heat and acid resistance, and receptivity to acid and acetate dyes. Acrylonitrile (qv) has also been radiation-polymerized onto cotton with a ^{60}Co source. Microscopical examination of ultrathin sections of the product shows the location of the polymer is within the fiber (111). Examination of the ir spectrum of cotton-containing polymerized acrylonitrile indicates grafting occurs at the hydroxyl site of the cellulose (112). Another monomer grafted onto cellulose by irradiation is styrene (qv). Chemical properties, mechanisms, and textile properties of these grafted polymers of cellulose have been summarized (113). Graft polymerization onto cotton has also been induced by both chemical (114) and photochemical (63) initiation (see RADIATION CURING).

11.3. Irradiation. The effects of high energy radiation (eg, gamma radiation) on cotton properties have also been investigated (116–118). Depolymerization of cellulose occurs with increasing energy absorption; carbonyl formation, carboxyl formation, and chain cleavage occur in the ratio of 20:1:1. With these chemical changes, there is a corresponding increase in solubility in water and alkali and a decrease in fiber strength. The gamma-irradiated cotton has base ion-exchange properties. Irradiation of cotton with near ultraviolet (uv) light (325–400 nm) causes formation of cellulose free radicals and mild oxidative degradation of the cotton (119). Carbonyl and carboxyl contents of the cotton cellulose increase, and DP and tensile strength decrease, with increasing time of irradiation (120) (see PHOTOCHEMICAL TECHNOLOGY). The induction of cellulose free radicals by near uv irradiation forms the basis for photofinishing with vinyl monomers to produce graft polymers on the cotton:

$$cell{-\!-}H \xrightarrow{h\nu} cell + H\cdot$$

$$cell + nM \longrightarrow cell{-\!-}(M)_{n-1}M\cdot$$

Another useful reaction of cotton cellulose occurs in an ionized atmosphere, which is essentially a surface reaction. Glow discharge treatment of cotton yarn in air increases water absorbency and strength (121), and surface-dependent properties of cotton fabric are drastically changed by exposure to low temperature–low pressure plasma generated by radio-frequency radiation (122). Because only a few extremely high energy electrons (10–15 eV) are generated, ambient temperature is maintained in the chamber. Light microscopy indicates a smoother surface after treatment, but scanning electron microscopy shows no change from native cotton. Spectral changes show some oxidation of the treated cotton, a decreased carbon/oxygen ratio. Free radicals similar to those produced from ^{60}Co radiation are formed. In addition, highly charged species are also formed, allowing such usually inert monomers as benzene to be polymerized onto the cotton with great capacity for bond cleavage. Plasma treatment produces an increased rate of wetting and drying and produces a highly absorbent cotton. The cohesiveness and fiber friction of cotton sliver was increased temporarily through air-trace chlorine corona treatments at 95°C and atmospheric pressure (123,124). With a 15-kV electrode voltage at a frequency of 2070 Hz, no chemical effects on the cotton could be noted. Dyeability, hand, and wettability were unaffected. The increase in cohesiveness allows the production of yarns with increased strength, abrasion resistance, and greater spinnability (125). Thus yarns of significantly lower twist can be produced with strength equal to, or higher than, untreated cotton yarns of higher twist.

11.4. Insolubilization. Insolubilization of compounds within textiles parallels the history of humanity; the direct dyeing techniques for cotton were highly advanced in the Bronze Age (see DYES,NATURAL). With the exception of fiber-reactive dyes discussed earlier, other cotton dyes, ie, vat and sulfur, are insolubilized within the fiber after an oxidization step (see DYES AND DYE INTERMEDIATES). Insoluble metal oxides have been used to flameproof cotton, and zirconium compounds have been insolubilized on cotton to render the fabric microbial resistant (126) or mildew resistant (127) via a mineral dyeing process (see TEXTILES).

Insolubilization and five other methods for imparting antimicrobial properties to cotton have been described (128). These methods can all be classified under one or more of the chemical reactions of cotton cited earlier; they include fiber reactions to form metastable bonds, grafting through thermosetting agents, formation of coordination compounds, ion-exchange methods, polymer formation with possible grafting, and a regeneration process. Also a commercialized process for antibacterial cotton fabrics uses insoluble peroxide complexes of zirconyl acetate (129).

When exposed to heat, cotton fabrics increase in temperature to an extent that is proportional to their specific heats. Altering the chemical composition of the fabrics such that large amounts of heat are absorbed and released in repeatable cycles of controllable temperature ranges produces fabrics that are described as temperature adaptable. The process insolubilizes polyethylene glycols by cross-linking with methylolamides on the cotton fabric (130). As with flame-retardant cotton, attachment to the cellulose is through an ether linkage at a relatively low DS.

11.5. Esterification. There are both inorganic and organic esters of cellulose (131) (see CELLULOSE ESTERS). Of the three most common inorganic esters, cellulose nitrate [9004-70-0], phosphate, and sulfate, only cellulose sulfate [9088-06-6] is soluble in water. Cellulose sulfate attains water solubility at a DS of 3, indicating esterification of all three hydroxyl groups, whereas the sodium salt of cellulose sulfate is soluble in hot and cold water with a DS of only 0.33. Sodium cellulose sulfate is used in applications requiring suspension, thickening, stabilizing, and film-forming properties. The class of phosphonic acid and phosphoric acid dyestuffs attach to cotton through esterification by the phosphonic acid or phosphoric acid group of the dyestuff. Until recently, organic esters of cotton cellulose, with two notable exceptions, were only of academic interest, although partial esterification of cotton by fatty acids has been reported to increase resiliency (132).

Acetylation of cotton to an acetyl content slightly $>21\%$ produces a material with greatly increased resistance to fungal and microbiological degradation, in addition to tolerance of high temperatures not exhibited by native cotton; fibrous appearance and physical properties are unchanged by the acetylation. X-ray diffractograms indicate that, at this extent of substitution, only accessible (noncrystalline) regions of the cotton are involved in the acetylation (133).

In the 1960's, esterification of cotton cellulose with polycarboxylic acids to produce smooth-drying fabrics was investigated (134,135). Catalysis was by partial neutralization of the carboxyl groups. Although improvements in resiliency were obtained, the levels were not commercially acceptable. In the late 1980's, better catalyst systems were discovered for the ester cross-linking of cellulose; inorganic salts of phosphorus-containing acids were found to give ester cross-links that are durable to multiple home launderings. Because of the improved catalysis, certain tricarboxylic and tetracarboxylic acids have shown promise for commercialization (136). These acids include 1,2,3,4-butanetetracarboxylic acid [1703-58-8], tricarballylic acid [99-14-9], and citric acid [77-92-9] (137), maleic acid and itaconic acid as copolymers (138,139), and monopolymers/terpolymers of maleic acid (140). An anhydride formation mechanism has been proposed for the esterification cross-linking of cellulose. An advantage of the polycarboxylic acids in finishing for attaining durable press is that these agents do not contain formaldehyde and thus do not release formaldehyde during processing or end use. Finishes from polycarboxylic acids are superior to those from other nonformaldehyde agents mentioned earlier, such as epoxides, sulfones, acetals, and cyclic urea derivatives, because they are innocuous and are durable to home laundering.

12. Enzymatic Modification

The industrial use of enzymes in the textile industry (141,142) has increased substantially in recent years. Lipases, proteases, and cellulases are being used. Lipases and proteases are used to assist in cleaning textiles. Treatments involving cellulases, which hydrolyze the cellulose polymer, are relatively new and are of particular importance. Cellulases obtained from both bacterial and fungal sources are being used to give fabrics a soft hand, to give cellulosic fabric surfaces a smooth and clear appearance by removing fabric fuzz fibers (biopolishing), and to provide a stone-washed appearance to denim (biostoning) (143–145). Cellulases are also being added to detergents to maintain the color appearance of cotton cellulose fabrics by removing fabric fuzz fibers and pills that form on wear and laundering. The effectiveness of cellulase for removal of material from the fabric is dependent on the type of mechanical action during processing. This includes the abrasive action of fabric- to-fabric contact or the cascading effect of aqueous solution on the cellulosic substrate (146). One of the main reasons for using enzymes instead of other chemicals as finishing agents for cotton cellulose is that they are environmentally safer. The small catalytic quantities of enzymes that are used for finishing treatments are biodegradeable like proteins in general.

13. New Products

13.1. Smart Cotton-Based Wound Dressings. Cotton gauze is still a standard care item in the management of chronic wounds. However, since the time of ancient Greece wound care and dressing strategies have primarily relied on empiricism. Smart wound dressings made from cotton gauze have more recently been designed and prepared with a rational approach based on knowledge of how destructive proteases play a role in the pathology of nonhealing wounds. Cotton gauze may be tailored to enhance the biochemistry of wound healing more effectively by designing formulations and conjugates of cotton cellulose that inhibit or neutralize destructive proteases, such as elastase, which prevent wound healing. Three approaches have been taken to develop protease fiber-inhibitors useful for chronic wounds: formulation of inhibitors on the dressing (147), synthesis of elastase recognition sequences on cotton cellulose (148), and the derivatization of cellulose with functional groups having an affinity for elastase (149). Understanding how these new cotton dressings work in accelerating healing of the chronic wound may signal a new product area of smart wound dressings that are useful in medical treatment modalities of pressure ulcers, leg ulcers, and diabetic foot sores.

13.2. Composites from Cotton. Cellulose fibers are abundant, readily available, versatile, and highly resistant to heat flow. They should be studied/evaluated as valuable starting materials for the design and development of thin low cost nonwoven composite insulation that can adhere to the walls of homes, office buildings, industrial complexes, warehouses, and tents. These applications currently can not use fiberglass insulation within their exterior wall spaces. Cotton and other cellulosic fibers have thermal resistance similar to fiberglass. However, they do not cause immune and skin sensitivities, nor pulmonary problems that are associated with fiberglass use. Initial research on evaluating the commercial potential of cotton fibers as insulating materials involved composite nonwoven insulation materials that were made from cotton, kenaf, jute, polyester, polypropylene, sucrose-based epoxy formulations, and aluminum foil (150). The needle punched fiber batts were rendered flame resistant by use of inorganic reagents and urea.

14. Economic Aspects

14.1. Marketing/Merchandizing Raw Cotton. There are several routes by which cotton fiber in the United States changes ownership from the grower to its final destination at the spinning mill. The grower may sell cotton directly to a spinning mill under a grower contract or the grower may sell cotton to a gin, broker, commission firm, or shipper. Some growers, after ginning their cotton, may sell through a cooperative organization or may place the cotton in a

Table 4. **World Cotton Production[a] [mil 217.7 kg (480 lb) bales]**

Year	World	China	US	India	Pakistan	Uzbekistan
1985[b]	80.3	19.0	13.4	9.0	5.6	7.9
1990	87.0	20.7	15.5	9.1	7.5	7.3
1995	93.0	21.9	17.9	13.2	8.2	5.7
1996	89.5	19.3	18.9	13.9	7.3	4.8
1997	91.6	21.1	18.8	12.3	7.2	5.2
1998	84.5	20.7	13.9	12.7	6.3	4.6
1999	87.4	17.6	17.0	12.2	8.6	5.2
2000[c]	88.8	20.3	17.2	10.9	8.2	4.4
2001[c]	98.2	24.4	20.3	11.9	8.3	4.8

[a] Ref. 151.

[b] A year begins Aug. 1 of the year given and ends July 31 of the following year.

[c] June 12, 2002 estimates by USDA—World Agricultural Outlook Board.

depository as collateral under the Commodity Credit Corporation Loan Program, to be either withdrawn on repayment of the loan plus interest and storage or forfeited for sale by the government. These intermediate buyers then sell the cotton to foreign or domestic mills.

14.2. World Production, Consumption and Prices. World production, consumption, and prices are shown in Tables 4 and 5. World cotton production in 2001 was ∼90 million bales (∼19.6 million metric tons; 21.6 million). Presently the chief cotton-growing countries of the world are China (23%), the United States (20%), India (12%), Pakistan (9%), and Uzbekistan (5%), which produced ∼70% of the world's cotton in 2000 (151). The price is widely variable because it is affected by many factors in the United States and internationally (152).

14.3. Uses. Cotton is used in many apparel and home furnishing items. Table 6 gives the approximate number of items that can be produced from one bale of cotton.

Table 5. **World Cotton Consumption [Mil 217.7 kg (480 lb bales)] and Price of Cotton[a]**

Year	World	China	US	India	Pakistan	Turkey	Price[b]
1985[c]	75.0	18.0	6.4	7.2	2.4	2.1	49.0
1990	85.1	20.0	8.7	9.0	5.6	2.5	82.9
1995	86.0	19.7	10.6	12.0	7.2	4.4	85.5
1996	87.3	20.3	11.1	12.4	7.0	4.7	78.6
1997	87.2	19.6	11.3	12.7	7.2	5.0	72.2
1998	84.7	19.2	10.4	12.6	7.0	4.6	58.9
1999	91.9	22.2	10.2	13.5	7.7	5.6	52.9
2000[d]	92.3	23.5	8.9	13.5	8.1	5.2	57.3
2001[d]	93.3	24.5	7.6	13.2	8.5	6.0	41.4

[a] Ref. 151.

[b] A year begins Aug. 1 of the year given and ends July 31 of the following year.

[c] Cotlook, Ltd. A Index; cents/lb (Ref. 152). 2001 estimate through June 28, 2002.

[d] June 12, 2002 estimates by USDA—World Agricultural Outlook Board.

Table 6. **Number of Items from a Cotton Bale (217.7 kg/ 480 lb)**

Women's wear	Number	Men's wear	Number	Other	Number
dresses	274	dress shirts (woven)	765	diapers	3085
jeans	249	sport shirts (woven)	906	sheets	249
socks (mid-calf)	4321	work shirts	543	pillow cases	1256
blouses (woven)	773	boxer shorts	2104	bath towels (terry)	690
sweaters	379	jockey shorts	2419		
nightgowns	780	T-shirts	1217		
slacks (woven)	415	trousers (dress/sport)	484		
shorts	733	trousers (work)	374		
		jeans	215		
socks (mid-calf)	3557				

15. Health and Safety Factors

15.1. Respiratory Disease. Byssinosis is an occupational lung disease that can affect a small number of textile workers after repeated inhalation of the dust generated during the processing of cotton and some other vegetable fibers (eg, flax and soft hemp) (153–157). Byssinosis may cause progressive and disabling airway narrowing. Cotton dust, an airborne particulate matter released into the working environment as cotton is handled or processed in textile processing, is a complex mixture of botanical trash, soil, and microbiological material (ie, bacteria and fungi) (158). The etiological agent and pathogenesis of byssinosis are not known (157,159,160). However, control studies in experimental cardrooms suggest that endotoxin from gram-negative bacteria is associated to some degree with worker reaction to dust (161). Appropriate engineering controls in cotton textile processing areas or washing cotton essentially can eliminate incidence of workers' reaction to cotton dust (155,156). The U.S. Occupational Safety and Health Administration (OSHA) issued revised standards for occupational exposure to cotton dust in 1985 (162) and revised the standard again in 2001 (163) to add batch washed cotton as an acceptable way to wash cotton to eliminate worker reaction to the dust.

15.2. Skin Irritation/Dermatitis. Handling or processing of cotton does not cause skin irritation, since nothing naturally on the surface of cotton fiber is known to cause dermatitis. However, it is possible for some atypical cottons that have been treated with something not approved for use on cotton or off-grade highly microbiologically contaminated cottons to cause skin irritation.

15.3. Formaldehyde. Formaldehyde is a component of resins used to impart durable-press and other properties to cotton fabrics. It can be released in small quantities from treated cotton fabrics. Formaldehyde is classified as a "probable human carcinogen", because it has been shown to be an animal carcinogen and there is limited evidence to indicate that it is a carcinogen in humans (164). Sensory irritation of the mucous membranes of the eyes and the respiratory tract, and cellular changes in the nasal cavity are the principal noncancer effects of exposure to low airborne concentrations of formaldehyde (164). Exposure to formaldehyde from cotton textiles is controlled by the chemical technology for low emitting formaldehyde resin technology and nonformaldehyde finishes discussed earlier and by increased ventilation in the workplace. OSHA has issued standards for control of occupational exposure to formaldehyde (165). The U.S. CPSC does not regulate formaldehyde in textiles because its studies did not indicate that there is an acute or chronic health problem due to formaldehyde exposures from textiles: "current evidence... does not indicate that formaldehyde exposure from resin treated textiles is likely to present a carcinogenic risk." (166,168).

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