Part II

Production processes for cotton

4
The genetic modification of cotton

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4.1 Introduction

For several thousand years, farmers have been altering the genetic makeup of the crops they grow. Human selection for features such as faster growth, larger seeds or sweeter fruits has dramatically changed domesticated plant species compared with their wild relatives. In cotton, sexual crosses between plants with desirable characteristics and selection within their progeny resulted in varieties with increased fibre quality and yield and the ability to grow in temperate regions (May, 1999). However, despite the remarkable advances made by traditional plant breeding in the twentieth century, yield potential has reportedly plateaued over the last 30 years (Meredith Jr, 2000). Such a scenario suggests that the limits of the material available for conventional plant breeding have been reached. The continued viability and future of the cotton industry therefore demands new sources of diversity and novel genetic techniques.

Plant breeding has been revolutionised by molecular genetic approaches which permit the manipulation and insertion of genes not only from sexually compatible species but of any origin. Foreign genes introduced into the plant genome may confer novel traits which enhance crop quality either directly, by influencing morphological traits, or indirectly by providing protection against biotic and abiotic stresses in the environment. Transgenic crops grown in the world today include soybean, rice, tomato, potato and cotton, in which characters such as nutritional quality, insect resistance, disease resistance, herbicide resistance and salinity tolerance have been genetically manipulated.

Current crop improvement programs involve a combination of plant breeding (hybridisation and selection) and plant biotechnology approaches, and it is the latter which will be considered in this chapter. The advantages and limitations of conventional plant breeding will be considered alongside the potential offered by DNA technology. Cotton crop genetics will be discussed, together with the gene delivery and regeneration systems used to generate transgenic lines. An overview of the transgenic cotton grown today on a commercial scale will be presented, and the hopes and fears for genetically modified (GM) crops discussed more generally. Examples of engineering projects for improved yield and cotton fibre quality will be used to illustrate prospects for the future of genetic manipulation in this species.

4.2 Advantages and limitations of conventional plant breeding

4.2.1 Evolutionary origins of cultivated cotton

Four species in the genus *Gossypium*, tribe Gossypiaeae and family Malvaceae comprise the cultivated cottons (Fryxell, 1969). Two species were domesticated in Africa and/or India, one in South America and one in Mesoamerica (Lee, 1980). The Old World cultivated cottons, *G. arboreum* and *G. herbaceum*, are diploid ($2n = 26$), that is, their cells contain two sets of chromosomes, one haploid set from each parent. They have a haploid chromosome number of 13, the basic number for the genus. The New World commercial cottons are the allotetraploid ($2n = 4x = 52$) cottons *G. hirsutum* (Upland cotton) and *G. barbadense* (Pima, Sea Island and Egyptian cottons). Their cells contain four haploid sets of chromosomes or two diploid sets, double the normal number. Although the diploid species *G. arboreum* is still intensively bred and cultivated in Asia, it is the improved tetraploid species that are most commonly grown, with medium staple *G. hirsutum* accounting for over 90% of world cotton production.

The genomes of diploid *Gossypium* species have been divided into eight groups (designated A to K) on the basis of cytogenetic features such as chromosome size and meiotic pairing (Endrizzi *et al.*, 1985). These groups correspond with distinct biogeographical regions, such that species that evolved in a particular region share a common genomic grouping. Hence species with A, B, E and F genomes have an African/Asian origin; species with C, G and K genomes originated in Australia; and D genome species evolved in the Americas. Nearly all the possible genomic combinations can be made artificially, though some of the hybrids are sterile. All of the tetraploid species intercross readily, although the progeny are frequently genetically unstable, and crossability does not always reflect phylogenetic affinities. For example, the Old World cultivated species (A and D genomes) are difficult to cross with AD allotetraploid species (Lee, 1980).

Allotetraploid cotton (designated AADD) is thought to have arisen from hybridisation between ancestral AA and DD diploid species to produce a hybrid (AD) that underwent chromosome duplication (reviewed by Adams and Wendel, 2004). *G. herbaceum* (A genome) and *G. raimondii* (D genome) are generally considered to be extant representatives of the ancestral A and D genome donors (Endrizzi *et al.*, 1985). The hybridisation and polyploidisation event is thought to have occurred after the ocean migration of the A genome from Asia to Mesoamerica approximately 1–2 million years ago (Wendel, 1989). Subsequent radiation of the allotetraploid gave rise to the five modern allopolyploid *Gossypium* species (*G. hirsutum, G. barbadense, G. tomentosum, G. darwinii* and *G. mustelinum*). In addition to the cultivated cottons, there are over 30 wild taxa in the genus *Malva*, distributed from dry to tropical and subtropical climates around the world (Fryxell, 1969). This germplasm, along with stocks and obsolete varieties of the cultivated species, provides an important resource for potential use in improving cultivated cottons. Many wild species of cotton have valuable agronomic traits such as disease and insect resistance and salinity and drought tolerance. However, only in one instance has a cross between *Gossypium* and a related *Malva* species been reported (Vysotski, 1958).

4.2.2 Conventional plant breeding

The generation of improved cotton varieties began with the domestication of cotton for textile production. Modern cotton breeding programs originated in the early 20th century, driven by an increasing demand for fibre strength and quality in the international textile market (May, 1999). Plant breeding programs have produced most of the varieties used in commercial cotton production. In Australia, for example, decades of organised plant breeding by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) have produced a range of elite cotton cultivars suited to Australian conditions that incorporate useful characteristics from a number of varieties. This effort has resulted in a 20% increase in average cotton fibre strength and a 5% increase in cotton fibre length in the last fifteen years.

Plant breeding and selection techniques have clearly produced substantial improvements in the cotton germplasm, but also have a number of disadvantages. For example, a large amount of time and significant resources are required for plant growth, reproduction and selection. Once a desirable gene has been introduced into a species, several rounds of backcrossing are required to restore the commercial genetic background, with the result that six to ten years of breeding are required for development of a new cotton variety (John, 1999). In addition, the need for hybridisation limits plant breeding to genetically compatible species capable of producing fertile progeny. This prevents the direct introduction of traits from wild cotton species into commercial cotton through conventional breeding programs.

4.2.3 Genetics in cotton breeding

The aim of a plant breeder is to achieve a favourable combination of genes for incorporation into a new crop. Traditionally this has been done with a basic knowledge of how genes are inherited but in the absence of any information about the molecular nature of the genes themselves. Many characteristics of horticultural and some agronomic interest are controlled by a single gene (are monogenic) whose effects fall into a small number of discontinuous classes. For example, resistance is mostly monogenic, so a plant containing one form of the gene will be resistant, whilst a plant with a variant gene is susceptible. In this case the plant breeder can make a prediction about the progeny of a particular cross and breeding programs can be readily directed towards a specific aim. However, many important agronomic targets for crop improvement, for example yield, are polygenic and show characteristically continuous variation that is more difficult to evaluate in breeding programs. That is, the trait has a wide spectrum of variation and is controlled by a number of genes, each of which exerts a small influence on the character we observe. The genes that contribute to a polygenic trait are referred to as quantitative trait loci, or QTLs, and the mapping and tracking of QTLs is being used increasingly to augment traditional methods of plant and animal breeding, by allowing marker-assisted selection.

Quantitative trait loci (QTLs) associated with fibre quality and other characteristics have been identified in a number of studies, and, once statistically linked to a particular trait, may be useful for the selection of superior lines during the breeding process (marker-assisted selection). For example, Zhang *et al.* (2003a) identified a QTL from Acala 3080 cotton which accounted for more than 30% of variation in fibre strength. Paterson *et al.* (2003) isolated a large number of QTLs associated with fibre quality traits expressed under well-irrigated and water-stressed conditions, and QTLs associated with lower osmotic potential, drought tolerance and increased seed cotton yield were identified by Saranga *et al.* (2001). Despite coming from an ancestor that does not produce spinnable fibres, the D genome interestingly appears to contribute substantially to the fibre quality of tetraploid cottons (Jiang *et al.*, 1998).

Once they have been identified in controlled experiments, tracking the inheritance of QTLs using molecular markers enables identification of the most promising cotton breeding lines. In this process genetic sequences or molecular markers that are part of, or closely linked to, a useful QTL are used to identify which plants in a progeny carry the targeted trait and which do not. This greatly facilitates the difficult or impossible task of evaluating minor changes in a particular trait, but the process is heavily reliant on the quality of the underpinning research that established the significance of a particular QTL. DNA markers used in cotton include restriction fragment length polymorphisms (RFLPs), random amplified polymorphic DNAs (RAPDs), simple sequence repeats (SSRs) and amplified fragment length polymorphisms (AFLPs) (reviewed in Mei *et al.*, 2004).

Determining the positions of DNA markers on the chromosomes, or genome mapping, has been hampered in cotton by inadequate DNA sequence information and the relatively large size of the cotton genome (particularly in the allotetraploid cottons). Linkage maps, in which genes and sequences are mapped by recombination during meiosis (the two-part process of cell division whereby gametes are produced with half the number of chromosomes of the parent cell), have been independently developed by a number of groups, but the maps have not been integrated with each other, and individually provide as little as 10% coverage of the genome (Mei *et al.*, 2004). In 2001 the International Cotton Genome Initiative was formed, with the aim of co-ordinating cotton genome research, and in 2004 more comprehensive genetic maps for the diploid (D) and allotetraploid (AD) cotton genomes were published (Rong *et al.*, 2004). These maps consist of sequence tagged sites (STS) at 3,347 loci, giving a resolution of 1.72 centiMorgans (cM) (~600 kilobases (kb)) in the AD genome and 1.96 cM (~500 kb) in the D genome. This work significantly increases the number of markers available for QTL analysis and positional cloning and provides a basis for the comprehensive sequencing of cotton genomes.

4.3 The molecular genetics of cotton

4.3.1 How genes control plant structure and function

Gene activity underlies the form and function associated with all life processes, from cell structure and behaviour to development and reproduction. Therefore, the genes of a plant, which number between 25,000 and 40,000, determine all its characteristics, such as leaf shape and flowering time, and determine its responses to the environment. For a crop this will include fluctuating biotic stresses, such as insect and fungal parasites, and abiotic stresses, such as drought and mineral deficiency, that influence crop yield and quality. Most genes carry the instructions for making specific proteins, and the process by which a gene generates a protein product, which then carries out its cellular function, is known as gene expression. At any one time, only some of the genes in a particular genome are active, and only a specific subset of genes is active in each tissue and organ. In this way a particular protein is only produced where and when it is needed. The suite of proteins produced by a specific subset of genes is what gives each cell, tissue and organ its unique properties and defines its biological function.

The phenotype of any organism, that is, anything which is part of its observable structure, function or behaviour, is determined by a combination of genetic (genotypic) and environmental factors. Some characters will be strongly influenced by the environment, while others will be more directly determined by the genes being expressed (i.e. have a higher heritability).

The latter have the most immediate potential as targets for genetic engineering. For example, most fibre properties are significantly influenced by genes, with heritability estimates varying between approximately 40 and 80% for most fibre parameters (May, 1999).

4.3.2 Gene discovery in cotton

The use of transgenic plants for the generation of improved cotton varieties relies firstly on the identification of useful genetic material that can be incorporated into existing commercial varieties. However, identifying and locating genes for agriculturally important traits is currently the most limiting step in the transgenic process. We still know relatively little about the specific genes required to enhance yield potential, improve stress tolerance, modify chemical properties of the harvested product, or otherwise affect plant characters. As previously discussed, many traits are polygenic, such that identifying a single gene involved with a trait is often not possible. Even in the case of single genes with large effects, simple identification is normally insufficient and scientists must understand how a gene is regulated, what other effects it might have on the plant, and how it interacts with other genes active in the same biochemical pathway.

A clear place to begin the search for useful genes is in the germplasm of the cotton species themselves. A number of molecular genetic techniques have been employed in this work, including isolation of genes on the basis of their known function in another species, characterisation of genes expressed specifically in particular tissues and, more recently, comprehensive analysis of gene expression using cDNA microarrays and random sequencing of expressed sequence tags (ESTs).

The four phases of cotton fibre growth and development are regulated by the expression of several thousand genes in the fibre cell (John and Crow, 1992). These genes are often expressed in both cotton fibres and other plant tissues, although a proportion (perhaps several hundred) are expressed predominantly or exclusively in the fibre (Ji *et al.*, 2003). Genes that are preferentially expressed in the fibre are likely to have important functions in normal fibre development and elongation and these have been the focus of numerous molecular studies (reviewed by Wilkins and Jernstedt, 1999). A referenced selection of fibre-expressed genes is presented in Table 4.1. In addition, expressed sequence tags (ESTs), generated by the random sequencing of cDNA clones, have been assembled by a number of research groups from fibre libraries of both diploid and tetraploid cotton, such that there are now many thousands of cotton ESTs in the public databases (e.g. see Arpat *et al.*, 2004, Haigler *et al.*, 2005).

Whilst we can assign putative functions for cotton genes on the basis of their sequence similarity to known genes, functional analysis of the genes

Table 4.1 Genes expressed in elongating cotton fibres

Gene	Function or putative function	Reference(s)
Cell wall development		
Expansins	Cell wall loosening and extension	Orford and Timmis, 1998; Ruan *et al.*, 2001; Harmer *et al.*, 2002
FKS1	β-1,3-glucan synthase	Cui *et al.*, 2001
Cellulose synthases	Cellulose synthesis and deposition	Pear *et al.*, 1996; Kim *et al.*, 2002; Peng *et al.*, 2002
Proline-rich proteins	Cell wall components	John and Keller, 1995; Orford and Timmis, 1997; Tan *et al.*, 2001
Sucrose synthase	Supply of UDP-glucose for cellulose synthesis	Ruan *et al.*, 1997, 2003
Reversibly glycosylated polypeptide (*GhRGP1*)	Non-cellulosic polysaccharide biosynthesis	Zhao and Liu, 2001
Chitinase-like genes (*GhCTL1* and *GhCTL2*)	Cellulose synthesis	Zhang *et al.*, 2004
Cytoskeleton components		
α-tubulin, β-tubulin	Microtubule subunits	Dixon *et al.*, 1994; Whittaker and Triplett, 1999; Dixon *et al.*, 2000; Li *et al.*, 2002
Actin genes	Actin cytoskeleton	Li *et al.*, 2005
Lipid metabolism		
Lipid transfer proteins	Cutin deposition, antipathogenic activity	Ma *et al.*, 1995; Ma *et al.*, 1997; Liu *et al.*, 2000; Orford and Timmis, 2000
Acyl carrier protein	Fatty acid synthesis	Song and Allen, 1997
Protein and secondary metabolism		
GaWRKY1	Transcriptional regulation of gossypol biosynthesis	Xu *et al.*, 2004
Ubiquitin-conjugating enzymes	Ubiquitin-mediated protein degradation	Zhang *et al.*, 2003b
Signal transduction and transcriptional regulation		
MYB transcription factors	Fibre differentiation and development	Loguercio and Wilkins, 1998; Suo *et al.*, 2003
Brassinosteroid insensitive 1 (*GhBRI1*)	Brassinosteroid signal transduction, fibre growth and development	Sun *et al.*, 2004a
Annexin	Signal transduction (ATPase/GTPase activity)	Shin and Brown, 1999

Table 4.1 Continued

Gene	Function or putative function	Reference(s)
Transporters		
ABC transporter (*GhWBC1*)	Osmotic regulation during fibre development	Zhu *et al.*, 2003
Sucrose and potassium transporters	Critical function in regulating fibre osmolality	Ruan *et al.*, 2001
Tonoplast intrinsic protein (δ-TIP)	Osmoregulation	Ferguson *et al.*, 1997
Vacuolar H^+-ATPase	Osmoregulation	Hasenfratz *et al.*, 1995
Analyses of multiple genes, coordinate gene expression		
Osmoregulatory genes	Osmoregulation and maintenance of turgor	Smart *et al.*, 1998
Fibre-specific transcripts	Genes specifically found in elongating fibres, isolated by differential screening techniques	John and Crow, 1992; Orford and Timmis, 1997; Smart *et al.*, 1998; Ji *et al.*, 2003; Haigler *et al.*, 2005

isolated in cotton studies has been slowed by a lack of comprehensive sequence information for the cotton genome and the time and resource-intensive technology required to generate transgenic cotton (see section 4.4). Detailed physical and genetic maps of the *G. hirsutum* genome are under construction by a number of groups (see section 4.2), but the size and complexity of the allotetraploid genome (estimated at 2.2–2.9 $\times$ 10^9 basepairs (bp)) has discouraged a comprehensive sequencing effort similar to the *Arabidopsis* and rice sequencing initiatives.

4.4 Genetic transformation of cotton

Genetic engineering offers a directed method of plant improvement whereby one or a few traits are selectively targeted for introduction into the crop plant. The first transgenic plants were created in the early 1980s and included laboratory specimens of tobacco, petunia and sunflower. A transgenic plant contains a single gene or a few genes that have been artificially inserted into its genome, instead of the plant acquiring them through fertilisation along with an entire haploid chromosome set. The genetic process by which this occurs is termed transformation. The inserted gene sequence, known as the transgene, is stably inherited and expressed in the progeny of subsequent generations and may originate from a close relative, another unrelated plant, or from a completely different species, even a bacterium. Genetic transformation requires two fundamental steps: introduction of the gene and regeneration of intact plants.

4.4.1 Transfer of genes into cotton

The most common method for engineering genetically modified plants uses the remarkable biology of the soil-borne bacterial pathogen *Agrobacterium tumefaciens*. Naturally occurring *Agrobacterium* infect damaged plant tissue and inject their DNA into the cells of the plant. The DNA stably integrates into the DNA of the plant and alters plant metabolism to produce conditions favourable to bacterial growth (visible as 'crown gall' disease). Wildtype *Agrobacterium* has been modified to remove its pathogenic characters and can be used to transfer any desired gene into the plant genome. The first successful *Agrobacterium*-mediated transformation of cotton (Firoozabady *et al.*, 1987; Umbeck *et al.*, 1987) paved the way for commercial release of the first generation of transgenic cotton (Perlak *et al.*, 1990) and most transgenic cotton grown commercially today was originally transformed using this method. Although used widely in cotton biotechnology and with a number of success stories, *Agrobacterium*-mediated transformation is not without its problems. Most notable is its limitation to a few specific cultivars which can be regenerated in tissue culture (see below).

Direct gene delivery systems, without using a bacterial vector, were developed by the biotechnology sector especially for recalcitrant species or those without established transformation protocols. The premise of such delivery systems is to introduce genes directly into the host genome in a manner which is genotype-independent and bypasses tissue culture-related regeneration difficulties. In cotton the methods which have been investigated include direct transfer of DNA into protoplasts and particle gun bombardment.

Although direct transformation of cotton protoplasts has been reported (Peeters *et al.*, 1994), the isolation of protoplasts is a difficult procedure and the method has not been extended beyond the easily regenerable varieties. Microprojectile bombardment (or 'biolistics') employs high-velocity metal particles to deliver biologically active DNA into plant cells, and its discovery was seen as a way for effective gene transfer into tissues and species that are otherwise inaccessible to genetic modifications using recombinant DNA techniques. Genetic engineering of such recalcitrant crops as soybean and rice is now possible and in some cases routine. A number of different cotton varieties, including a few in commercial production, have been transformed by biolistic bombardment (Wilkins *et al.*, 2000). However, this gene delivery system is beset by a number of disadvantages and is certainly not a panacea; major technical and scientific barriers need to be overcome to bring the technology to its full potential (Wilkins *et al.*, 2000).

4.4.2 Regeneration of transgenic cotton plants

The second requirement of transformation, the generation of fertile plants derived from single cells, has proven to be particularly difficult to surmount in cotton. The development of cell culture techniques that permit efficient DNA delivery, selection of transformed cells and regeneration to normal transgenic plants has involved many years of research and all available systems for cotton are inefficient compared with more amenable species such as tobacco.

Somatic embryogenesis is the process by which plant embryos are generated from single isolated plant cells, rather than via the normal reproductive process. It is the most common and reliable technique for the recovery of whole cotton plants from single transformed cells. First reported in cotton by Firoozabady *et al.* (1987) and Umbeck *et al.* (1987), somatic embryogenesis involves the *Agrobacterium*-mediated transformation of cotton cells with constructs containing antibiotic selectable marker genes, followed by extensive tissue culture to generate embryogenic callus, somatic embryos and (after approximately 12 months) whole transgenic plants. After antibiotic selection and tissue culture, a high percentage of somatic embryos are germline transformants derived from single cells, such that several independently transformed lines may be generated in a single transformation (Leelavathi *et al.*, 2004). The main disadvantage with somatic embryogenesis is that the process is poorly understood and highly genotype-dependent, with many elite cotton varieties having a low regeneration potential. The strategy used internationally is to first transfer the gene of interest to a variety with high embryogenic potential (usually Coker), and then introduce the trait into a commercial line by backcrossing. This procedure adds several years to the development of an elite transgenic variety.

In recent times there has been an increasing focus on the direct transformation of meristems, shoot apices and protoplasts in cotton genetic engineering (Wilkins *et al.*, 2000; Li *et al.*, 2004), in an effort to bypass the genotype dependence associated with somatic embryogenesis. In this case whole plants are generated in as little as three months, but the frequency of stable germline integration events is low. That is, the transgene cannot be passed on to the progeny. An improvement in the procedure is the use of vacuum infiltration to directly transform pollen (Li *et al.*, 2004), which is then used to fertilise cotton plants. This simple technique is *Agrobacterium*-mediated but does not require tedious preparation of target explant or tissue culture to regenerate plants. Somatic hybridisation provides another potential method for cotton transformation, and is a protoplast-based technique that permits the combination of genomes from sexually incompatible species. Sun *et al.* (2004b) applied this method to generate a fusion between Coker 201 (*G. hirsutum*) and a wild variety (*G. klotzschianum*). Although confirmed somatic hybrids were produced, the stability of the hybrids was unknown and several rounds of backcrossing will be required to generate a novel hybrid cultivar.

Despite these technical advances, alternative techniques for cotton transformation all suffer from low transformation efficiencies and have perhaps not realised the potential first envisaged for them. In the past five years the research emphasis has returned to *Agrobacterium*-mediated transformation and regeneration via somatic embryogenesis, and this method is likely to remain the preferred method for transformation of cotton, since its advantages significantly outweigh the disadvantages compared to other methods. In addition, recent research has shed light on the process of embryogenesis (Poon *et al.*, 2004) and refined regeneration protocols have significantly increased the range of varieties which can be genetically modified (Sakhanokho *et al.*, 2001; Zhang *et al.*, 2001; Mishra *et al.*, 2003). Such advances have made somatic embryogenesis more effective and led the industry a step closer to transformation of elite cotton cultivars and enhancement of genetic diversity in molecular breeding programs.

4.5 Genetic engineering in cotton

The implementation of transgenic crops has been dramatic over the last ten years, with the driving force behind the biotechnological revolution attributed to only two classes of genes (Willmitzer, 1999). One class confers resistance to herbicides, whilst the other confers resistance to larvae of certain detrimental insects. In cotton, insect pests and competition from weeds contribute substantially to crop losses and to fibre yield and quality. Cotton crops are targeted by a variety of lepidopteran and coleopteran insects, and over 100 weed species have been recorded in cotton fields worldwide (Wilkins *et al.*, 2000). Weeds compete with crop plants for water, nutrients and available sunlight, harbour insect pests and reduce the quality of the harvested cotton fibre by increasing the trash content. Together with conventional crop management practices, growers rely heavily on chemicals to control both insects and weeds. Pesticides are routinely used to control insect populations, but heavy pesticide use encourages the evolution of insect resistance and increases the costs and environmental effects of cotton production. Herbicides may reduce or eliminate the cost of manual or mechanical weeding, but conventional cotton is generally susceptible to herbicide damage. Therefore, the development of insect- and herbicide-resistant cotton has been a major focus of cotton transformation research.

Insect-resistant transgenic cotton (or *Bt* cotton) represents the first major crop genetically engineered for commercial production. It was first developed in the 1980s by Monsanto and is now widely used in commercial cotton production. Grown initially as Bollgard® in the USA and Ingard® in Australia, *Bt* cotton contains one or two *cry* toxin genes from the soil bacterium *Bacillus* *thuringiensis*. The *cry* genes encode crystalline proteins that cause lethal damage to the gut lining (lamae) of insect larvae that feed preferentially on cotton. In contrast with many insecticides, cry proteins are not toxic to mammals or birds and have limited effects on non-target invertebrates. Moreover, field resistance to *Bt* transgenic plants has not been observed since the commercial release of *Bt* cotton in 1996. This suggests that resistance management strategies and the biology of *Bt* action may be successful in preventing the rapid evolution of resistance (see section 4.6). After ten years of commercial production, it is clear that *Bt* cotton has been economically advantageous to growers and has significantly reduced the use of pesticide sprays. In Australia, for example, the planting of *Bt* cotton has reduced pesticide applications by up to 80% per growing season since 1998 (Fitt, 2003).

The large variety of weeds that infest cotton crops and the herbicides available to combat them have been covered elsewhere (Wilkins *et al.*, 2000) and will not be considered in detail here. Most herbicides have a narrow range of effectiveness, so usually a combination of herbicides is required to control all problematic weed species over a growing season. An exception is glyphosate [(*N*-phosphonomethyl)glycine] or Roundup®, a broad-spectrum, non-selective herbicide which is active on most species of green plants but is non-toxic to mammals and fish and rapidly degraded by soil microorganisms (Williams *et al.*, 2000). Roundup Ready® cotton contains a herbicide tolerance gene (*cp4 epsps*) from *Agrobacterium* that confers resistance to glyphosate (Kishore and Shah, 1988). Glyphosate can therefore be used as a foliar spray to control weeds in a young Roundup Ready® cotton crop, and provides growers with an important new tool in weed control.

Crossing of *Bt* transgenic cotton with Roundup Ready® cotton has produced 'stacked' varieties, containing *Bt* toxin genes coupled with herbicide-resistance genes. The benefits of these dual insect- and herbicide-resistant lines encouraged an increase in the planting of transgenic cotton to 28% of the total world cotton crop in 2004 (Lawrence, 2005). In the USA, adoption of all GM cotton, taking into account acreage with either or both *Bt* and herbicide-tolerant traits, reached 79% in 2005 (Fernandez-Corneio, 2005). In addition, over 95% of Australia's cotton growers planted Bollgard®II or Roundup Ready® GM cotton for the 2004–2005 season, translating to over 70% of the crop (CottonAustralia, 2005).

Transgenic varieties with a number of commercially valuable traits other than insect- and herbicide-resistance have also been developed. These varieties have not been commercially released as yet and instead may contribute to conventional breeding programmes. Included are varieties with improved tolerance to desiccation and nutritionally enhanced oilseed. In addition, genetic modification has been used extensively in scientific research aimed at investigating the function of cotton genes, many of which may have a commercial application. Transgenic cotton varieties generated prior to 2000 are reviewed in Wilkins *et al.* (2000), and subsequent reports are presented in Table 4.2 and discussed in the following section.

Table 4.2 Transgenic cotton varieties generated since 2000

Reference(s)	Promoter/transgene cassette	Summary of results
He *et al.*, 2005	Synthetic 'super' promoter derived from *Agrobacterium* mannopine synthase driving expression of a vacuolar Na^+/H^+ antiporter encoded by the *Arabidopsis AtNHX1* gene	Increased fibre yield (accompanied by improved photosynthesis and nitrogen assimilation) under high salt conditions
Light *et al.*, 2005	CaMV *35S* promoter driving expression of the glutathione-*S*-transferase (GST)/glutathione peroxidase (GPX) gene *Nt107* from *Nicotiana tabacum* (tobacco)	Overexpression of *Nt107* in tobacco increased tolerance to a number of stressors (including herbicide, temperature extremes and salt), but these effects were not observed in *Nt107* cotton
Li *et al.*, 2002	β-tubulin gene promoter (*GhTUB1*) driving GUS gene *gusA*	High-level GUS expression only in fibre and primary root tips
Li *et al.*, 2004	CaMV *35S* promoter driving expression of the cellulose synthase genes *acsA* and *acsB* from *Acetobacter sylinum*	Increased fibre length and strength but reduced micronaire
Li *et al.*, 2005	Promoter of actin gene *GhACT1* driving expression of GUS or dsRNA designed to inhibit expression of endogenous *GhACT1* by RNA interference.	GUS expression was detected predominantly in young fibres of *GhACT1*::*GUS* plants. Fibre elongation was significantly reduced in *GhACT1* RNAi plants, indicating a role for *GhACT1* in fibre elongation.
Liu *et al.*, 2002a; Liu *et al.*, 2002b	Soybean lectin promoter driving seed-specific expression of antisense or hairpin RNA to alter fatty acid composition of cottonseed oil by silencing fatty acid desaturase genes *ghSAD1* and *ghFAD2-1*.	Nutritionally enhanced seeds with high oleic or high steric acid and low palmitic acid content

Table 4.2 Continued

Reference(s)	Promoter/transgene cassette	Summary of results
Martin *et al.*, 2003	CaMV *35S* promoter driving expression of antisense sequence directed against (+)-delta-cadinene synthase	Significant reduction in gossypol and heliocide production in plant tissues (especially leaves)
Ruan *et al.*, 2003	Strong S7 promoter of the subterranean stunt virus driving expression of sense and antisense sequences directed against sucrose synthase	Strong suppression of fibre initiation and elongation
Sanjaya *et al.*, 2005	CaMV *35S* promoter driving expression of antisense sequence directed against movement protein (*AV2*) of cotton leaf curl disease (CLCuD) virus	Preliminary results suggest improved resistance to CLCuD virus infection
Singh *et al.*, 2004	Constitutive promoter driving expression of a hybrid *cry1Ea/cry1Ca Bt* toxin gene	Hybrid *Bt* gene produced a functional *Bt* toxin with enhanced toxicity to the *Bt*-tolerant Lepidopteran pest *Spodoptera litura*
Sunilkumar *et al.*, 2002b	CaMV *35S* promoter driving green fluorescent protein (GFP) gene *mgfp5*-ER	GFP detected in most plant tissues including cotton fibres
Sunilkumar *et al.*, 2002a	Cotton α-globulin promoter driving *gusA*	GUS expressed at high levels in cotton seed and almost entirely absent from other plant tissues
Yan *et al.*, 2004	CaMV *35S* promoter driving expression of *Arabidopsis GF14λ* 14-3-3 protein gene	Improved resistance to wilting and increased photosynthesis under water-deficit conditions
Zhang *et al.*, 2004	Chitinase-like gene promoter (*GhCTL2*) driving *gusA*	GUS expression in numerous cell types during secondary wall deposition

4.6 Recent experiments and future targets for genetic manipulation of cotton

Fibre yield and quality are the major determinants of the value of the cotton crop. Hence, improvement of fibre properties by the introduction of specific genes is emerging as an important area of research in cotton biotechnology. Methods for controlling gene expression within the cotton plant are also receiving increased attention, since tissue-specific expression is likely to optimise the benefits of the transgene. The second generation of transgenic cotton is therefore likely to include varieties with enhanced seed and/or fibre quality in which the expression of a few defined genes is tightly controlled.

Genes with a significant influence on fibre quality have been identified in a number of studies and are attractive targets for genetic manipulation. For example, Ruan *et al.* (2003) demonstrated that suppression of sucrose synthase (SuSy) expression in transgenic cotton prevented fibre formation. It follows that over-expression of SuSy in the elongating cotton fibre could increase fibre length. Similarly, the large number of identified genes that are expressed preferentially or exclusively in the cotton fibre (see Table 4.1) are likely to have important roles in fibre development, and manipulation of their expression may improve fibre characteristics. Li *et al.* (2004) generated transgenic cotton expressing two cellulose synthase genes (*acsA* and *acsB*) from the bacterium *Acetobacter xylinum*. The fibres of the transgenic plant were approximately 15% longer and 17% stronger than wildtype, suggesting that cellulose synthase genes may be useful in improving fibre properties.

Gene expression is primarily regulated by regions of DNA known as promoters. The majority of transgenic cotton varieties contain a transgene regulated by a strong or constitutive promoter such as the *35S* promoter from the cauliflower mosaic virus (CaMV) (see Table 4.2 and Wilkins *et al.*, 2000). Constitutive promoters produce a high level of gene expression in most plant tissues. This increases the likelihood of the transgene producing the desired phenotype, but may also have a number of disadvantages. Transgene containment, for example, may be more difficult when the transgene is coupled to a constitutive plant promoter, since plants that gained the promoter-transgene cassette through outbreeding would be likely to express the transgene (see section 4.7). Similarly, excessive levels of transgene protein may have unintended environmental or phenotypic effects. These could include the accidental targeting of beneficial insects with a toxin gene, or reductions in viability or yield due to transgene expression in a large number of non-target tissues.

These problems may be avoided by using a tissue-specific promoter to drive transgene expression primarily within the target tissue. This approach may also have the advantage of coupling transgene expression to developmental signals, resulting in developmentally appropriate modifications to the timing and level of gene expression and enhancement of the desired transgenic phenotype. For example, Sunilkumar *et al.* (2002a) used the cotton α-globulin promoter to drive expression of the GUS (β-glucuronidase) reporter gene in transgenic cotton. GUS activity was restricted primarily to the cottonseed, and was enhanced during seed development. This promoter may be useful for the engineering of cottonseed with enhanced nutritional or other properties, but with no effect on other properties of the plant.

Fibre-specific promoters restrict gene expression almost completely to the cotton fibre, and have been used in a number of studies to generate transgenic cotton. These studies have primarily involved investigations of fibre development and promoter activity, but have also included attempts to enhance fibre properties (see Wilkins *et al.* (2000) and Table 4.2). For example, John and co-workers used promoters from the fibre-specific genes *FbL2A* and *E6* to drive expression of the biopolymer synthesis genes *phaA* and *phaB* (John and Keller, 1996; Rinehart *et al.*, 1996). These genes enabled production of the polypropylene-related polymer poly-D(-)-3-hydroxybutyrate (PHB) in the cotton fibre. Fabric spun from PHB-containing fibres demonstrated a slightly lower thermal conductivity than control fabric (John and Keller, 1996). However, no improvements were obtained in other fibre properties, and the benefits were insufficient for commercial production (John, 1999). Li *et al.* (2002) demonstrated that the *GhTUB1* promoter drives gene expression almost exclusively in the fibre of transgenic plants, and may be useful in the genetic modification of fibre properties. A number of other promoters from genes expressed preferentially in the fibre are also promising, however, their expression profiles have not been verified in transgenic cotton (e.g. Hsu *et al.*, 1999; Liu *et al.*, 2000; Wang *et al.*, 2004). Similarly, the effects of coupling a strong fibre-specific promoter to a gene with a strong influence on fibre development (e.g. sucrose synthase) are yet to be reported. In 1999 a report appeared in the popular press (Jingen, 1999) that Chinese scientists had produced transgenic cotton expressing rabbit keratin genes in the fibre. Fibres from the transgenic varieties were reported to have improved strength and thermal properties, and were 60% longer than wildtype fibres. These results are promising, but are difficult to assess since the work is commercially sensitive and has not yet been published in the open scientific or patent literature.

Future improvement programmes are also likely to focus on emerging insect pests of cotton crops, such as aphids and mirids, and on diseases such as seedling diseases, nematodes, bacterial blight, and the fungal infections which cause Verticillum wilt and Fusarium wilt. Despite the large crop losses which occur as a result of diseases, disease-resistant cotton varieties have yet to reach the marketplace. Existing strategies to combat diseases of cotton rely entirely on crop management practices such as farm hygiene, crop nutrition, crop rotation and use of quality seeds and fungicides. Very little is known about the molecular basis of the virulence of cotton pathogens or of plant resistance. Current research includes identification of disease tolerance in existing commercial cultivars, screening wild cotton germplasm for tolerance and therefore presence of useful resistance genes and using molecular tools such as microarrays to compare the activity of genes upon infection of susceptible and more resistant varieties. Other studies are focused on the pathogens themselves, such as genetic comparison between different strains of Fusarium, in order to identify genes involved in pathogenicity.

4.7 Potential impacts of GM crops

Cultivation of genetically modified (GM) crops is standard practice in modern agriculture. The eight years between 1996 and 2003 saw a staggering 40-fold increase in the worldwide acreage planted to GM crops, with 25% of cultivated land devoted to GM crops in 2003 (University of Richmond, 2004). The development and widespread use of transgenic food crops has stimulated intense debate on the potential socioeconomic, health and environmental impacts of genetic modification. Many of the same issues and concerns are applicable to non-food crops such as GM cotton, although debate on GM crops should be reviewed on a case-by-case basis. The following review describes recent research on the possible impacts of GM crops, with a focus on transgenic cotton. Technologies and management strategies designed to reduce the environmental impacts of GM crops are also discussed.

GM crops present a number of potential risks relative to their conventional (non-GM) equivalents (reviewed by Dale *et al.* (2002)). Transgenes that confer a selective advantage (e.g. herbicide resistance) could increase the persistence or invasiveness of crop species, and could produce ‘superweeds’ if transferred to other transgenic varieties or sexually compatible relatives by hybridisation. High-level expression of insect toxins in *Bt* crops could place undue selection pressure on insects to adapt, encouraging the development of resistant populations, and may have toxic effects on non-target insects or other organisms. Antibiotic resistance genes are commonly inserted into GM crops during transformation, and transfer of these genes could encourage the evolution of antibiotic-resistant bacteria. The proteins produced by transgenes could also have an allergenic effect or be unexpectedly toxic to humans or animals, reducing the safety of the GM crop. The incorporation of herbicide-resistance genes in GM crops could encourage increased herbicide use, resulting in an increase in herbicide contamination of soil and water and reduced weed (and hence farm) biodiversity. A more general concern is that multinational corporations will gain excessive control over the cultivation and use of GM crops.

In cotton, the potential for transgene introgression and ‘superweed’ evolution are limited by the biology and agronomy of the species. Cotton is generally self-pollinating and there is limited overlap between cotton crops and sexually compatible relatives (see section 4.2), suggesting that transgene flow into wild relatives is unlikely. There is no evidence to suggest that current varieties of *Bt* cotton and herbicide-resistant cotton are significantly more invasive than their conventional counterparts. However, cotton varieties with novel transgenes (e.g. drought or salt tolerance) that confer a selective advantage may be more invasive, and could encourage the development of ‘superweeds’ in the unlikely event of a gene passing to a wild relative. A number of methods have been proposed for limiting the flow of genes from GM crops to wild relatives. These include the induction of pollen or seed sterility and the manipulation of GM crops to produce seed set without fertilisation (or apomixis) (Daniell, 2002). Kumar *et al.* (2004) reported the development of a cotton variety containing a transgene inserted into the chloroplast genome. The chloroplast displays strict maternal inheritance in most flowering plants (including cotton), and so this method may be useful in preventing the movement of transgenes to wild relatives in pollen. However, Huang *et al.* (2003) demonstrated gene transfer from the chloroplast to the nuclear genome in the pollen of transgenic tobacco. This result suggests that trials of a large number of cotton plants will be necessary to assess whether maternal inheritance effectively prevents gene flow in transgenic cotton.

Although resistance genes have been detected in insects, there have been no field failures of *Bt* cotton due to resistance, suggesting that the insect resistance management (IRM) strategies used with *Bt* crops have so far been effective in minimising and managing the risk of insect resistance (Tabashnik *et al.*, 2003). Several IRM strategies, including both agronomic and genetic approaches, have been used in *Bt* crops, but the 'high dose/refuge' approach is the most widespread (Bates *et al.*, 2005). This approach involves expressing the *Bt* toxin at a high enough level in the transgenic plant to kill all target insects, including individuals with one or two copies of a *Bt* resistance gene, while providing a 'refuge' crop that permits target insect breeding. The refuge crop encourages the mating of resistant and susceptible individuals to 'dilute' any resistance genes in the population, and also discourages the evolution of resistance by reducing selection pressure. The high dose/refuge strategy makes a few assumptions that may be violated in a number of target insects (reviewed by Bates *et al.*, 2005), and the effectiveness of refuges is limited by their size and location and by the level of grower compliance with refuge cropping programmes. Moreover, insect resistance to *Bt* plants can emerge rapidly under laboratory selection (Tabashnik *et al.*, 2003), and resistance to *Bt* sprays has been recorded in greenhouse and field environments (Tabashnik *et al.*, 1990; Shelton *et al.*, 1993; Janmaat and Myers, 2003). These observations suggest that the high dosage/refuge strategy has significantly delayed, but perhaps not prevented, the evolution of insect resistance to *Bt* crops.

The high dose/refuge strategy is likely to be most effective when combined with another IRM approach such as the 'pyramiding' of toxin genes. Pyramiding involves the generation of transgenic plants expressing two or more toxin genes. The probability of any individual insect gaining resistance to both toxins is extremely low, and significantly delays the evolution of resistance. Several pyramided cotton varieties have been developed, including WideStrike® (Dow AgroSciences) and Bollgard®II (Monsanto). These varieties contain a second *Bt* gene in addition to the *cry1Ac* gene present in first-generation *Bt* cottons. Zhao *et al.* (2005) demonstrated that concurrent growth of plants containing one and two *Bt* toxins can encourage the rapid evolution of resistance to the pyramided variety when the two varieties contain an identical *Bt* gene. This suggests that first generation *Bt* cotton should be completely removed from the farming landscape prior to the introduction of two-gene varieties. In Australia, the use of one-gene *Bt* cotton was permitted for only two years after the commercial release of Bollgard®II, and now only two-gene varieties are allowed (CSIRO, 2003; Bates *et al.*, 2005). In addition, a minimum non-*Bt* refuge of 20% is required for two-gene *Bt* cotton, compared with 30% for first-generation *Bt* varieties (CSIRO, 2003). This strategy should significantly reduce the potential for insect resistance to the two-gene varieties, and provides a regulatory model for the full introduction of two-gene varieties in the United States and other countries.

Current varieties of transgenic cotton appear to have few negative impacts on human health or the environment. *Bt* proteins have been extensively studied for toxic effects and are non-toxic and non-allergenic to humans and a large number of vertebrate and invertebrate species (including beneficial insects) (Wilkins *et al.*, 2000; Dale *et al.*, 2002). This contrasts sharply with many synthetic pesticides. The pollen of *Bt* maize was found to have toxic effects on the larvae of monarch butterflies, but the impact on butterfly populations was shown to be negligible under field conditions. *Bt* proteins are stabilised in clay and humic soils and may persist for several hundred days (Stotzky, 2000, 2004), but *Cry1Ac* protein from transgenic cotton appears to degrade rapidly in the field (Head *et al.*, 2002). Processing of cottonseed oil involves complete separation of the oil component from protein, and intact *Bt* proteins or genes have not been detected in the meat or milk of stock fed on *Bt* cotton products (Castillo *et al.*, 2004). Similarly, the enzyme present in Roundup Ready® cotton cannot be detected in cottonseed oil or processed fibres (Sims *et al.*, 1996), and there is no evidence to suggest that the transgene poses a health risk to humans or animals.

Transgenes (including antibiotic resistance genes) could be transferred from GM cotton to bacteria or other organisms during the consumption or degradation of transgenic plant material. However, free DNA is often degraded rapidly in the environment, and horizontal transfer of functional transgenes from GM plants to other organisms has not been documented (reviewed by Dale *et al.*, 2002). Farm-scale evaluations of glyphosate and glufosinate-ammonium herbicide-tolerant GM crops in Britain suggested lower levels of biodiversity than in conventional crops (Squire *et al.*, 2003). This was attributed to a lower number and diversity of weeds (and hence reduced animal food and habitat), since glyphosate and glufosinate-ammonium are significantly less toxic to animals than other herbicides (Giesy *et al.*, 2000). However, the use of glyphosate-resistant crops has permitted a reduction in the use of more toxic herbicides (Smyth *et al.*, 2002). Moreover, reduced biodiversity within a crop can be readily addressed by land management initiatives such as the planting of refuges and/or the conservation of natural vegetation.

The herbicide- and pesticide-tolerance traits in GM cotton provide cotton producers with clear economic benefits. Multinational corporations and government regulators largely control the use and distribution of GM cotton and other crops, but this has not resulted in excessive control over individual producers and has enabled the implementation of coordinated IRM strategies. Technologies designed to restrict the use of genetically modified crops, such as the controversial 'Terminator' seed sterilisation technology (US Patent 5,723,765), have not been used in GM cotton or other crops due to public opposition. These technologies are unlikely to be further implemented provided that licensing mechanisms provide the developers of GM crops with an adequate return on investment.

4.8 Conclusions

Genetic manipulation is not restricted to sexually compatible species and may enable the rapid introduction of commercially valuable traits. Hence, a combination of genetic modification and plant breeding is likely to reduce the time required to develop improved cotton varieties. Biotechnology has been used to develop cotton varieties with a number of improvements including herbicide and insect resistance, stress tolerance and novel fibre properties. Insect- and herbicide-resistant GM cotton varieties have achieved substantial commercial success, and now account for approximately a third of the world cotton crop.

Cotton biology and the management of GM cotton crops address many of the environmental and health concerns relating to genetic manipulation. Hybridisation between GM cotton and related wild species is unlikely, resulting in limited potential for gene flow or the evolution of 'superweeds'. Effective insect resistance management (IRM) strategies have so far been successful in delaying insect resistance to *Bt* cotton, and the maintenance of a high dose/refuge IRM strategy, together with the introduction of pyramided varieties with two or more toxin genes, is likely to further delay or prevent the emergence of resistance. The commercial herbicide- and insect-resistant GM cotton varieties have limited impacts on non-target species and provide a clear environmental benefit by reducing the application of more detrimental pesticides and herbicides. Future genetic manipulation of the cotton crop is likely to focus on the improvement of fibre quality and yield, management of diseases and the control of gene expression in specific cotton tissues.

4.9 Sources of further information

Review articles

A comprehensive review of cotton biotechnology until 2000: (Wilkins *et al.*, 2000).

A report on the global impact of the first ten years of transgenic crops: (Brookes and Barfoot, 2005).
Environmental impact of transgenic crops: (Dale *et al.*, 2002).
Containment of genes in GM crops: (Daniell, 2002).
Emergence of insect resistance: (Tabashnik *et al.*, 2003).
Gene pyramiding in transgenic crops: (Zhao *et al.*, 2005).

Websites

International Cotton Advisory Committee: http://www.icac.org/
World Cotton Database: http://www.econcentral.com/wcd/
Cotton Functional Genomics Centre: http://cottongenomecenter.ucdavis.edu/
International Cotton Genome Initiative: http://algodon.tamu.edu/icgi/

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5
Organic cotton

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5.1 Introduction

Cotton grown without the use of any synthetically compounded chemicals (i.e., pesticides, plant growth regulators, defoliants, etc.) and fertilizers is considered 'organic' cotton (National Organic Program, 2005; Kuepper and Gegner, 2004; Pick and Givens, 2004; Guerena and Sullivan, 2003; Myers and Stolton, 1999; Chaudhry, 1998 and 2003; International Cotton Advisory Committee (ICAC), 1996; Le Guillou and Scharpé, 2000; Marquardt, 2003). However, chemicals considered 'natural' can be used in the production of organic cotton (see Appendix 5.1; Synthetic substances allowed for use in organic crop production) as well as natural fertilizers. The different certification organizations have similar lists for allowed chemicals (e.g., see Official Journal European Union, 2006). *Bacillus thuringiensis* (Bt), a naturally occurring soil bacterium, can be used as a natural insecticide in organic agriculture (Zarb *et al*., 2005). Bt is the bacterium, that produces the insect toxins that scientists use to produce genes for insect-resistant biotech cottons. However, biotech cottons, containing Bt genes, are not allowed to be used for the production of organic cotton – the general reason being that the technique is synthetic not natural.

The production of cotton using organic farming techniques seeks to maintain soil fertility and to use materials and practices that enhance the ecological balance of natural systems and integrate the parts of the farming system into an ecological whole. 'Organic farming is part philosophy and part business sense' according to an article in the *Lubbock Avalanche Journal* of 31 October 2005 (E. Blackburn, 'Organic cotton not all fluff'; http://www.lubbockonline.com/cgi-bin/printit2000.pl).

According to Le Guillou and Scharpé (2000), organic farming originated in England on the theories developed by Albert Howard in *An Agricultural Testament* (1940). 'Biodynamic agriculture', developed from the teachings of Rudolf Steiner in Germany in the 1920s, and 'biological agriculture', developed in Switzerland by Hans-Peter Rusch and Hans Müller, are types of organic farming. There are several principles that characterize certified organic farming: biodiversity, integration, sustainability, natural plant nutrition, and natural pest management (Kuepper and Gegner, 2004). The US National Organic Standards Board adopted the following definition of 'organic' agriculture (National Organic Program, 2002):

> Organic agriculture is an ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity. It is based on minimal use of off-farm inputs and on management practices that restore, maintain and enhance ecological harmony.

'Organic' is a labeling term. For cotton to be sold as 'organic cotton', it must be certified by an independent organization that verifies that it meets or exceeds defined organic agricultural production standards (see section 5.8). To produce 'organic cotton textiles', certified organic cotton should be manufactured according to organic fiber processing standards/guidelines (see sections 5.5 and 5.8.5). Regulations are important because they standardize criteria for organic production and post-harvest handling/processing that will facilitate domestic and international trade. A three-year transitional period from conventional to organic cotton production is required for certification. Cotton produced during this three-year period is described variously as 'transitional', 'pending certification' (in California), or 'organic B' (in Australia). Labels such as 'green', 'clean', or 'natural', which can cause confusion, are used by some manufacturers (Myers and Stolton, 1999). To avoid confusion, this chapter refers to cotton produced by modern organic farming techniques as 'organic cotton'. Regarding organic labeling, according to Laurie Demeritt (2006), for most consumers the word 'organic' is primarily a marker – a word that symbolizes a lifestyle that they want to be part of. Certification or regulation itself and the 'science' behind organic products is not what most consumers care about when buying organic products.

5.2 World organic cotton production

Certified organic cotton was introduced in about 1989/90 and over 20 countries have tried to produce organic cotton (see Table 5.1). Serious efforts have been made, with the help of international and national institutions, mostly from Europe, to produce organic cotton in many African countries (Paul Reinhart AG, 2006). This includes Burkina Faso, Benin, Mali, Tanzania and Uganda, where insecticides and fertilizer were either not used or minimally used even in conventional production (Ratter, 2004). There are small projects in Mali (35 metric tons (MT) in 2003/04, expected to be >300MT in 2006/07 (Garrott, 2006)), Kyrgyzstan (~65MT in 2004/05), and some other developing countries (Anonymous, 2004; Traoré, 2005). Some countries have already stopped organic cotton production for economic reasons but others are expanding their production.

Table 5.1 World organic cotton production

Country	1990/91	1991/92	1992/93	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05
Argentina					75	75									
Australia			500	500	750	400	300	300							
Benin							1	5	20	20	30	38	46	25	67
Brazil				1	5	1	1	1	5	10	20				
Burkina Faso															45
China (PRC)												106	596	1,601	1,870
Egypt	14	45	50	153	600	650	625	500	360	200	200	200	122	122	240
Greece					300	150	125	100	75	50	50				
India			200	250	400	925	850	1,000	825	1,150	1,000	696	855	2,231	6,320
Israel												<425	390	380	436
Kenya								5	5	5					2
Kyrgyzstan															65
Mali													19	35	296
Mozambique						100	75	50							
Nicaragua					20	20	20	20							
Pakistan													256	400	600
Paraguay				100	75	50	50	50					9	60	70
Peru			200	675	900	900	900	650	650	500	550	300	300	404	813
Senegal						1	1	10	50	146	200	–	6	6	27
Tanzania						30	30	100	230	190	180	400	380	600	1,213
Turkey			789	200	463	725	933	1,000	835	7,840	7,697	5,504	12,865	11,625	10,460
Uganda					25	75	75	450	250	246	248	250	500	740	900
USA	330	820	2,155	4,274	5,365	7,425	3,396	2,852	1,878	2,955	1,860	2,227	1,571	1,041	1,968
Zambia															2
Zimbabwe								1	5	5		2	3		
TOTAL	344	865	3,894	6,153	8,978	11,527	7,382	7,094	5,188	13,317	12,035	10,148	19,270	17,645	25,394

Source: Organic Exchange, 2005–06 and ICAC, 2005–06 for most of the data; and Baird Garrott, Paul Reinhart AG (Garrott, 2006), for Turkey, Israel, Mali and Burkina Faso in 2004/05.

In the USA, organic cotton production increased from 330 MT (1,516 US 480-lb US bale equivalents) in 1990/91 to 7425 metric tons (16,338 US 480-lb bale equivalents) in 1995/96 but since then, organic production has declined to about 1,000–1,500 metric tons (4593–6890 US 480-lb bale equivalents) per year (Organic Exchange, 2006; Anonymous, 2004a). In the 1999/00 crop year, Turkey surpassed the USA in organic cotton production and since then has been by far the largest producer of organic cotton in the world (see Table 5.1). In 2003/04, in the USA, 1,008 metric tons (4,628 US 480 lb bale equivalents) of organic cotton were produced on 4,060 planted acres; in 2004/05, 5,550 acres were planted and about 1,480 metric tons (6,814 US 480 lb bale equivalents) were produced; and in 2005/06 6,577 acres were planted, according to 2004 and 2005 surveys of organic cotton farmers reported by the Organic Trade Association (OTA) (Anonymous, 2004a, 2006, 2006a).

In 2001/02 about 14 countries in the world produced about 5,700 metric tons (26,000 480 lb US bale equivalents) of organic cotton, according to OTA, with Turkey, the USA, and India accounting for about 75% of production (Marquardt, 2003). The Organic Exchange and ICAC data for world organic cotton production are higher than the OTA numbers (10,148 MT vs. 5,700 MT in 2001/02; see Table 5.1). In 2004/05, the world production of organic cotton, according to the Organic Exchange (2006), ICAC and Baird Garrott, Paul Reinhart AG (Garrott, 2006), was about 25,394 metric tons (116,600 US 480 lb bale equivalents) [~0.1% of world cotton production, which was about 25 million MT (120 million US 480 lb bales)] (see Table 5.1). The big increases have been since 2001–02, from about 10,000 MT to about 25,000 MT, because of big increases in Turkey, India, and China. The proportion of certified organic wool is similar to organic cotton – the major suppliers are South America (Patagonia) and Australia. Natural fibers like flax, hemp, and silk are not yet produced in any significant quantity as certified organic fibers.

5.3 Why organic cotton?

'Why organic cotton?' is an important question. Consider – is organic cotton more 'sustainable' than conventional cotton; an environmentally preferable product, of added benefit to the environment, farmers, and consumers; or is it essentially a marketing tool or is it both? Proponents of organic cotton and those who market organic cotton products promote the perception that conventional cotton is not an environmentally responsibly produced crop (Myers, 1999; Yafa, 2005; Organic; Exchange, 2006; Patagonia, 2006; Organic Essentials, 2006; Hae Now, 2006; Greenfeet, 2006). Some of the reasons used to support their contentions are that conventional cotton production greatly overuses and misuses pesticides/crop protection products that have an adverse effect on the environment and agricultural workers and conventionally grown cotton fiber/fabrics/apparel has chemical residues on the cotton that can cause cancer, skin irritation, and other health-related problems to consumers. Factual documentation for many of the statements expressed by proponents of organic cotton is lacking and some global corporations base their marketing programs around undocumented, misleading, incorrect, information.

Proponents also indicate that organic cotton is a more sustainable approach (Myers and Stolton, 1999). Organic cotton production is not equivalent to sustainable – either organic or conventional cotton production practices may be sustainable. According to the US Environmental Protection Agency:

> Sustainability has many definitions but the basic principles and concepts remain constant: balancing a growing economy, protection for the environment, and social responsibility, so they together lead to an improved quality of life for ourselves and future generations (US EPA, 2006d).

'Sustainable agriculture' was addressed by the US Congress in the 1990 'Farm Bill'. Under that law, the term 'sustainable agriculture' means (Farm Bill, 1990):

> an integrated system of plant and animal production practices having a site-specific application that will, over the long term;
>
> - satisfy human food and fiber needs
> - enhance environmental quality and the natural resource base upon which the agricultural economy depends
> - make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls
> - sustain the economic viability of farm operations
> - enhance the quality of life for farmers and society as a whole.

Sustainable agriculture has three long-term concurrent goals:

1. quality of life (i.e. to satisfy personal, family, and community needs for health safety, food, and happiness);
2. environmental quality (i.e., to enhance finite soil, water, air, and other resources);
3. economics (i.e., to be profitable).

The most sustainable choice is the one where the net effects come closest to meeting these goals. Sustainable production must supply the world's demand for natural fiber and food; it must maintain environmental quality and the natural resource base upon which the agricultural economy depends; and it must sustain the economic viability of cotton farming operations. If a production system requires significantly more land and significantly more labor to produce the crop and production costs are significantly higher, it is questionable if it is sustainable.

5.3.1 Cotton production/farming practices considerations

As discussed in section 5.4.1, some aspects of conventional farming practices have not always been environmentally sound. Irresponsibly used insecticides and other pesticides/crop protection products can lead to serious consequences in agriculture and, while some of the effects are long term, others are reversible. Excessive use of insecticides can significantly affect the natural biological control system, at the same time as it increases production. Insect populations can continue to increase because of the lack of appropriate cultural operations and the availability of alternative hosts during off seasons. Years ago, as the population of insects increased, the number of sprays increased. Researchers have tried to compensate the natural biological control with artificial rearing of natural enemies, but no significant success has been achieved in most countries. Biotech cottons, which are not allowed to be used in organic cotton production, greatly reduce the use of insecticides, reduced the use of herbicides, and minimize adverse effects on non-target species and beneficial insects (Fitt *et al*., 2004; Wakelyn *et al*., 2004). With biotech cottons there has been a significant return of beneficial insects to the fields, which also has reduced the number of pesticide applications necessary to control insects. The use of insect-resistant cotton plants (e.g., 'Bt cotton') reduces the use of harmful insecticides needed to control certain insect pests in the crop. Use of plants tolerant to a specific broad-spectrum herbicide ('HT cotton') allows this herbicide to be used to remove a range of weed species in the crop without destroying the genetically modified plants themselves. This type of herbicide reduces the need for a greater number of spray treatments with specific herbicides that destroy only a single or a few weed species.

Earlier excessive reliance on crop protection chemicals was a problem in cotton production but according to Hake *et al*. (1996), modern conventional cotton production is part of the solution, not the problem. The cost of crop protection products and the cost of production relative to the selling price of cotton, demands that insecticides, herbicides and other crop protection products are applied judiciously and environmentally responsibly – only when and where necessary to protect the crop, using integrated pest management practices (IPM), integrated weed management (IWM), in some cases, remote sensing/precision farming techniques (GPS and satellite technology), and computer-aided crop and pest management (Australian Cotton Industry, 2005). Reducing input costs drives many producer decisions today.

Crop protection products

Today, it is incorrect to say pesticides/crop protection products are overused and misused in conventional cotton production in developed countries and in many developing countries. Because of better management practices, the use of crop protection products is decreasing in all countries and what is used is heavily regulated in developed countries and regulated to some degree in developing countries.

In 2004, about 8.5% of all global crop protection chemical use (based on sales data in millions of US$) was on cotton (Cropnosis, 2005). Fruit and vegetables consumed about 29% and cereal crops including rice and corn about 35% (Table 5.2). Some organizations suggest that about 680 kg (1,500 lb) of pesticide and herbicide are used per acre to grow cotton – the correct figure, in the USA, where accurate, transparent data are available, is about 0.48 kg (1.06 lb) of insecticide and 0.91 kg (2.0 lb) of herbicide/acre (USDA-NASS, 2004). Total US pesticide used in cotton for 2003 (USDA-NASS, 2004) was about 4.8 kg/ha (4.3 lb/acre) – 6.2 g/kg (0.1 oz/lb) of fiber produced. It is unfortunate that incorrect, misleading, undocumented data regarding the use of crop protection products sometimes is accepted as true and used as a basis for marketing organic cotton by some corporations and organizations.

Historically, health hazards of insecticide spraying, disposal of insecticide containers and many other aspects of insecticide storage, handling and disposal

Table 5.2 (a) World pesticides sold in 2004 by crop and (b) world pesticides sold in 2004 by product type

(a)

Crop	Total sales ($M)	%
Fruit & veg.	9,298	28.7
Cereals	5,136	15.9
Soybeans	3,409	10.5
Rice	3,084	9.6
Maize	3,002	9.3
Cotton	2,745	8.5
Sugar beet	611	1.9
OSR/Canola	482	1.5
Other crops	4,582	
TOTAL	32,349	

(b)

Product type	Total sales($M)	Cotton sales ($M)
Herbicides	14,849	777 (5.2%)
Insecticides	8,635	1618 (18.7%)
Fungicides	7,296	70 (1.0%)
Others	1,569	280 (17.8%)
TOTAL	32,349	2745 (8.5%)

Source: Cropnosis, Ltd Edinburgh, UK.

have caused damage to human life and environment. However, the development of new insecticide products, less persistent and less toxic to humans, has been helpful in reducing risks to human life and the environment. New crop protection products, on the average, cost millions of US$ and take years to develop. In fact, in the USA each new crop protection product is subjected to about 120 separate tests and it costs about US$180–220 million and 8–9 years to develop a new product (from discovery to first sales) (CropLife International, 2005). Tolerances usually are set at about 1,000 times less than the no observable effect level (NOEL) depending on the risk factors (e.g., cancer risk, infants and children's exposure, etc.) used (US EPA, 1999 and 2006a ; US EPA, 2006b (40 CFR 158, Subpart F)).

Since cotton is both a fiber and food crop, any crop protection products that are used in the production of cotton have to meet the same regulations as any food crop. In addition, countries like the USA have strict regulations for approval and use of crop protection products as discussed above (US EPA, 1999, 2006a and 2006b) as well as strict worker protection standards for application of crop protection products, field re-entry (US EPA, 2006), and for storage and disposal of crop protection products and used containers (US EPA, 2006c). This greatly reduces health risks to workers and the environment. No crop protection products registered for use on US cotton and cotton from many other countries are on the list of restricted products that have to be tested to comply with the EU Ecolabel for Textiles (EU, 2002; *Bremen Cotton Report*, 1993). According to USEPA, US pesticide safety is the highest in the world (USEPA, 2006e). Biotech (transgenic) cottons, containing Bt genes, also can greatly reduce health risks to workers from agricultural chemicals (Fitt *et al.*, 2004; Wakelyn *et al.*, 2004) but are not allowed for organic cotton production even though Bt can be used for insect control for organic cotton production.

Crop production

If a lifecycle assessment of cotton production is looked at, it can be seen that all methods of cotton production (see section 5.4) have some practices that are not necessarily environmentally friendly but are necessary to produce the crop. For example, conventional cotton typically uses between 90–168 kg/ha (80–150 lb/acre) of a nitrogen fertilizer as well as about 0–90 kg/ha (0–80 lb/acre) of phosphorus, and about 90 kg/ha (80 lb/acre) of potassium, applied in most cases to fields using some form of conservation tillage. (In the USA in 2003 159 kg/ha (142 lb/acre) of synthetic fertilizers were applied to conventional cotton (USDA-NASS, 2004). Whereas, to replenish nutrients in the soil, organic production uses 6.7–10.8 metric tons/ha (3–5 tons/acre) of poultry manure (Alabama Cooperative Extension System, 2006) or about three times that amount of cattle/dairy manure (about 20–30 MT/ha; (9–15 tons/acre)) (Agronomy Facts 55, 1997) (see section 5.4.4). This presents a problem in containing nutrient runoff into streams (phosphates to surface water can cause eutrophication) (Schmidt and Rehm, 2002) or leaching into groundwater (nitrates in ground water can be a mammalian toxin). Also bio-hazards can be associated with manure, e.g., the H5N1 virus (avian flu) and pathogenic bacteria are carried in poultry manure, the preferred source of manure for organic cotton production. The manure, which may or may not be composted, is applied to fields that have been worked with initial tillage operations, by spreading and incorporating into the soil by two additional diskings (Swezey and Goldman, 1999). These organic production tillage practices of increased tillage can have adverse effects on the soil and can lead to more soil erosion as well as use more fossil fuels. Whereas, over 60% of conventional cotton production in countries like the USA use conservation tillage practices. Conservation tillage leaves more crop residue on the soil surface and also reduces greenhouse gas emissions – by burning less fossil fuel and by sequestering carbon in the soil.

Conventional cotton production controls weeds with herbicides that are applied by integrated weed management (IWM) practices. Organic production, for weed control, uses mechanical cultivation and hand hoeing and other hand practices, which are the main source of ergonomic worker health problems in agriculture. Conservation tillage is difficult or impossible to implement in organic cotton production systems because of the heavy reliance on mechanical cultivation or use of extensive hand labor for weed control. This increases risk of soil erosion and use of fossil fuels for mechanical cultivation.

Organic cotton production does not use synthetically compounded chemicals but does use 'natural' chemicals like sulfur dust and Bt and other biological control agents in pest management and organic acid-based foliar sprays (e.g., citric acid) and nitrogen and zinc sulphate in harvest preparation. These natural chemicals used in harvest preparation are not as effective for leaf drop, which can lead to slower harvesting, reduced grade of the cotton, and increased cost of ginning (Swezey and Goldman, 1999).

Organic cotton is more expensive to produce – results from a six-year study in the USA (Swezey, 2002) showed organic cotton production costs at about 50% higher than those of conventional cotton. Organic cotton usually has lower yields, which requires more land to produce the same quantity of cotton and can have lower grades, which affects economics; and it requires significantly more labor to produce. For example, the growing of organic cotton usually requires many workers with hoes to kill weeds, which increases labor and production costs. It also can require more energy than conventional cotton production because of increase tillage. Differences in cotton production techniques should be considered when assessing the sustainability of organic cotton vs. conventional cotton.

5.3.2 Fiber/fabric/apparel

Another main marketing point that organic proponents suggest is that conventional cotton is covered with pesticides harmful to consumers and that certified organic means 'pesticide residue-free'. This is a common misconception (Kuepper and Gegner, 2004). The facts are that from a residue-free standpoint, there is essentially no difference between conventionally grown cotton and organic cotton.

- In response to numerous inquiries concerning agricultural chemical residues on cotton, the Bremen Cotton Exchange, since 1991, has tested for pesticides residues (herbicides, insecticides, fungicides) on US and other cottons. The results showed that all cotton, including US cottons, satisfy the Eco-Label standard and easily pass the regulations for foodstuffs, 'Thus cotton under German law theoretically can be used as a foodstuff' (*Bremen Cotton Report*, 1993).
- US cotton and cottons grown in some other countries meet the requirements for the current EU Eco-label for textile products (2002) without testing. This is because none of the pesticides that have to be tested is registered by US EPA for use on US cotton as well as registered for use on many other countries' cotton. So, if these pesticides are used, they are being used in violation of regulations.
- 'The customer demand for organically grown cotton is not a residue-free issue' (Fox 1994), since there is no difference between organic and conventionally grown cotton from a residue standpoint.
- In preparation for dyeing and finishing, cotton fabrics undergo scouring and bleaching treatments that would remove any pesticide residues, if they were present (Kuster, 1994).

5.3.3 Summary

In summary, it can be seen that organic cotton production is not any more environmentally friendly or sustainable than current conventional cotton production. It can require more land to produce the same amount of cotton, it can require more labor, and, it costs significantly more to produce. From a consumer residue standpoint, there is no difference between conventionally grown cotton and organically grown cotton.

5.4 Production of organic cotton and how it varies from conventional cotton production

Cotton is produced in over 80 subtropical and tropical countries (59 grow at least 5,000 ha) in the world under a great diversity of farming practices. Cotton production (Hake *et al.*, 1996) is considered highly technical and difficult because of both crop vulnerability to a variety of pests and sensitivities of quality and yield to environmental (e.g., drought and temperature) and nutritional conditions. Current production practices in conventional and organic cotton are similar in some ways and not in other ways depending upon the operation (Guerena and Sullivan, 2003; Myers and Stolton, 1999). If all conventional practices were followed in organic production, organic production would be ineligible for certification as organic cotton. Organic cotton production does not allow the use of most synthetically compounded chemicals (fertilizers, insecticides, herbicides, growth regulators and defoliants) that are registered for use for conventional cotton production or biotech cottons varieties, whereas current conventional cotton production depends on appropriate use of pesticides, fertilizers and other crop protection products/chemicals. Since the use of these products are critical inputs to conventional production as are biotech cotton varieties in some countries, alternative methods are necessary for organic production. Organic production can be a particular challenge on some soils and if pest pressures are high. 'Growing organic cotton is demanding, but with commitment, experience, and determination, it can be done' (Guerena and Sullivan, 2003).

Both organic and conventional cotton production employ crop rotation. For organic production all other crops grown on the organic fields would have to be grown using organic production practices. Also no non-natural crop protection products can be used on organic fields for three years prior to the start of organic production. It also should be noted that many of the environmentally friendly procedures that are used in some organic cotton production are also used in producing conventional cotton – cover crops, trap crops, strip cropping, wind breaks, biological control of insects, including pheromone trapping and mating disruption, etc. (Australian Cotton Industry, 2005; Wakelyn, 1994; Wakelyn *et al.*, 2000). In conventional cotton production computer-aided management based modeling systems, like COTMAN (ICAC, 2005), are used by some to help manage and monitor crop and pest development as well as precision farming/remote sensing (Smith, 1996). Organic cotton production uses some 'IPM systems', which have shown a high potential for success both ecologically and economically, but does not and cannot consider all available IPM techniques – conventional cotton production does. About 60% of USA cotton acreage uses IPM (USDA-NASS, 2001).

5.4.1 Historical background

Before mechanized agriculture and the use of synthetic crop protection products, which began in the 1930s, cotton production practices of planting and cultivation were performed with mule-drawn farm equipment, weeds were controlled by the hoe, the use of fertilizer was sporadic, and the crop was harvested by hand (Lee, 1984). From 1926 through 1945 it required 175 man-hours to produce a 480-lb bale of US cotton; in 2004 three man-hours were required per bale. Table 5.3 compares US cotton acreage and production in the 1930s with US cotton production from 1999–2004. Yields were less than a quarter of what they are today and it took a large amount of land to produce much less product. In 1930 in the USA, 3,159,000 MT (14,517,000 480-lb bales) were produced on 17,534,296 ha (43,329,000 acres) vs. in 2004/05, 5,062,000 MT (23,256,000 480-lb bales) were produced on 5,527,500 ha (13,659,000 acres) – about 12,140,000 ha (30 million acres) to produce about 40% less cotton. Beginning in the 1930s yields began to rise because the use of synthetic fertilizer increased, there were attempts at insect and weed control, which allowed the crop to be managed, and the first steps toward mechanization of the crop began.

Table 5.3 US cotton acreage and production – (a) 1930–1940 and (b) 1999–2004

(a)

	Acreage		Production	
USA crop year	In cultivation July 1* 1000 acres	Harvested	500-lb. bales 1000 bales (metric tons)	480-lb. bales
1930	43,329	42,444	13,932 (3159)	14,517
1931	39,110	38,704	17,097 (3877)	17,809
1932	36,494	35,891	13,003 (2949)	13,545
1933	40,248	29,383	13,047 (2959)	13,591
1934	27,860	26,866	9,636 (2185)	10,037
1935	28,063	27,509	10,638 (2412)	11,081
1936	30,627	29,755	12,399 (2812)	12,916
1937	34,090	33,623	18,946 (4296)	19,735
1938	25,018	24,248	11,943 (2708)	12,441
1939	24,683	23,805	11,817 (2680)	12,309
1940	24,871	23,861	12,566 (2849)	13,090

*Planted acre data not available.
Source: USDA-ERS, Statistics on Cotton and Related Data.

(b)

	Acreage		Production	
USA crop year	Planted 1,000 acres	Harvested	500-lb. bales 1000 bales (metric tons)	480-lb. bales
2000/01	15,517	13,053	16,501 (3742)	17,188
2001/02	15,769	13,828	19,491 (4420)	20,303
2002/03	13,958	12,417	16,520 (3746)	17,209
2003/04	13,480	12,003	17,525 (3974)	18,255
2004/05	13,659	13,057	22,321 (5062)	23,251
2005/06	13,900	13,700	22,752 (5160) est.	23,700 est.

Source: USDA-NASS.

Production agriculture has changed considerably in many ways, since the 1930s. Since then cotton production has shifted from not using synthetic compounded chemicals to the currently chemical based production system and higher yielding varieties with improved quality have been introduced. Organic fertilizers (animal manure) and green manure (decomposed plant matter) were the only sources of replenishment of soil nutrients. Insect pressures from the boll weevil and other insects and plant diseases were mainly controlled through agronomic operations, crop rotations, and mixed cropping in addition to natural biological control. Table 5.4 indicates the amount of yield losses caused by insects and plant diseases in the 1930s.

Cotton is a major cash crop in many countries in the world and cotton production and processing is an important source of income. This has led to increased cotton production. The demands for increased production since the 1930s has mainly been met by increasing yields through the intensive use of chemical inputs, irrigation and the use of higher yielding varieties. Improvements in cotton production have benefited farmers but have involved some environmental and social costs. Organic fertilization and agronomic operations could not cope with the needs of higher cropping intensity that depleted soils. Lower soil fertility resulted in lower yields. Higher cropping intensity provided continuous availability of host plants and favorable conditions for insects to multiply at faster rates. The insect population started building up and researchers turned from natural chemicals to the use of synthetically compounded chemicals to control insects, without necessarily adequately considering the long-term consequences. Herbicides and other crop protection products started to be used. Organic fertilizers were supplemented with inorganic synthetic fertilizers. Economic conditions in

Table 5.4 Reduction from full yield per acre of cotton, by stated causes

USA crop year	Deficient moisture	Excessive moisture	Other climatic	Plant diseases	Boll weevil	Other insects
			Percent (%)			
1930	27.7	2.8	6.3	1.7	5.0	1.9
1931	8.3	2.6	3.5	2.0	8.3	1.8
1932	8.0	3.9	6.1	3.2	15.2	3.1
1933	6.8	2.6	3.7	2.3	9.1	2.2
1934	20.7	1.9	7.3	1.9	7.3	1.6
1935	9.2	3.7	6.5	2.2	8.1	5.0
1936	16.2	1.9	8.4	2.2	4.9	3.0
1937	5.7	1.5	4.1	2.2	5.3	3.0
1938	6.8	3.3	4.0	1.9	9.9	4.2
1939	10.1	4.2	5.9	1.8	8.7	2.2
1940	5.5	6.5	6.5	2.0	6.5	1.9

Source: USDA-ERS, Statistics on Cotton and Related Data the developed countries allowed them to embrace the new chemical based production system faster than developing countries. Governments of developed and developing countries provided subsidies to promote the use of fertilizers and pesticides. In hindsight, the earlier overemphasis on the use of fertilizers and pesticides was done without fully understanding the consequences. Cotton in the USA has a history mostly of strong growth, but some of its history recounts the farming conditions that were environmentally unsound and are discussed above.

5.4.2 Planting seed

Unlike most other field crops, seedcotton cannot be stored for a year and planted the next year. Seedcotton is a perishable commodity that must be separated into fiber and seed by ginning. So farmers usually have to sell their seedcotton and thus lose the possession of the seed. Obtaining the seed from the gin or through a middleman can cause the seed purity to be questionable. Planting seed for organic production is not different from conventional production, except it cannot be a biotech cotton variety – mechanical or acid delinting are options for smooth flow of upland cotton (*G. hirsutum*) seed during planting and extra long staple (ELS) cotton (*G. barbadense*) seed is usually smooth and does not require delinting. In addition the planting seed for certified organic production cannot be treated with synthetic fungicides, insecticides or any other synthetic chemicals, which are used in conventional cotton planting seed. Both organic and conventional planting seed contain calcium carbonate (to neutralize the seed), biological fungicides, and a polymer coating. Seed treatments are necessary to protect the seed from fungi and bacteria which can affect germination and lower yields.

5.4.3 Soil/land preparation (tillage) and planting

Organic agriculture is often incorrectly characterized as addicted to 'maximum tillage' (Kuepper and Gegner, 2004). Soil and seedbed preparation can be about the same for organic production as for conventional but may involve more tillage for preparing soil for planting. Organic production conditions require that soil is rich in organic matter and seed bed preparation begins with working the ground with initial tillage operations. Higher organic matter could also be helpful in better germination, better plant-stand and higher yields, particularly, if other resources are not available for preparing the seed bed. Plant densities are sometimes lower in organic than conventional systems without necessarily sacrificing yield. The resultant changes in the microclimate around the plants can reduce pest populations and improve plant growth parameters (Van Elzakker and Caldas, 1999).

5.4.4 Fertilization

Meeting the nutrient needs of the cotton plant as closely as possible, assures high yields if the crop is properly protected against losses due to pests. Dryland and irrigated cotton take up between 15.7–22.4 kg of N/ha (14 to 20 lb of N/acre) to produce each 45.4 kg (100 lb) of lint (www.ppi-ppic.org). Since soil fertilization needs vary for different soils in the world, the N rate to lint output range is much wider, e.g., in Australia conventionally grown (irrigated) cotton works on a different N fertilizer to lint production ratio. Typical N rates do not exceed 200 kg/ha for return lint yields in excess of 1,500 kg/ha. Organic farming and conventional farming vary greatly in fertilization of the crop. Soil fertility in organic farming is a long-term issue compared to conventional production, where there is more flexibility in precision application and dosage of plant nutrients. In conventional production nutrient applications, particularly nitrogen, can be split into two or three doses in consonance with the plant growth. If the plant is behind or advanced of the normal growth curve, nitrogen applications can be adjusted to match the decreased or increased yield potential. Conventional production can lose a portion of the nitrogen, which is a reason why nitrogen applications are split in smaller doses. Organic production does not have this option. Organic production must start with a good soil fertility status. Soil fertility practices typically include crop rotation, cover cropping, animal manures, and use of naturally occurring rock powders (Guerena and Sullivan, 2003). Livestock manure is the key nitrogen (N) fertilizer for organic farming.

Organic production of cotton as a component of the farming system will build up phosphorus, potassium and micronutrients but the nitrogen level has to be augmented through the use of animal manure (6.7–10.8 MT/ha (3–5 tons/acre) of poultry (16.5–32.6 kg N/MT; 37–73 lb N/ton) or about three times that amount (20.2–33.6 MT/ha; 9–15 tons/acre) of cattle/dairy manure (4.5–4.9 kg N/MT; 10–11 lb N/ton) (Agronomy Facts 55, 1997; Agronomy Series Alabama Cooperative Extension System, 2006)), as the basic fertilizer, along with green manure, crop rotation, nitrogen fixing crops and incorporation of cotton stalks. The total N in poultry manure is slightly less effective as N in an ammonium nitrate fertilizer (Alabama Cooperative Extension System, 2006). Poultry manure contains more N than cattle manure and is preferred for organic cotton production. Conventional cotton production uses a small amount of a nitrogen fertilizer, phosphorous and potassium (see section 5.3; about 89.7–168.1 kg/ha (80–150 lb/acre N), 0–89.7 kg/ha (0–80 lb/acre P), and 0–89.7 kg/ha (80 lb/acre K)).

5.4.5 Water use

Cotton is a drought- and heat-tolerant crop that does not require excessive amounts of water to grow. Cotton requires about 610–660 ha mm (24–26 acre inches) of water during the growing season as rainfall or supplemental irrigation to produce about 750 kg lint/ha of cotton. The yields achieved, which depend not only on water and method of irrigation (e.g., sub-surface drip, furrow, flood irrigation) but many other factors, determine the water use efficiency (WUE) (ICAC, 2003). According to Orgaz *et al.* (1992), cotton WUE is 2.7 kg lint ha^{-1} mm^{-1}. WUE varies considerably between countries – about 227 kg lint/mega liter water in Australia, about 139 kg/mega liter in California, about 136 kg/mega liter in Egypt, and only about 50 kg/mega liter in Pakistan (ICAC, 2003).

Cotton uses about as much water as a Bermuda grass lawn. Proper irrigation management is essential for cotton, and is used to balance vegetative growth with boll development, as well as to manage disease and insect populations. About 35% of the USA acreage receives supplemental irrigation and about 55% of world cotton production comes from irrigated land (ICAC, 1998 and 2003). The delivery method, number of applications, and the amount of applied surface water varies from location to location. Total applied water depends on the soil type, residual soil moisture and water availability. For cotton, furrow irrigation is the preferred application method. Methods should be used to improve irrigation efficiency by minimizing evaporative water loss and reducing labor costs. Without access to irrigation technology to stabilize and optimize cotton production, many more millions of hectares of land would be required to maintain current levels of world output. Conventional cotton production should not require more water/irrigation than organic cotton production as is sometimes alleged, unless there is a great difference in the organic matter in the soil. The water use requirements per acre for conventional and organic cotton should be similar, although if yields are reduced with one system relative to the other, then water use efficiency would also be reduced.

5.4.6 Weed control/management

Control of weeds can be a major problem in cotton production (McWorter and Abernathy, 1992). Cotton production can be affected by a wide variety of weed pests, including, velvetleaf (*Abutilon theophrasti*), pigweed (*Amaranthus* spp.) tropical spiderwort (*Commelina benghalensis*), bermudagrass (*Cynodon dactylon*), yellow nutsedge (*Cyperus esculentus*), purple nutsedge (*Cyperus rotundus*), crabgrass (*Digitaria sanguinalis*), morning glory (*Ipomoea* spp.), common purslane (*Portulaca oleracea*), foxtail (*Portulaca oleracea*), johnsongrass (*Sorghum halepense*), cocklebur (*Xanthium* spp.), etc. Weed control during the cotton production year can be one of the biggest challenges in organic production (Swezey and Goldman, 1999). Elimination of synthetic herbicides in organic production gives rise to a different weed management approach in organic farming vs. conventional farming.

Organic production conditions can result in a wide variety of weeds in the cotton field, but they may be easier to control than conventional cotton. Crop rotation, which is used in both conventional and organic cotton production, reduces the weed problem to some extent. Other current methods of weed management for organically produced cotton include a combination of mechanical cultivation, flame weeding, and other cultural practices, such as hand hoeing, but these manual and cultural operations may not be adequate to produce clean fields (Guerena and Sullivan, 2003). If there are weeds in the cotton field, they could harbor insects and also steal nutrients from cotton. Smaller growers can handle the weed management issue but it can be a concern for large organic growers.

5.4.7 Insect control/management

Cotton is attacked by a wide variety of insects (King *et al.*, 1996) including the American cotton bollworm (*Helicoverpa armiger*), pink bollworm *(Pectinophora gossypiella)*, tobacco budworm (*Heliothis virescens*), spiny, Egyptian, and spotted bollworms (*Earias spp.*), red or Sudan bollworm (*Diparopsis spp.*), cutworms (*Agrotis spp.*), beet armyworm (*Spodoptera exigua*), armyworms (*Spodoptera spp.*), boll weevil (*Anthonomus grandis*), cotton aphid (*Aphis gossypii*), silver leaf whitefly (*Bemisia argentifolii*), sweetpotato whitefly (*Bemisia tabaci*), lygus (*Lygus spp.*), alfalfa looper (*Autographa californica*), cabbage looper (*Trichoplusia ni*), thrips (*Thrips spp.*), spider mites (*Oligonchus spp.* & *Tetranychus spp.*), etc. Synthetic chemical insecticides used in conventional cotton production are not allowed in organic production. This is one of the most significant changes/differences in production practices with organic farming. Elimination of synthetic insecticides can be the biggest savings for organic producers. These savings could be used to improve other field operations and management of crop. Organic cotton producers not only save in cost of insecticides, but also in spray equipment.

Pest management in organic farming is directed toward enhancing and utilizing the natural balance of useful pests. The primary insect and mite pest management tools of organic growers are field strips of vegetation as beneficial insect habitats (i.e., trap cropping, strip cropping, and border vegetation), regular and systematic monitoring of the population levels of pests, natural predators, parasites, and the release of biopesticides/biological control agents (i.e., bacteria, like Bt, viruses, and fungal insect pathogens) (Swezey and Goldman, 1999; Guerena and Sullivan, 2003). Organic cotton production also may use 'natural' chemicals like sulfur dust. The first two years of transition from using synthetic insecticides could be difficult but by the third year, natural balances usually build up reducing the need for insecticides. The need for laboratory rearing of biological control agents and utilization of other cultural control measures is more necessary in organic farming than in conventional production. While conventional cotton production is dependent on insecticides for control of pests, conventional cotton production also uses integrated pest management (IPM) systems that apply a number of different controls on insect pests as well as pesticides including biotech cotton, systematic monitoring of the population levels of pests, beneficial natural predators and field strips of vegetation as beneficial insect habitats.

5.4.8 Disease control/management

Cotton may require management for seedling disease, soil disease, boll rot, and foliar disease (Guerena and Sullivan, 2003). Causes of cotton diseases include fungi, bacteria, viruses, and nematodes. Seedling diseases are due to soil-borne fungi (primarily *Rhizoctonia solani, Phyium* spp., and *Thielaviopsis basicola*). The most common fungal soil diseases of economic significance are Fusarium wilt (*Fusarium oxysporum*), Verticillium wilt (*Verticillium dahliae*), and Texas root rot (*Phymatotrichum omnivorum*). Boll rots are a problem where bolls are starting to open or have been damaged by insects in areas of high rainfall and humidity. Foliar diseases include bacterial blight (*Xanthomonas campestris*), common in areas with warm, wet weather during the growing season, alternaria leaf spot (*Alternaria macrospore*), and cotton leaf crumple virus, which can be vectored by silverleaf whitefly (*Bemisia argentifolii*).

Most cotton diseases are controlled through the use of naturally resistant/tolerant cotton varieties to pathogens (host-plant resistance) or creating conditions unfavorable for pathogens to grow and spread. Resistant varieties used in conventional production are the best option against most diseases. If the soil is well drained due to sufficient organic matter and proper crop rotations are followed (which is usually the case in organic farming) diseases may not be a major concern for organic production. Control measures under organic farming conditions (such as sanitation and planting when the soil is warm) are more important compared to conventional farming conditions, since synthetically compounded crop protection products cannot be used in organic production.

5.4.9 Nematode control/management

Nematodes are soil-dwelling, worm-like animals which cause damage that is usually considered soil disease. The main nematodes affecting cotton are reniform (*Rotylenchulus reniformis*), root-knot (*Meloidogyne incognita*), and Columbia lance (*Hoplolaimus columbus*). The purpose of nematode management is to keep nematode population densities at a low level during the early growing season to allow cotton plants to establish healthy root systems (National Cotton Council, 2006b). The goal is not the complete elimination of nematodes, because they are a normal part of the soil microbial population and most are beneficial.

Use of tolerant varieties of cotton and cultural practices are the control measures used for organic farming. Many early resistant cotton varieties were developed primarily to control the root-knot nematode/fusarium wilt complex. Currently, most commercial varieties have some tolerance to this complex, but very few varieties of cotton show significant tolerance to other major cotton nematodes. Effective cultural practices, include, tillage, water management, clean equipment, and crop rotation. Conventional cotton production, in addition to using tolerant varieties of cotton and cultural practices, also when necessary, uses synthetically compounded crop protection products that cannot be used in organic cotton production. Chemical controls include fumigants and non-fumigants. Fumigants are non-selective materials that vaporize when applied in the soil and as gases, they move up through air spaces in the soil, killing nematodes and other microorganisms. Non-fumigants are available in liquid or granular forms that are applied either in a band or in the seed furrow at planting. Non-fumigants protect plants early in the growing season allowing them to produce deep, healthy root systems.

5.4.10 Harvest preparation, boll maturation, and harvesting

Hand picking is the method used in about 75% of world production. Hand picking of organic cotton is the same as for conventional cotton. Hand picking can result in cleaner cotton, if only the fiber is removed from the boll during hand harvesting, instead of the whole boll, and other contaminants from the workers and the field (e.g., synthetic fibers from clothing and plastic), natural 'organic matter' from inadequate defoliation, and 'inorganic matter' from sand or dust, are avoided. In addition, there can be seed-coat fragments and stickiness (insect and plant sugars). Efficient ginning of the cotton also makes a difference in trash/contamination in the lint. According to the 'Cotton Contamination Surveys 1999–2001–2003–2005' by the International Textile Manufacturers Federation (ITMF) (ITMF, 2005), the most contaminated cottons originate in India, Turkey, and Central Asia (Uzbekistan and Tajikistan), all hand picked cotton, whereas the cleanest cottons can be sourced from the US, which is all machine harvested, Zimbabwe, and selected West African cottons (Senegal and Chad), which are hand harvested.

If machine picking (picker or stripper harvesting) is used to harvest the cotton, usually defoliation is necessary, particularly where timely frost does not occur. Defoliation is a significant obstacle to organic production (Guerena and Sullivan, 2003). Synthetic chemical defoliants are prohibited for use on organic cotton and no other strong choice is available for mechanized farmers to get rid of green leaves, except frost. 'Natural' chemicals like organic acid-based foliar sprays, like citric acid, and nitrogen and zinc sulphate can be used in harvest preparation in organic production as well as flamers. Ceasing irrigation can assist leaf drop and boll maturation in some growing areas. These techniques help boll maturation, plant desiccation, and leaf drop, but they usually do not achieve the same results as the synthetic materials used in addition to frost in conventional cotton production (Swezey and Goldman, 1999).

Green leaves (leaf drop) must be removed prior to harvesting because low leaf drop slows the harvest, reduces the grade of the cotton, and increases gin costs (Swezey and Goldman, 1999). Frost helps to drop leaves but it may not occur or, if it does, it may not be advisable to wait for the freezing temperatures when most bolls on the plant have already opened. Damage to cotton quality as well as increases in aflatoxin levels, in areas where it is prevalent, are related to harvest date. So it is always advisable to harvest as soon as possible after a sufficient number of bolls have opened. Development of naturally leaf-shedding varieties is another choice, but no such varieties have been commercialized so far. Proper water management could also help to enhance leaf shedding. But, in order for organic cotton to progress with large-scale growers, alternative defoliants need to be developed that are acceptable under organic conditions since the current practices of using organic acid-based foliar sprays and nitrogen and zinc sulphate in harvest preparation are not always very effective (Swezey and Goldman, 1999).

5.5 Post-harvest handling/processing of organic cotton

To protect organic integrity, all stages of processing, storage, and transport of organic fiber products should be segregated and protected from comingling with conventional fiber products and not come into contact with prohibited materials or other contaminants. Seedcotton (consisting of cotton fiber (lint) attached to cottonseed plus plant foreign matter) obtained at harvest is a perishable raw agricultural commodity. The seedcotton is transported to the ginning plant in trailers or modules, or is stored in the field in modules. When the cotton is stored in the field in modules, the modules have to be properly covered to protect the cotton from wet weather to prevent loss of quality. Ginning, which is part of the harvest (Wakelyn *et al.*, 2005), is the process of removing and separating lint fibers from the seed and plant foreign matter (Anthony and Mayfield, 1994). Cotton essentially has no commercial value/use until the fiber is separated from the cottonseed and foreign matter at the gin.

The three major post-harvest processes in the conversion of raw cotton fiber into a finished fabric are: yarn manufacturing (spinning, or yarn making), fabric manufacturing (weaving, knitting, or non-woven), and dyeing and finishing. To produce organic textiles, certified organically produced cotton should be processed according to processes certified as organic (Tripathi, 2005). It should be spun, woven/knitted, and processed with energy-efficient and toxic-free methods. All processing agents used must meet requirements for toxicity and degradability/eliminability. All wet processing facilities should have water conservation and resource management in place and should conform with waste water disposal standards.

The Organic Trade Association (OTA) developed voluntary organic standards for fiber processing standards (post-harvest handling, processing, recordkeeping and labeling; 'Organic Trade Association's Fiber Processing Standards') in 2004 (Murray and Coody, 2003; OTA, 2005a). They cover all post-harvest processing, from storage of organic fiber at the gin or warehouse, to yarn manufacturing, fabric manufacturing, wet finishing, quality assurance, and labeling and list chemicals that can be used (see section 5.8.5). The Organic Exchange (OE) developed voluntary guidelines, the Organic Exchange 100 standard (OE 100), and the OE Blended Standard to help companies producing organic products understand what they need to do to track and document the purchase, handling and use of organic cotton in their products (see section 5.8.4).

5.5.1 Ginning

Organic cotton has to be ginned separately from conventional cotton so the gin has to be thoroughly cleaned prior to ginning the organic cotton and organic cotton is stored in a segregated section of the gin yard unless a gin is designated only for organic production. The movement and quarantine of gin trash/by-products is sometimes necessary to reduce transmission of soil/plant borne pathogens from conventional and organically raised cotton. After cleaning the gin, the first bale of cotton ginned is considered 'conventional cotton' in case any conventional lint still remained in the ginning system. Ginning is no different for organic and conventional cotton unless there is high trash content. Ginning operations are normally considered to include conditioning (to adjust moisture content), seed-fiber separation, cleaning (to remove plant trash), and packaging. Upland cottons are ginned on saw gins, whereas roller gins are used for ELS cottons. Higher trash in seed cotton requires additional cleaning (i.e., stick machines, incline cleaner) at the gin before ginning the seed cotton and additional cleaning (lint cleaners) after the lint fiber has been through the gin stand and before baling. Additional mechanical processing can have an effect on fiber quality as well as cause higher gin loss. In the case of mechanical harvesting, if the picker or stripper harvesters have picked green leaves along with cotton because harvest aid chemicals were not used where necessary, there could be a noticeable impact on quality.

5.5.2 Yarn manufacturing

The textile manufacturing of organic cotton from opening, blending, carding, drawing, combing, if necessary, roving, spinning into yarn and winding is no different than for conventional cotton, particularly if no processing oils are used. Processing oils are not usually necessary because of the natural waxes on the surface of cotton. Sometimes biodegradable oils are used in ring spinning, but these oils are removed by fabric scouring and bleaching prior to dyeing.

Prior to yarn and fabric manufacturing all lines must be thoroughly cleaned to remove conventional cotton or lines have to be dedicated to organic cotton yarn and fabric manufacturing. The first step in textile mill processing is opening and blending (Wakelyn, 1997). The quality parameters of cotton (i.e., length, length uniformity, strength, micronaire (an indicator of fineness and maturity), color, leaf, and extraneous matter) vary considerably from bale to bale and from growing region to growing region. To ensure consistency in processing efficiency and product quality, many cotton bales of similar quality are 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 up to 100 bales of cotton at a time, thereby ensuring consistency of fiber properties along the length of the yarn. If the cotton is not blended properly there can be problems later with the dyed (e.g., barre) and finished fabric/textile. Since the supply of organic cotton is limited, it may be difficult sometimes to get sufficient bales of organic cotton with similar properties from one growing area, to blend to avoid these quality problems.

5.5.3 Fabric manufacturing

Weaving, knitting or non-woven fabric manufacturing of organic cotton and conventional cotton should be similar as long as natural starch sizes are used. Weaving preparation (i.e., direct and indirect warping and sizing) is an important process in the production of woven fabric, especially for high-speed weaving, and will continue to be so depending on the future technology of woven fabric production (Diehl, 2004). It requires the yarn to be coated with starch or some other 'size', prior to weaving for extra strength and abrasion resistance. Sizing is the only operation that may have some environmental concerns in weaving. The size has to be removed, prior to dyeing and finishing. If starch is used for sizing, it is normally removed with enzymes and scouring. The starch size is not recycled and has to be handled in a manner that does not cause water pollution or other environmental problems. Starch breaks down during the enzymatic treatment and is removed by washing. It consumes oxygen thus lowering oxygen (biological oxygen demand, 'BOD') in the washing water. Polyvinyl alcohol size, usually used in conventional sizing, can be removed by scouring and can be recycled. It is, therefore, considered to be more environmentally friendly than 'natural' starch. There is research under way on sizeless weaving, but there are no commercial processes. Sizing is not required in the manufacture of knitted fabrics, but knitting oils are usually used. They are removed during normal scouring in preparation for dyeing and finishing. Non-woven fabric manufacturing does not require the use of natural or synthetic sizes either, but various additives can be used, which would need to be considered natural.

5.5.4 Preparation, dyeing, and finishing

Typically, in normal preparation for dyeing or printing and finishing, raw (greige) fabric is singed, desized, scoured, bleached, and mercerized (Cotton Incorporated, 1996, Wakelyn *et al.*, 2006). These treatments remove natural non-cellulosic constituents/impurities and increase the affinity of cellulose for dyes and finishes. Caustic soda (sodium hydroxide) is commonly used in scouring which removes natural waxes and impurities from the fabric. Bleaching is done with hydrogen peroxide but without optical whiteners and the temperature must be over 60 °C, which increases energy consumption. Bleaching removes residual impurities and changes the fabric color to clear white rather than the off white it was before bleaching. If chlorine bleaching methods, which are very rarely used today, are used it is sometimes incorrectly claimed (Green Cotton Thailand, 2006) that 'dioxins' are created. Cotton is not a ligninified cellulose and it has been shown that dioxins are not formed by chlorine bleaching of cotton (Wakelyn, 1994). Mercerization, treatment of the fabric with strong aqueous solution of sodium hydroxide, is done to add luster, strength and dye absorption properties of the fabric. Fabric appearance and strength are greatly enhanced by mercerization. Appendix 2 contains a list of some chemicals allowed and prohibited in preparation, dyeing, printing and finishing of textiles that follow various voluntary organic standards for wet finishing of organic cotton textiles.

The fabric is dyed after preparation. For organic processing, all dyes should conform to the Ecological and Toxicological Association of Dyes and Organic Pigments Manufacturers (ETAD) Guidance Documents regarding residual heavy metals and aromatic amines found in finished products (ETAD, 1997; EU Directive, 2002). Dyeing of organic cotton should use dyes free of heavy metals, e.g., chromium, and formaldehyde or other hazardous chemicals. A closed water circuit dyeing process is used to filter and neutralize the waste (Tripathi, 2005).

Conventional cotton textiles are dyed with an extensive number of dye classes, including reactive, azoic, direct, indigo, pigment, sulfur, and vat dyes (Cotton Incorporated, 1996). The first choice to be used on organic fabric, when applicable, should be plant-based natural dyes. But commercially available natural dyes are extremely limited, usually require fixing agents (metal-based 'mordants', which can be pollutants), high temperatures, can have poor light and wash fastness, and can have variation in color tones. The next choice should be low impact dyes. Many dyes used in conventional dyeing of cotton fabric are synthetic and are prohibited for use on organic cotton textiles. However, some 'non-toxic' dyes that are used on conventional textiles, including some azo reactive dyes, are allowed to be used on organic cotton textiles. Azo dyes, which by reductive cleavage upon degradation can release one or more of 22 aromatic amines (ETAD, 1997; EU Directive, 2002), are prohibited for use in organic processing. These dyes are also prohibited for use in the EU and are no longer used in the USA and most other countries. Pigment dyes, except for non-toxic, naturally occurring pigments, e.g., indigo and clays, are also prohibited in organic processing. Only printing methods based on water or natural oils are allowed in organic processing. Printing using heavy metals as discharging agents is prohibited.

After dyeing/printing fabrics can be treated with chemicals to convey flame resistance, water repellence, durable press/crease resistance, etc. Chemicals that can release or contain formaldehyde are prohibited. Stone washing and other environmentally harsh textile finishing processes that use auxiliary additives and large amounts of water are prohibited in organic processing. Products that meet criteria established by ecolabels are intended to be a market-oriented tool to guide consumers. However, ecolabels may not identify products which are 'better' for the environment than non-labeled products, because the process by which products are assessed can be flawed due to difficulties inherent in life cycle analysis (Hardy, 1998).

It is suggested that dyeing should be skipped to prevent pollution (Green Cotton Thailand, 2006). However, most dyeing and finishing processes cannot be avoided if organic cotton textiles are to have the same aesthetics as conventional textiles, but they can be substituted with more environment friendly operations and chemicals. Since some operations and treatments, though not organic, cannot be avoided, it is important that energy efficient processing with less use of toxic chemicals and low water use be applied. Large quantities of chemicals and water can be used in finishing of a fabric, but today most conventional and organic dyeing and finishing processes use low inputs for water and chemicals. The conventional dyeing and finishing processing systems at textile mills can pollute the environment if proper practices, including effluent guidelines, are not followed. The resultant effluent should be treated in a waste water treatment process at the dyeing and finishing plant prior to being emitted as an effluent. The effect of chemicals on workers' health can also be a concern if workplace occupational health and safety regulations are not followed.

5.5.5 Product assembly

For organic textiles, natural fibers such as cotton (organic if available) are preferred for use as sewing thread but synthetic sewing thread may be used. Labels made of natural fiber can be used.

5.5.6 Quality assurance

To meet consumer demands for good aesthetic and fastness properties organic textiles should meet the same quality/fastness parameters for color uniformity, light and wash fastness, wet and dry crock fastness, and shrinkage (Tripathi, 2005), that the consumer expects for conventional textiles.

5.6 Limitations to organic production

Various issues hinder the adoption of organic cotton production. These include production problems, particularly insect and weed control, and marketing problems, particularly price variability and unstable, underdeveloped markets.

5.6.1 Problems with organic production practices

In 2002/03, the OTA (Pick and Givens, 2004), in a project funded by Cotton Incorporated, attempted to identify limitations to organic cotton production in the US. The Organic Fiber Council of the OTA surveyed all US organic cotton growers concerning organic cotton production practices and problems. The International Cotton Advisory Committee (ICAC) collected similar information in 1994, in addition to information on the cost of production and the price premium for organic versus conventional production. These studies concluded that the main problems for organic cotton production are weed control (due to prohibition of herbicides), defoliation (due to lack of efficient natural products), and insect control (due to lack of efficient natural/organic insecticides). Defoliation is a limitation, particularly in the USA, where all cotton is machine harvested, because the plant needs to be treated for leaf drop (defoliated) before harvesting machines enter fields. Some farmers also indicated lack of seed treatment, which is not permitted in organic production. Availability of inputs needed for organic farming and additional paper work/record keeping also hinder adoption of organic cotton production.

The boll weevil has caused heavy losses to cotton production in the USA since the 1920s (Dickerson *et al.*, 2001). The boll weevil eradication program, which has successfully eliminated the boll weevil from many parts of the US cotton belt, particularly in the southern states (El-Lissy and Grefensette, 2002), continues in many other parts of the USA (National Cotton Council, 2006a). Farmers are not able to grow organic cotton in these boll weevil eradication treatment areas. The same is true in the pink bollworm eradication areas. In the areas where eradication is completed, there should be fewer insect problems – this would be helpful to organic cotton production.

The USDA, AMS, National Organic Program (NOP) at first did not allow acid delinted seed, but had to amend its decision since no machines for planting un-delinted fuzzy seed are being manufactured. Acceptance of acid delinted seed for organic planting did not increase organic cotton production, but was helpful to planting of organic seed. In the OTA report (Pick and Givens, 2004), the NOP rule was identified 'as creating some difficulties for farmers, including some increased costs, the sourcing of agricultural inputs, increased paperwork, and inconsistencies in interpretation of the rule by certifiers'.

US organic standards as well as international standards do not allow the use of biotech cotton. The current biotech varieties convey insect resistance and herbicide tolerance (Fitt *et al*., 2004; Wakelyn *et al*., 2004). Insect resistance is conferred through the incorporation of genes from *Bacillus thuringiensis* (Bt) that produce Bt δ-endotoxins, naturally occurring insect poisons for bollworms and budworms. The use of Bt biotech cotton reduces the use of insecticides and minimizes adverse effects on non-target species and beneficial insects. Herbicide tolerance (HT) enables reduced use of herbicides and use of safer, less persistent materials to control a wide spectrum of weeds that reduce yield and lint quality of cotton. Biotech herbicide tolerance moves cotton weed management away from protective, presumptive treatments toward responsive, as-needed treatments. If biotech varieties were allowed, it would be helpful to organic production.

5.6.2 Other issues that hinder the adoption of organic cotton

Various other issues that are hindering the adoption of organic cotton include alternative inputs, crop rotation problems, ineligibility of transgenic cotton for organic certification, lack of organic cotton marketing information, and organic certification issues. One of the most important aspects of organic cotton production and expansion requires improvement in marketing, and market linkages between cotton producers and international organic cotton buyers, including access to market information distribution channels. Improvements in all these areas are needed to promote organic cotton properly.

Lack of information on cost of production

Elimination of some conventional inputs is expected to lower the cost of production per hectare (cost/ha), but may not mean lower cost of production per kilogram of lint, if reduction in yield is more than compared to reduction in input costs. Also other organic practices, such as the control of weeds by hand hoeing, increase costs. The cost of production greatly varies among growers, production regions and countries, but unfortunately no authentic data are available to compare cost of production of organic cotton versus conventional production. In the absence of such information or limited information, farmers can be reluctant to adopt organic agricultural practices.

Price premium/unstable markets

Organic producers expect a price premium in exchange for the cost of certification, risk for lower yield, and possibly lower quality due to spotted or more trash in the cotton due to imperfect control of bollworms or other insects and problems in harvesting. Spotted and higher trash cotton – lower grades of cotton – could cause the farmer to receive a discounted price rather than a premium.

There appears to be no fixed premium for organic production efforts. The OTA survey (Pick and Givens, 2004) data indicated that in the US 'the average price per pound received by farmers showed a wide range, from $0.69 to $1.40 for upland (organic) cotton' compared to US$0.57–76 in 2003/04 and US$0.48–0.57 in 2004/05 for base grade conventional cotton (A-index world price). The enormous variability in prices received by farmers is an indication of how unstable the market is. The premium is supposed to be enough to compensate for the loss in yield or even to increase farmers' income over conventional production. No authentic information is available to potential organic cotton growers on how much premium an organic producer should expect when shifting to organic production and this has discouraged some growers from growing organic cotton. Solid indications that price premiums will be received would encourage organic production.

Development of national markets

Most organic cotton produced in Turkey and the USA has been exported to other countries. Organic cotton production in Turkey was initiated by a multinational company called the Good Food Foundation in 1989, which was followed by a second project by a German company called Rapunzel. Currently, a number of companies are involved in organic cotton production in Turkey and almost all organic production is through contract farming. Companies contract growers to produce organic cotton for them and also arrange their own certification. In the USA organic cotton certification is by the USDA. In spite of many years of organic production in both countries, a local market for consumption of organic cotton has not developed, thus leaving organic cotton producers at the mercy of unknown international buyers scattered in many countries. Beyond production and local markets, the standards for eco-friendly textile products have been variable. There is a need to develop local markets for organic cotton closer to the production chain and harmonization of international labeling schemes for eco-friendly organic textile products.

5.7 Methods to improve organic cotton production

If some of the factors that have limited the adoption of organic farming practices (discussed in section 5.6) and that keep it a niche market are removed, organic production could spread to more countries and expand production in those countries. The chances of obtaining higher prices for organically produced cotton are much better if it is produced under contract for a committed business. Suitable varieties and improved insect and weed control and defoliation technology are some of the parameters that could help increase organic cotton markets.

5.7.1 Suitable varieties

In all of the 20-plus countries where farmers have tried to produce organic cotton, they have used the conventionally grown varieties developed for that growing area for organic production. These commercially grown varieties have been developed for high input conditions, synthetic fertilizer, and insecticide usage. Varieties that perform well under optimum conventional conditions cannot maintain their yield level when the conditions they have been developed for change so drastically. Varieties suitable for organic farming production conditions must be developed (Chaudhry, 1993, 2003).

5.7.2 Production technology

For conventional cotton production breeders, agronomists, entomologists, and pathologists jointly develop a technological package that includes the best use of inputs and production practices. These practices recommend the production technology practices for achieving high yields. Next the information is disseminated to cotton growers in many ways through federal and state extension workers and consultants. The communication of the technology is equally as important as the development of the technology. The third component, the adoption of technology, is at the discretion of individual growers. Development, transfer and adoption of technology help give the farmer some assurance that high yields will be obtained. For conventional cotton production this is the normal practice. Organic cotton production technology needs to be and should be developed and formally transferred by specialized extension workers to organic cotton growers.

5.7.3 Soil fertility

The soil has to be replenished to maintain the optimum supply of nutrients the plant requires to grow and if it is not done, growth and yields are affected. Nutrient needs change from minimum to maximum for N, P and K during the course of crop development. Matching nitrogen is more critical, because nitrogen moves in the soil and could leach out by the time the plant's needs reach their peak. This is why nitrogen fertilizers are always split into doses so that supply is close to the needs of the plant. Organic fertilizers (manure) and other permissible sources of nutrient for organic conditions fail to meet the plant's changing needs for nitrogen and thus, limit organic cotton production. New methods are required to keep soil fertility high and sufficient to meet plant needs. This is necessary for high yields.

5.7.4 Pest control

The cotton plant is naturally vulnerable to a variety of insects. Unless efficient and effective control methods are available under organic conditions, yield is going to be affected negatively. Insects like bollworms/budworms and whitefly can lower cotton grade and depress prices received by farmers. Sucking insects at early stages of cotton plant growth affect physiological activities in leaves and result in the plant producing less fruit. Insecticides provide efficient and effective control but are not allowed. Biological control and non-conventional insect control insecticides like products from the Neem tree (*Azadirachta indica)* do not provide control equivalent to synthetic insecticides. Moreover, after synthetic insecticides are eliminated, the reduction in yield is the greatest in the first year but may improve as natural biological defense builds. Many farmers cannot sustain the loss in yields in the first few years. This is a disincentive for potential organic producers. Research must be conducted to keep the loss in yield to the minimum for the first two years, when loss in yield is high and there is no premium since the cotton is still in the transitional stage.

5.8 Certification

Certification is a prerequisite for a product to be sold as 'organic' cotton. Certification provides a guarantee that a specific set of standards has been followed in the production of the organic cotton. Cotton was first certified as organic in 1989/90 in Turkey. Currently there are hundreds of private organic standards worldwide for all organic products. Organic standards have been codified in the technical regulations of more than 60 governments. There are 99 accredited certifying companies/organizations in the world dealing with cotton with 56 located in the USA and 43 in all the other organic cotton producing, processing, and consuming countries. European Union (EU) regulations, International Federation of Organic Agriculture Movements (IFOAM) standards, and the US National Organic Standards (NOP) have helped to formulate organic farming legislation and standards throughout the world. Certifying companies develop their own standards but all are essentially comparable. Organic cotton producers have to commit to follow the standards set by the certifying organizations/companies, which includes verification through field visits by independent third parties. The certifying agency must be accredited, recognized by buyers, and the system must be independent and transparent. The fee for certification must be low enough so that it does not add significantly to the cost of production, otherwise it can become a disincentive to grow organic cotton.

In many cases for cotton, certification has been limited to fiber production. Yarn and fabric manufacturing and dyeing and finishing are done in the conventional way. Such efforts can facilitate organic production and at the same time recognize the difficulties faced in certifying the whole chain as organic. The Organic Trade Association (OTA) has adopted voluntary organic standards for fiber processing standards for post-harvest handling, processing, recordkeeping and labeling (Murray and Coody, 2003; OTA, 2005a) (see Section 5.8.5) as has the Organic Exchange (see section 5.8.4).

5.8.1 International Federation of Organic Agriculture Movements (IFOAM)

The International Federation of Organic Agriculture Movements (IFOAM) was established in 1972 (IFOAM, 2005). IFOAM implements specific projects that facilitate the adoption of organic agriculture, particularly in developing countries. The IFOAM adopted basic standards for organic farming and processing in 1998. The IFOAM standards, revised over time, are not binding for any country/producer of organic agricultural products, but they do provide valuable guidelines for organic producers and processors. The IFOAM Organic Guarantee System enables organic certifiers to become 'IFOAM Accredited' and for their certified operators to label products with the IFOAM Seal, next to their own seal of certified production/processing.

5.8.2 European Union (EU) regulation of organic cotton

The European Union adopted Regulation No. 2092/91 in June 1991 for organic production of agricultural products and labeling of organic plant products (EU, 1991; Dimitri and Oberholtzer, 2005 and 2006). It came into effect in 1993. Since then it has been amended on several occasions. The regulation defines a minimum framework of requirements for organic agricultural products, including organic production methods, labeling, importation, and marketing for the whole of Europe, but each member state is responsible for interpreting and implementing the rules, as well as enforcement, monitoring, and inspection. EU labeling of organic products is complex because some member states have public labels, while private certifiers in other member states have their own labels. According to this regulation, the minimum period to convert from conventional farming to organic production is two years (before planting) for annual crops and three years (before the first harvest) for perennial crops. According to the EU regulation, just as in the US regulations, biotech cotton varieties cannot be used for certified organic production nor can ionizing radiation be used on products.

In March 2000, to improve the credibility of organic products, the EU introduced a voluntary logo for organic production bearing the words 'Organic Farming' (EU, 2000). It can be used throughout the EU by producers whose systems and products, on inspection, satisfy EU regulations. The logo assures that the product complies with the EU rules on organic production. The EU regulation 2092/91 permits labeling a product as 'organic farming' if:

- at least 95% of the product's ingredients have been organically produced
- the product complies with the rules of the official inspection scheme
- the product has come directly from the producer or preparer in a sealed package
- the product bears the name of the producer, the preparer or vendor and the name or code of the inspection body
- 70–95% of the ingredients are from organic production conditions, the product may refer to organic production methods in the list of ingredients but not in the sales description
- less than 70% of the ingredients are from organic production conditions, the product cannot make any reference to organic production methods.

In December 2005, the European Commission made compulsory the use of either the EU logo or the words 'EU-organic' on products with at least 95% organic ingredients. Organic products from other countries can be imported into EU countries and freely moved within the EU countries if the organic production rules in the exporting country are equivalent to the EU regulations.

5.8.3 USA National Organic Standards

The 1990 USA Farm Bill contained provisions (Organic Foods Production Act of 1990 ('OFPA') as amended (7 US Code 6501 *et seq.*)) requiring the US Department of Agriculture (USDA) and the Agricultural Market Service (AMS) to develop National Organic Standards. USDA promulgated the regulations/standards governing organic products in December 1997, which became effective October 21, 2002 (National Organic Program, 2002; Dimitri and Oberholtzer, 2005 and 2006). Organic certification in the USA is voluntary and self-imposed. According to the US standards, biotech products, irradiated foods, and crops fertilized with municipal sewage sludge cannot be certified as 'organic'. USDA, AMS is in charge of implementation of the standards. Any company involved in certification of organic products must have authority from the USDA to carry out certification activities. On the NOP website (http://www.ams.usda.gov/nop/certifyingAgents/Accredited.html) is a comprehensive list of the USDA Accredited Certifying Agents (ACAs) organized alphabetically by state for domestic ACAs and by country for foreign ACAs. In the USA, if a cotton grower decides to produce organic cotton, an 'Organic System Plan' must be submitted to a USDA accredited certifying company/department for approval. All natural materials are permitted to be used in organic production or processing unless prohibited on the national list. A product is certified as '100 percent organic', if it is all organic or contains 95% organic ingredients and it is 'made with organic ingredients' or if it has at least 70% organic product ingredients.

The National Organic Program (NOP) issued a statement on August 23, 2005 intended to clarify its position with respect to the issue of products that meet the NOP program standards for organic products based on content, irrespective of the end use of the product (NOP, 2005). Agricultural commodities or products that meet the NOP standards for certification under the Organic Foods Production Act of 1990, 7 USC §§ 6501–6522, can be certified under the NOP and be labeled as 'organic' or 'made with organic' pursuant to the NOP regulations, 7 CFR part 205.300 *et seq*. Operations currently certified under the NOP that produce agricultural products that meet the NOP standards to be labeled as 'organic' and to carry the USDA organic seal, or which meet NOP standards to be labeled as 'made with organic', may continue to be so labeled as long as they continue to meet the NOP standards.

5.8.4 Organic Exchange

The Organic Exchange is a non-profit organization in the USA committed to expanding organic agriculture, with a specific focus on increasing the production and use of organically grown fibers, such as cotton (Organic Exchange, 2006). It also tracks world production of organic cotton. The Organic Exchange is funded through company sponsorships and revenues from its activities. It has an 'Organic Cotton' logo for use by its member companies to identify their products or family of products, from yarn to finished goods, that contain organic cotton. The Organic Exchange has developed voluntary guidelines (Organic Exchange Guidelines, 2004) to help companies involved in the production of organic products containing certified organic cotton fiber understand how to track and document the purchase, handling and use of organic cotton in their products. The Organic Exchange 100 standard (OE 100) was developed and approved in 2004

(Organic Exchange Guidelines, 2004) to allow companies to have their operations certified by a third party as complying with the handling, tracking, and documentation for products containing a percentage blend of organic cotton. In 2005, the Organic Exchange finalized their OE Blended Standard (2005).

5.8.5 Organic Trade Association (OTA)

The Organic Trade Association (OTA) is the membership-based business association for the organic industry in North America. OTA develops guidelines but is not a certification organization (OTA, 2005). Since there are already US and other organic fiber production standards in place concerning the on-farm production of raw fiber (cotton), OTA does not have their own separate standards for organic cotton production. However, since there are no US standards for the processing of organic raw fiber from the time it leaves the farm, to when a finished product is available for retail, the OTA developed organic fiber processing guidelines (OTA, 2005a), approved January 2004, that address all stages of textile processing, from post-harvest handling to wet processing (including bleaching, dyeing, printing), fabrication, product assembly, storage and transportation, pest management, and labeling of finished products. These standards also include an extensive list of materials permitted for, or prohibited from, use in organic fiber processing under the standards (see Appendix 5.2). The evaluation criteria are designed to minimize negative environmental effects and risks to human health. For example, materials allowed under the standards cannot be known to cause cancer, genetic damage, birth defects or endocrine disruption. In addition, they must be biodegradable and meet strict requirements which limit toxicity. Examples of materials prohibited by the standards include chlorine bleach, formaldehyde, and some azo dyes.

OTA's standards for claims that can be put on labels are the USDA NOP standards and include four label categories that are modeled after the standards for organic foods in the USA organic regulations: '100% organic', 'organic', 'made with organic', and listing of the individual organic components on the ingredients panel. However, the USDA prescribed system for labeling fiber products allows only one category for organic cotton textiles. The USDA rule says goods that utilize certified organic fibers in their manufacture may be labeled only as 'made with organic cotton'. USDA has addressed the scope of the federal program. Certifiers are able to certify according to the OTA standards, using OTA's labeling provisions. So long as the processed fiber product is certified clearly to OTA's American Organic Standards, the OTA's language can be used to describe a product. The US Federal Trade Commission has indicated that companies may list the percentage of organic fiber content on a product's content label and include the word 'organic' to describe the fiber. Because there are no federal standards for finished fiber products in the USA and the OTA standards are voluntary, a company may sell in the USA organic fiber products certified under these or other standards as long as the certifier of the organic fiber is accredited by the USDA and the label claims are truthful.

5.8.6 Quality Assurance International

Quality Assurance International (QAI, Inc.), an NSF International company, is one of the global leaders in organic certification services (http://www.qai-inc.com/). QAI currently offer organic certification under the USDA NOP and fiber certification under the OTA or other USA organic standards.

5.8.7 ECOCERT International

ECOCERT International (http://www.ecocert.com/index.php?id=about&l=en), with operational offices in Germany, is an inspection and certification body accredited to verify the conformity of organic agricultural products against the organic regulations of Europe, Japan and the USA. They currently perform such inspection and certification services in 70 countries outside the EU, on all continents. ECOCERT is accredited according to ISO Guide 65 (equals to European Norm EN 45011), by a member of European Accreditation (EA) and IAF (International Accreditation Forum) and thus is an internationally recognized accreditation body. In the USA, they have been accredited to the NOP standard by the USDA and in Japan to the JAS organic standard by MAFF. ECOCERT certifies organic cotton production in many African and European countries. Their website does not mention certification or guidance for organic cotton textiles, although some organic cotton textiles carry the ECOCERT label.

5.9 Naturally colored organic cotton

Organic production of naturally colored cotton has been tried but none is currently available as 'certified organic'. Since the late 1980s and early 1990s, there has been a renewed interest in naturally colored cottons, which have existed for over 5,000 years (Vreeland, 1993 and 1999).The need for higher output cotton production and the availability of inexpensive dyes caused naturally colored cottons to almost disappear about 50 years ago. Yields were low and the fiber was essentially too short and weak to be machine spun. These cotton varieties are spontaneous mutants of plants that normally produce white fiber. Naturally colored cotton exists in various shades of brown and green. Very light blue colored cotton is also available in the germplasm in Uzbekistan. Researchers have tried to develop other colors through conventional breeding, but have not been successful. Some naturally colored cottons have botanically formed material bodies in the lumen (Ryser, 1999) of the fiber (brown, red, mocha, and mauve cottons) that conveys the color whereas the color of green cotton is due to a lipid biopolymer (suberin) sandwiched between the lamellae of cellulose microfibrils in the secondary wall (Ryser, 1983 and 1999; Schmutz *et al.*, 1993).

Breeding research over the last 15 years in many countries reportedly has led to some improvement in yields, fiber quality, fiber length and strength, and color intensity and variation (Kimmel and Day, 2001; Öktem *et al.*, 2003; Wakelyn and Gordon, 1995). There are claims of development of colored cotton equivalent to white cotton in fiber quality, but no colored cotton varieties have been officially approved for commercial cultivation. Progress has been made, but still there is a long way to go before the quality of colored cotton is equivalent to white cotton and the same yields are achieved. Research undertaken to improve colored cotton is limited. Availability of suitable germplasm in colored cotton for use in breeding is the biggest hurdle for improvement in colored cotton.

Naturally colored cottons are a very small niche market. Those available today are usually shorter, weaker, and finer than regular Upland cottons, but they can be spun successfully into ring and rotor yarns for many applications (Kimmel and Day, 2001; Öktem *et al.*, 2003). For a limited number of colors, the use of dyes and other chemicals can be completely omitted in textile finishing, which can compensate for the higher raw material price. The color of the manufactured goods can intensify with washing (up to 5–10 washings), however colors vary somewhat from batch to batch (Wakelyn and Gordon, 1995) and colors have low light fastness and start fading in the sun after a few washings.

The amount available in 2005/06 in the world was very small, perhaps 10,000 US 480 lb bale equivalents (about 2,180 MT). Some naturally colored cotton is presently being grown in China, Peru, India, Brazil, and Israel. Colored cotton projects were initiated in many countries including India, Israel and the USA, but the momentum for producing colored organic cotton could not be sustained due to limited color choice for consumers and lower quality fiber. In efforts to make naturally colored cotton economically advantageous to produce, organic farming of naturally colored fiber has been tried. There is a market for colored organic cotton but the consumer demand for more color choices is limiting the spread of colored organic cotton. Some countries, particularly Brazil, China, India, Israel and Peru, continue to produce some colored cotton, but not much as certified organic.

5.10 Conclusions

There continues to be worldwide interest in organic cotton as a potentially environmentally friendly way to produce cotton and for economic reasons.

Production of organic cotton has increased recently to about 0.1% of world cotton production, mainly due to increased production in Turkey as well as India, China and some African countries. Organic production is not necessarily any more environmentally friendly or sustainable than current conventional cotton production. From a consumer residue standpoint there is no difference between conventionally grown cotton and organically grown cotton. There are limitations to organic cotton production that need to be overcome if organic cotton is to become more than a small niche market. Growing organic cotton is more demanding and more expensive than growing cotton conventionally. Organic production can be a real challenge if pest pressures are high. But with commitment and experience, it may be possible and could provide price premiums for growers willing to meet the challenges. Conventional and organic cotton production can co-exist. Profitability will drive decisions in the supply chain.

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Appendix 5.1

The National list of Allowed and Prohibited Substances (US National Organic Program)

Synthetic substances allowed for use in organic crop production (7 Code of Federal Regulations (CFR) Sec. 205.601)

In accordance with restrictions specified in this section, the following synthetic substances may be used in organic crop production: Provided, That, use of such substances does not contribute to contamination of crops, soil, or water. Substances allowed by this section, except disinfectants and sanitizers in paragraph (a) and those substances in paragraphs (c), (j), (k), and (l) of this section, may only be used when the provisions set forth in Sec. 205.206(a) through (d) prove insufficient to prevent or control the target pest.

(b) As herbicides, weed barriers, as applicable

(1) Herbicides, soap-based – for use in farmstead maintenance roadways, ditches, right of ways, building perimeters) and ornamental crops.
(2) Mulches.
  (i) Newspaper or other recycled paper, without glossy or colored inks.
  (ii) Plastic mulch and covers (petroleum-based other than polyvinyl chloride (PVC)).

(c) As compost feedstocks

Newspapers or other recycled paper, without glossy or colored inks.

(d) As animal repellents

Soaps, ammonium – for use as a large animal repellent only, no contact with soil or edible portion of crop.

(e) As insecticides (including acaricides or mite control)

(1) Ammonium carbonate – for use as bait in insect traps only, no direct contact with crop or soil.
(2) Boric acid – structural pest control, no direct contact with organic food or crops.
(3) Copper sulfate – for use as tadpole shrimp control in aquatic rice production, is limited to one application per field during any 24-month period. Application rates are limited to levels which do not increase baseline soil test values for copper over a timeframe agreed upon by the producer and accredited certifying agent.
(4) Elemental sulfur.
(5) Lime sulfur – including calcium polysulfide.
(6) Oils, horticultural – narrow range oils as dormant, suffocating, and summer oils.
(7) Soaps, insecticidal.
(8) Sticky traps/barriers.

(f) As insect management

Pheromones.

(g) As rodenticides

(1) Sulfur dioxide – underground rodent control only (smoke bombs).
(2) Vitamin D.

(i) As plant disease control

(1) Coppers, fixed – copper hydroxide, copper oxide, copper oxychloride, includes products exempted from EPA tolerance, provided, that, copper-based materials must be used in a manner that minimizes accumulation in the soil and shall not be used as herbicides.
(2) Copper sulfate – Substance must be used in a manner that minimizes accumulation of copper in the soil.
(3) Hydrated lime.
(4) Hydrogen peroxide.
(5) Lime sulfur.
(6) Oils, horticultural, narrow range oils as dormant, suffocating, and summer oils.
(7) Peracetic acid – for use to control fire blight bacteria.
(8) Potassium bicarbonate.
(9) Elemental sulfur.

(10) Streptomycin, for fire blight control in apples and pears only.
(11) Tetracycline (oxytetracycline calcium complex), for fire blight control only.

(j) As plant or soil amendments

(1) Aquatic plant extracts (other than hydrolyzed) – Extraction process is limited to the use of potassium hydroxide or sodium hydroxide; solvent amount used is limited to that amount necessary for extraction.
(2) Elemental sulfur.
(3) Humic acids – naturally occurring deposits, water and alkali extracts only.
(4) Lignin sulfonate – chelating agent, dust suppressant, floatation agent.
(5) Magnesium sulfate – allowed with a documented soil deficiency.
(6) Micronutrients – not to be used as a defoliant, herbicide, or desiccant. Those made from nitrates or chlorides are not allowed. Soil deficiency must be documented by testing.
  (i) Soluble boron products.
  (ii) Sulfates, carbonates, oxides, or silicates of zinc, copper, iron, manganese, molybdenum, selenium, and cobalt.
(7) Liquid fish products – can be pH adjusted with sulfuric, citric or phosphoric acid. The amount of acid used shall not exceed the minimum needed to lower the pH to 3.5.
(8) Vitamins, B, C, and E.

(k) As plant growth regulators

Ethylene gas – for regulation of pineapple flowering.

(l) As floating agents in postharvest handling

(1) Lignin sulfonate.
(2) Sodium silicate – for tree fruit and fiber processing.

(m) As synthetic inert ingredients

As classified by the Environmental Protection Agency (EPA), for use with nonsynthetic substances or synthetic substances listed in this section and used as an active pesticide ingredient in accordance with any limitations on the use of such substances.
(1) EPA List 4 – Inerts of Minimal Concern.
(2) EPA List 3 – Inerts of unknown toxicity – for use only in passive pheromone dispensers.

Appendix 5.2

Guidelines–Some Chemicals allowed and prohibited for use in preparation, dyeing, printing, and finishing of organic cotton textiles (Organic Exchange Guidelines, 2004; Organic Trade Association, 2005a)

(a) Synthetic chemicals allowed

Aluminum silicate (scouring agent, deflocculant, anticoagulant, dispersant)
Aluminum sulfate (scouring or mordant agent)
Fatty acids and their esters (softener)
Hydrogen peroxide (bleaching agent)
Oxalic acid
Ozone (bleaching agent)
Polyethylene (restricted softener)
Potassium hydroxide (mercerizing, scouring)
Biodegradable soaps
Sodium hydroxide (mercerizing, scouring)
Sodium silicate (bleaching and color brightener)
Sodium sulfate (bleaching and color brightener)
Surfactants (that are biodegradable) (scouring agent, emulsifier, wetting agent) (may not be silicon based, contain petroleum solvents or be alkyl phenol ethoxylates)

(b) Non-synthetic chemicals allowed

Acetic acid
Chelating agents (stabilizers)
Citric acid
Clay-based scours
Copper, iron, tin (for mordant dyeing)
Natural dyes (animal and plant)
Enzymes (non-GMO)
Flow agents (natural)
Mined minerals
Pigment dyes (natural indigo and clays only)
Potassium acid tartrate

Sodium carbonate (soda ash) pH adjuster
Sodium chloride (salt) **auxiliary**
Tannic acid
Tartaric acid

(c) Chemicals prohibited

Ammonium soaps
Absorbable halogenated hydrocarbon (AOX)
Bluing agents (for bleaching and color brightening)
Chelating agents
Chlorine compounds (bleaching)
Dyes non-conformant with criteria
Formaldehyde
Synthetic fire retardants
Functional finishes for anti-crease, antifungal, anti-microbial, anti-pilling, antistatic

(d) Conformant dyes

Natural dyes (animal and plant)
Pigment dyes (natural indigo and clays only)
Most fiber reactive dyes
Not allowed: Benzidine and benzidine congener azo dyes; other azo dyes that can undergo reduction decomposition to form carcinogenic aromatic amines (currently this includes the 24 amines classified as substances known to be human carcinogens).
Dyes should not contain heavy metals (restricted level of residues allowed) except iron, copper, tin (for mordant dyeing).
Dyes should not contain chelated metals (residues >1 mg metal/kg textile).
Dyes should not contain AOX – Absorbable halogenated hydrocarbon and substances that can cause their formation.
Dyes should not contain formaldehyde.

6 The harvesting and ginning of cotton*

W S ANTHONY, formerly United States Department of Agriculture, USA

6.1 Introduction

Cotton possesses its highest fiber quality and best potential for spinning when the bolls are mature and freshly opened. Quality of the fiber in the bale depends on many factors including variety, weather conditions, cultural practices, harvesting and storage practices, moisture and trash content, and ginning processes. Genetics plays an important role in fiber quality, both in the initial quality of the fiber as well as how well the fiber withstands gin processes. For example, varieties with high numbers of trichomes (plant hairs) on the plant parts usually require additional cleaning equipment because it is more difficult to remove those trash particles. Harvesting practices from hand-picked to machine-stripped dramatically impact the amount of trash entangled with the cotton and thus the amount of cleaning machinery required at the gin.

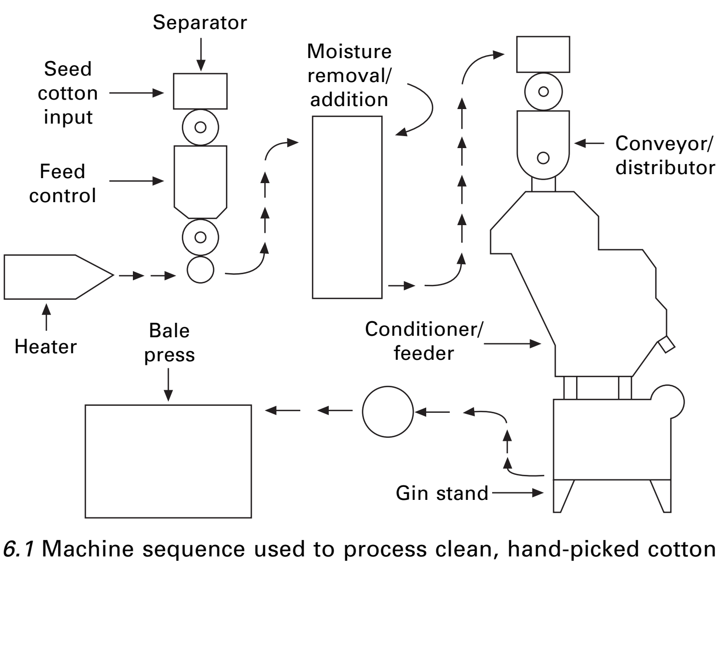
Fiber quality factors such as length, uniformity, micronaire, strength, short fiber content, neps, and seedcoat fragments may differ dramatically for varieties grown under nearly identical conditions. Field weathering impacts most quality factors by weakening and discoloring the fiber. The color is substantially affected by weather and length of exposure to weather conditions after the bolls open. Abnormal color (light-spot, spotted, tinged, yellow-stained, etc.) indicates a deterioration in quality. Continued exposure to weather and the action of micro-organisms can cause white cotton to lose its brightness and become darker in color. The weakened fibers cannot withstand the standard lint-seed separation or lint cleaning processes without additional damage and fiber loss. In fact, varieties and excessive weathering have a far greater impact on fiber quality than do the most rigorous of gin processes. The quality aspects of cotton varieties, weathering, and the impact of gin machinery on fiber quality are available in numerous published references (Anthony,

*Taken in part from the *Handbook for cotton ginners*, editors W Stanley Anthony and W D Mayfield (1994), *Agricultural Handbook 503*, United States Department of Agriculture.

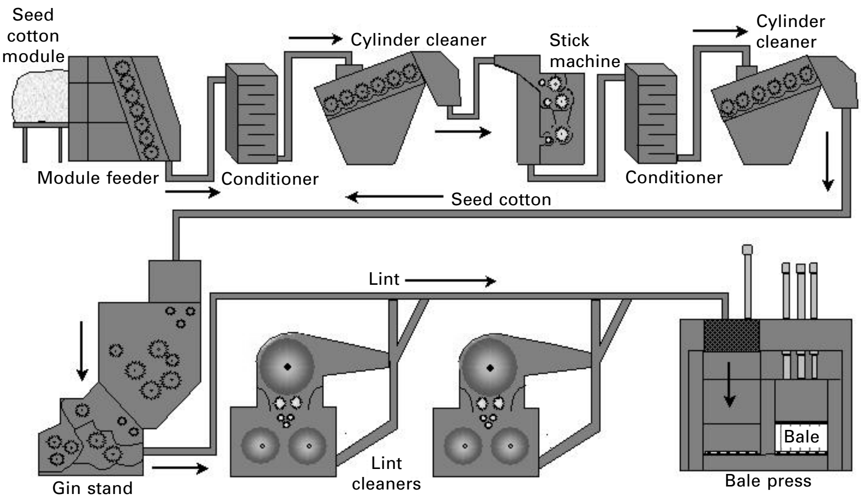
1982, 1990a, b, c, d, 1994a, b, 1996, 1999; Anthony and Calhoun, 1997). Cotton gins are responsible for converting a raw agricultural product, seed cotton, into commodities such as bales of lint, cottonseed, motes, compost, etc. Gins are a focal point of the cotton community and their location, resources, and contributions to the economy are critical to the cotton industry.

Enormous differences exist across the worldwide spectrum of cotton production, harvesting and ginning. Harvest methods range from totally hand-harvested in some countries to totally machine-harvested in others, in fact, only the United States and Australia are fully mechanized. Cotton storage after harvesting ranges from small piles of cotton on the ground in some countries to mechanically made modules containing over 12 tons of cotton in others. Gin machinery sequences vary from little more than a gin stand as shown in Fig. 6.1 to a complex arrangement of machines as shown in Fig. 6.2. In a growing number of instances, gins are vertically integrated enterprises that include components that range from cotton production to marketing and/or spinning. Production of high quality cotton begins with the selection of varieties and continues through the use of good production practices that include harvesting, storage, and ginning. Gins can preserve fiber quality and dramatically improve market grade and value. Yield and market qualities such as color, leaf, micronaire, length, length uniformity and strength are important characteristics of fiber as well as neps (fiber entanglements), short fiber content (fibers shorter than 12.7 mm or 0.5 in.), and fragments from the seed coats.

The principal function of the cotton gin is to separate lint from seed and produce the highest total monetary return for the resulting lint, seeds, etc.,



6.1 Machine sequence used to process clean, hand-picked cotton.



6.2 Representative cross-sections of typical types of gin machinery arrayed in a sequence used for spindle-picked cotton.

under the marketing conditions that prevail. These marketing quality standards most often reward cleaner cotton and a certain traditional appearance of the lint. The gin then must also be equipped to remove a large percentage of the foreign matter from the cotton that would significantly reduce the value of the ginned lint, especially if the cotton is machine harvested. A ginner must have two objectives: first, to produce lint of satisfactory quality for the grower's classing and market system, and secondly, to gin the cotton with minimum reduction in fiber spinning quality so that the cotton will meet the demands of its ultimate users, the spinner and the consumer. Thus, quality preservation during ginning requires the proper selection and operation of each machine that is included in a ginning system. The ginner must also consider the weight loss that occurs in the various cleaning machines. Often the weight loss to achieve a higher grade results in a lower total monetary return.

6.2 Harvesting

About 35% of the over 100 million bales of cotton produced globally is harvested by hand. Although 40 countries harvest some cotton by machine, only three (United States, Australia and Israel) harvest 100% by machine. Two types of mechanical harvesting equipment are used to harvest cotton: the spindle picker (Fig. 6.3) and the cotton stripper harvester (Fig. 6.4). Plant height should not exceed about 1.21m (4 ft) for picked cotton and about 0.91 m (3 ft) for stripped cotton because too much foreign matter will be collected. In fact, a height of 0.6 m (2 ft) is preferred for stripper harvesting.

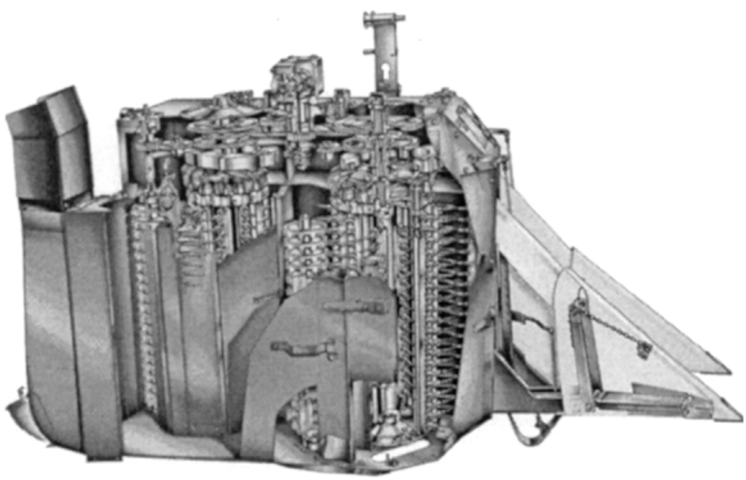
6.3 Typical spindle-type mechanical harvester for cotton.

6.4 Typical stripper harvester for cotton.

In certain areas in Texas, Oklahoma, Missouri and Kansas in the United States as well as Australia, soil types, low moisture and/or high winds necessitate the use of cotton that is conducive to stripper harvesting. Typically, spindle and stripper-harvested seed cotton contains about 6% and 30% plant parts, respectively. Some stripper harvesters are equipped with field cleaners or extractors that are similar to stick machines used as precleaners in the cotton gin. These units are capable of removing 60–70% of the foreign matter and can thus reduce the amount of material processed at the cotton gin.

The spindle picker is a selective-type harvester that uses tapered, barbed spindles to remove seed cotton from bolls as shown in the cut-away view in Fig. 6.5. This harvester can be used on a field more than once to provide stratified harvests. Spindle pickers are available to harvest row spacings from 38.1 cm (15 in.) to 106.7 cm (42 in.) as well as skip-row patterns. Although the spindle picker was initially used as a one-row machine that harvested less than one bale per hour, it is now available as a six-row machine capable of harvesting over 12 bales per hour. They can harvest at 95% efficiency but are commonly operated at 85% to 90% efficiency. Special care should be given to the spindles, moistener pads, doffers, bearings, bushings, and cam track. Moisture is added to the spindles to keep them clean and to enhance the adherence of the fiber to the spindle. Harvesting should begin after the dew has dried and the relative humidity is below 60%. The spindles generally require less moisture in the morning than in the afternoon. Tap water is usually sufficient to keep the spindles clean. Wetting agents, spindle cleaners, or a soluble oil may also be added to the water. These additives are usually helpful when harvesting rank cotton that has green leaves.

The cotton stripper is a nonselective or once-over harvester that removes not only the well-opened bolls but also the cracked and unopened bolls along



6.5 Harvesting components of a spindle picker.

with the burs (carpel walls) and other plant parts. Agronomic practices that produce a high-quality, uniform crop will generally contribute to good harvesting efficiency. Cotton strippers have evolved from two-row, one bale per hour machines to eight-row, 15 bale per hour machines. The cotton stripper is a simple and efficient machine for harvesting cotton and has the capacity to harvest up to 99% of the cotton from the plant. Cotton strippers use either finger-type or roll-type harvesting mechanisms. The finger-type mechanism utilizes multiple fingers made from metal angle iron with the vee turned up and operating at a 15° to 20° approach angle with the ground. The roll-type strippers utilize two stripper rolls angled 30° with the ground and rotating in opposite directions with the upward direction next to the plant. Each roll consists of three brushes and three paddles mounted in alternating sequence.

6.3 Seed cotton storage

In the early 1970s, technology was developed for packing harvested cotton into freestanding modules (Fig. 6.6) containing about 9000 kg (20 000 lbs). These modules could be mechanically handled as a single unit and dramatically changed the way cotton was stored, transported, and ginned. Adequate storage facilities for seed cotton on the farm or at the gin are essential so that the cotton may be harvested quickly before weathering reduces its quality. Seed cotton may be stored in piles on the ground, sheds, storage houses, trailers or modules so long as it is protected from weather damage and from excessive ground moisture. Cotton modules, predominantly used in the United States,

6.6 Typical free-standing modules of seed cotton.

Australia, Israel and Brazil, are a freestanding stack of cotton produced by dumping harvested material into a form known as a module builder (Fig. 6.7), where it is compacted to a density of about 193 kg/m^3 (12 lb/ft^3). When seed cotton is consolidated for storage, it should be in a covered storage area or covered with a high-quality tarpaulin.

6.3.1 Monitoring temperatures during storage

Temperatures should be checked daily at several locations with a temperature probe for the first five to seven days, typically about 1.5 m (5 ft) apart. After that, the temperature probing can be done every three to four days or as the temperature dictates. The temperature probe should reach at least 0.8 m (2.5 ft) into the seed cotton. The temperature of cotton harvested at safe storage moisture will generally not increase more than 8 °C (15 °F) during the initial five to seven days and will then level off and even cool down as storage continues. A rapid and continuing rise in temperature above 8 °C (15 °F) or more during the first few days generally signifies a moisture problem. If a temperature of 49 °C (120 °F) is reached, or if the temperature increases by more than 11 °C (20 °F), the cotton should be ginned immediately to avoid damage to fiber and seed.

6.7 Spindle picker dumping into a module builder.

6.3.2 Quality changes during storage

Moisture content, length of storage, amount of high-moisture foreign matter, variation in moisture content throughout the stored mass, initial temperature of the seed cotton, temperature of the seed cotton during storage, weather factors during storage (temperature, relative humidity, rainfall), and protection of the seed cotton from rain and wet ground all affect seed and fiber quality during seed cotton storage. Some color degradation (spotting) occurs in seed cotton stored at a moisture level above 11%. At high moisture levels, bacterial action causes temperature increases within 48 hours that result in discoloration. Moisture content levels above 13% cause yellowness to increase sharply, especially when the storage period exceeds 45 days. For long storage periods, moisture should be below 12%. Yellowing is accelerated at high temperatures. The rate of lint yellowing increases sharply at moistures above 13% and can increase even after the temperature of a module drops.

6.3.3 Seed quality

When seed cotton is stored, the length of the storage period is important in preserving seed quality and should be based on the moisture content of the seed cotton. Seed quality factors such as germination, free fatty acid content and aflatoxin level can be degraded during storage. Seed cotton moisture content during storage is the most important variable affecting seed germination and oil quality. Seed cotton moisture content should not exceed 10% for storage when the seed will be saved for planting. Oil quality can be preserved at 12% moisture content during storage.

6.4 Gin machinery

The minimum machinery required to process clean, hand-harvested cotton consists of a dryer and/or moisture restoration device followed by a feeder to uniformly meter seed cotton into a gin stand. The ginner must be able to adjust the moisture of the cotton up or down, individualize the locules of cotton, meter the locules uniformly into the gin stand to separate the fiber from the seed, and then package the fiber and seed for market. The simplified machine sequence in Fig. 6.1 illustrates the minimum machinery necessary to produce marketable fiber. This simplified sequence, however, does not provide versatility to properly manage cotton that has excessive moisture or trash, or cotton that must meet specialized textile needs. Since saw-type lint cleaning is not included in Fig. 6.1, the baled fiber will contain imperfections such as motes and trash, and will not have a smooth appearance. A more extensive machine sequence such as that shown in Fig. 6.2 provides the flexibility to meet almost any situation for hand or machine-picked cotton.

The sequence of gin machinery to dry and clean spindle-harvested Upland cotton is as follows: dryer, cylinder cleaner, stick machine, dryer, cylinder cleaner, extractor-feeder and saw-type gin stand followed by two stages of saw-type lint cleaning (Fig. 6.2). These gin machinery recommendations are applicable worldwide, although they are used in varying amounts depending upon the needs of the respective countries. Marketing system premiums and discounts as well as the cleaning efficiency and fiber damage resulting from various gin machines serve as a starting point in determining how much machinery to use. Variation from these recommendations is necessary for stripper-harvested cotton as well as other special conditions. For stripper cotton, at least one additional extractor is added to the sequence in Fig. 6.2 prior to ginning. Moisture restoration equipment before and after fiber-seed separation should also be included – before to maintain fiber length, and after to reduce bale compression requirements.

Foreign-matter (carpel walls, leaves, stems, sticks, soil, etc.) levels in seed cotton before gin processing usually range from 1 to 5% for hand harvested, from 5 to 10% for spindle-harvested, and from 10 to 30% for stripper-harvested cottons. The foreign matter level dictates the amount of cleaning needed. The quality of ginned lint is directly related to the quality of the cotton before ginning. High grades will result from cotton that comes from clean fields. Lower grades will result from cotton that comes from grassy, weedy fields in which poor defoliation or harvesting practices are used.

When gin machinery is used in the recommended sequence, 75 to 85% of the foreign matter is usually removed from the cotton. Unfortunately, this machinery also removes small quantities of good quality cotton in the process of removing foreign matter, so the quantity of marketable cotton is reduced during cleaning. Cleaning cotton is a compromise between foreign matter level, and fiber loss and damage. The trash removal efficiency and fiber damage are inversely related to the fiber moisture.

6.4.1 Seed cotton unloading

Unloading systems remove seed cotton from the transport vehicle and feed cotton into the gin at a constant and uniform rate. An auxiliary function is to remove rocks, metal, or other hazardous material and to remove wet green bolls and some sand and dirt. There are two types of seed cotton unloading systems associated with module storage: (i) pneumatic suction through swinging telescopes that remove cotton directly from the trailer or module and (ii) module disperser systems that break up the module mechanically and deposit the seed cotton onto a conveyor that delivers it to a fixed suction pickup point. For seed cotton stored on trailers, the suction system is used.

6.4.2 Feed control

Cotton should be steadily and uniformly metered into the gin system. This is normally accomplished by a feed control which consists of a small storage chamber as well as multiple rotating cylinders that may be manually or automatically controlled. The efficiency of the drying, cleaning and conveying systems increases as the uniformity of flow increases.

6.4.3 Drying

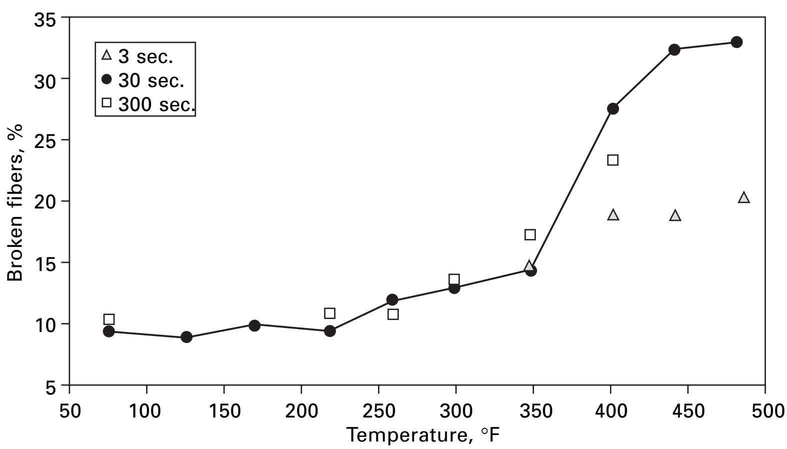
The moisture content of seed cotton is very important in the ginning process. When seed cotton enters the gin plant with high moisture content, it should be exposed to as little machinery as possible (especially extractors) before entering the drying system. Seed cotton having too high a moisture content will not clean or gin properly and will not easily separate into single locks but will form wads that may choke and damage gin machinery or entirely stop the ginning process. Seed cotton with too much moisture will also form tight twists known as 'fish hooks' that remain in the ginned lint and degrade appearance. Excess moisture is removed by exposing the cotton to heated, dry air. Drying systems include reel-type, tower, tower hybrid, fountain, hi-slip, combination drier-cleaners, and belt-type systems. Drying systems can seriously overdry cotton and must be used properly to avoid reducing cotton quality. Drying at low temperatures is much less harmful than drying at high temperatures. Larger volumes of drying air allow drying at lower temperatures.

Both constituents of seed cotton – fiber and seed – are hygroscopic but at different levels. Dry cotton placed in damp air for long periods will gain moisture, and wet cotton placed in dry air will lose moisture. For every combination of ambient air temperature and relative humidity, there are corresponding equilibrium moisture contents for the seed cotton, fiber, and seed. For example, if seed cotton is placed in air of 50% relative humidity and 21 °C (70 °F), the fibers will tend to reach a moisture content (wet basis) of approximately 6%; the seed will tend to reach a moisture content of about 9%; and the composite mass will approach a moisture content of 8%. The equilibrium moisture content at a given relative humidity is also a function of the temperature and barometric pressure.

The effects of atmospheric conditions, particularly relative humidity, must be considered when harvesting seed cotton. The effect of relative humidity on cotton moisture is relatively simple, useful, and easily understood for ambient conditions. Cotton can be dried at gins by using either ambient or heated air. When ambient air is used, the relative humidity must be equal to that necessary to achieve the desired equilibrium moisture content of the cotton fiber. Most of the drying in cotton gins is done with heated air. As the air and seed cotton move through a dryer, the air temperature will drop because (i) heat is lost, (ii) heat is used to increase the temperature of the cotton, and (iii) moisture is vaporized from the cotton which causes by far the greatest temperature drop. In addition, transport of cotton between machines with moist or dry ambient air will change the moisture content of the fiber significantly.

Drying cotton at high temperatures may damage the cotton fiber. Cotton should be dried at the lowest temperature that will produce satisfactory market grades and allow satisfactory gin operation. Cotton will scorch at 232 °C (450 °F), ignite at 460 °C (500 °F), and flash at 316 °C (600 °F). In no case should the temperature in any portion of the drying system exceed 177 °C (350 °F) because irreversible damage may occur. Temperatures over 93 °C (200 °F) damage dry fiber and should not be used if at all possible. Figure 6.8 illustrates the impact of temperatures on fiber breakage. There is an optimum fiber moisture content for each process in the gin. The effort required to control moisture will pay dividends in gin operating efficiency and market value of the baled cotton.

Cotton with too low a moisture content may stick to metal surfaces as a result of static electricity generated on the fibers and cause machinery to choke and stop. Fiber dried to very low moisture content becomes brittle and will be damaged by the mechanical processes required for cleaning and ginning. Dry cotton requires more force and power to compress than does moist cotton. When pressing and baling such low-moisture cotton, it is often difficult to achieve the desired bale weight and density without adding moisture. When two stages of seed cotton cleaning are employed, a second drying system should be used when high moisture cotton is processed. This



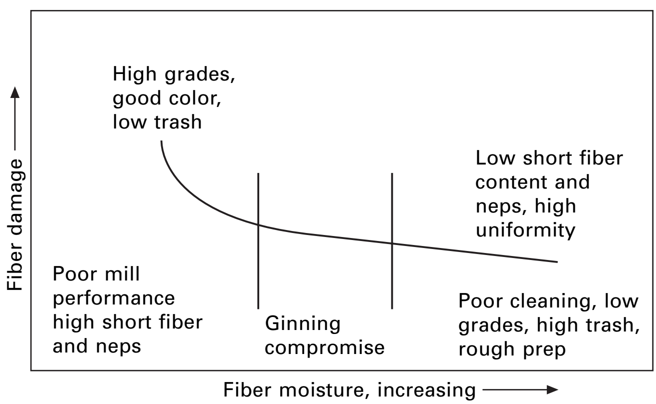
6.8 When drying temperatures exceed 220 °F, the percentages of broken fibers increase.

second drying system can have less drying capacity than the first drying system, as the major moisture removal should be done in the first system. The primary function of the second drying system is to extend the drying time and to keep the seed cotton and the machinery hot and prevent condensation of moisture.

Almost all of the moisture removed during the short drying time in commercial gin dryers comes from the fibers rather than from the seed and trash. The seed constitutes 55 to 60% of the weight of spindle-harvested seed cotton. The moisture content of the seed is considerably less important from a ginning standpoint than the moisture content of the fibers, unless the seeds are so wet that they are soft or mushy. For satisfactory ginning, seed moisture content should not exceed 12%.

Dryers should be adjusted to supply the gin stand with lint having a moisture content of 6 to 7% to preserve fiber quality. Cotton at this moisture level is more able to withstand the stresses of ginning without breaking. However, cotton at 5% moisture content will result in better cleaning and a smoother appearance, which is erroneously preferred by many classing and marketing systems. Gin cleaners remove more trash at moisture levels below 6 to 7% but not without more fiber damage. Fiber moisture higher than 7% preserves fiber length but results in ginning problems and poor cleaning (Fig. 6.9).

Also, overheating will cause increased fiber breakage from the mechanical action of cleaning in the gin and textile mill. Fiber length preservation can best be attained with fiber moisture from 6.5 to 8%; however, both cleaning efficiency and ginning rate are reduced at higher moistures. As a compromise, moisture contents of 6 to 7% are feasible. Ginning below 5% moisture can cause serious damage to the fibers, while ginning above 8% may produce rougher lint, decreased gin capacity, and less effective cleaning. For a given



6.9 Moisture content during gin processing is a compromise between cleaning efficiency and fiber quality.

cotton, fiber lengths of 2.97, 2.95, 2.90, and 2.84 cm (1.17, 1.16, 1.14 and 1.12 in.) might result from processing at 9.4, 7.4, 4.9, and 3.7% fiber moisture, respectively (Anthony 1990d). The effects of ginning cotton below 5% moisture are decreased yarn strength and yarn appearance and increased short fibers in the card sliver.

6.4.4 Seed cotton cleaning

The term 'seed cotton cleaning' refers to the use of various types of cylinder cleaners designed primarily for removal of dirt and small pieces of leaves, bracts, and other vegetative matter, as well as 'extractors' that are used to remove large trash, such as burs and sticks, from the seed cotton. Bur machines, stick machines, extractor-feeders, and combination bur and stick machines are examples of extracting-type machinery. The cleaning and extracting system serves a dual purpose. First, large trash components such as burs, limbs, and branches, must be extracted from the seed cotton before they are broken up and embedded in the cotton and so that the gin stand will operate at peak efficiency and without excessive downtime. Second, seed cotton cleaning is often necessary to obtain optimum grades and market values, especially when ginning high-trash-content cotton. Also, cleaners and extractors help open the seed cotton for more effective drying, which is usually done concurrently with cleaning. The amount of cleaning and extracting machinery required to satisfactorily clean seed cotton varies with the trash content of the seed cotton, which depends in large measure on the method of harvest.

Cylinder cleaners

Cylinder cleaners are used for removing small trash particles and for opening and preparing the seed cotton for the drying and extraction processes. The cylinder cleaner consists of a series of spiked cylinders, usually four to seven in number that agitate and convey the seed cotton across cleaning surfaces containing small openings or slots. In the impact or revolving screen cleaner, cotton is conveyed between a series of parallel, revolving serrated disks. The impact cleaner also includes a reclaimer section. It is also used as a lint cleaner in roller gins.

Air line cleaners are usually mounted in a horizontal position in the unloading-system air line. These installations normally permit both the air and seed cotton to pass through the cleaner. In some designs, an air line cleaner is combined with a separator in series to provide both cleaning and seed cotton/air separation. Air line cleaners have gained wide acceptance in stripper-harvested areas as a means for removing soil particles from seed cotton and for opening partially closed bolls and wads of seed cotton for further cleaning.

Extractors

Stick machines utilize the sling-off action of high-speed, toothed cylinders that hold the fiber while the seed cotton is beaten against grid bars to extract burs and sticks. Stick machines are usually preceded by one or two stages of drying and at least one stage of cleaning with a cleaner consisting of multiple spiked-tooth cylinders. The preceding cylinder cleaner will open cotton for more efficient cleaning by the stick machine and reduce seed cotton losses. A combination bur and stick machine (CBS), which is used for stripper-harvested cotton, is a hybrid type of extractor that combines the best features of the bur machine and the stick machine. The upper section of a CBS machine resembles a bur machine in that it is equipped with an auger feed and trash extraction system and a large-diameter saw cylinder. Gin stand feeders may include extractor cylinders as well as spiked cylinders. The primary function of an extractor-feeder is to feed seed cotton to the gin stand uniformly and at controllable rates, with extracting and cleaning as a secondary function.

Cleaning and extracting efficiency

The efficiency of a cleaner or extractor depends on many factors, including machine design; cotton moisture level; processing rate; adjustments, speed, and condition of the machine; the amount and nature of trash in the cotton; distribution of cotton across the machine; and the cotton variety. The total trash removal efficiency of cylinder cleaners is generally low compared to extractors when measured by weight of trash, as the trash particles are small. However, they are usually used in combination with other machines. Cylinder cleaners perform a most useful function in opening the cotton and removing fine trash. Studies using both machine-picked and machine-stripped cottons have shown that the total trash removal efficiency of a six-cylinder inclined cleaner with grid rods generally ranges from 10 to 40% as measured by weight. Cylinder cleaners known as 'hot air' machines also separate conveying and drying air from the seed cotton and require a vacuum dropper to return the cotton to atmospheric pressure. In this case, air is discharged with the trash.

The cleaning efficiencies of extractors vary widely, depending on the condition of the seed cotton and on machine design variables. For machine-stripped cotton, a modern commercial stick machine can be expected to remove about 65% of the burs, 50% of the sticks, and 10 to 35% of the fine trash. The total cleaning efficiency for stripped cotton is normally in the 60% to 65% range. The total cleaning efficiency can range from about 20% for cleanly picked seed cotton to as high as 50% for picked cotton containing significant amounts of burs and sticks.

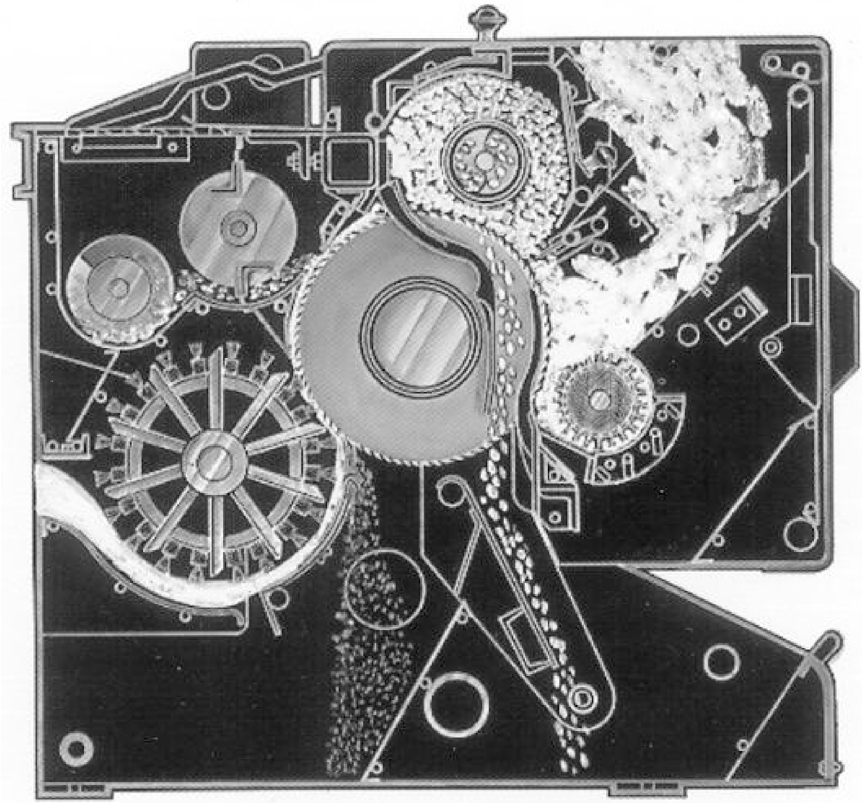
Extractor-feeders are efficient cleaners. Seed cotton is usually well dispersed when it enters an extractor-feeder, and the feed rate through this machine is often lower than the feed rate of other seed cotton cleaning machinery. Studies wherein all seed cotton cleaners prior to the extractor-feeder were bypassed have indicated that the extractor-feeder removes 70% of the hulls, 15% of the motes, and 40% of the remaining trash components and has an overall cleaning efficiency of about 40% for machine-picked cotton.

Cleaning efficiencies for sequences of four seed cotton machines consisting of a cylinder cleaner, a stick machine, a second cylinder cleaner, and an extractor-feeder range from 40% to 80%, depending on the factors previously discussed. The amount of each type of trash in cotton also varies substantially. Hand- or spindle-harvested cotton normally contains less than 10% foreign material. Each type of seed cotton cleaner is designed to remove different types of trash, and any calculation of machine efficiency is predicated on the type of trash involved.

6.4.5 Gin stands

Saw gin stands typically have 30.5 to 45.7 cm (12 to 18 in.) diameter saws spaced from 0.5 to 1 in. apart with as many as 198 saws stacked on a single mandrel. Each of these saws project through ginning ribs, grasp the fiber and pull the fiber from the seed as they are too large to pass through the opening in the ginning ribs. The diameter of seed generally follows a normal bell-shaped distribution, and occasionally a small seed escapes the gin stand and is removed by the moting sections of the gin stand or by a subsequent lint cleaner. The capacity of a single gin stand has increased from less than one bale per hour to more than 15. In the United States, gin plants typically have three or four gin stands per plant and process rates range from a few to over 100 bales per hour.

The fiber-seed attachment force differs for varieties, field deterioration, moisture content, and other factors; but is typically about 55% of the breaking force (Anthony and Griffin, 2001) suggesting that the fibers could be removed from the seed without breakage. The gin stand, whether saw (Fig. 6.10) or roller, removes (pulls) the fiber from the seed and is the heart of the ginning system. The capacity of the system and the quality and potential spinning performance of the lint depend on the operating condition and adjustment of the gin stand. Gin stands must be properly adjusted, kept in good condition, and operated at or below design capacity. If gin stands are overloaded, the quality of the cotton may be reduced. Short fiber content increases as the ginning rate increases above the manufacturer's recommendation. Short fiber also increases as saw speed increases. Increased ginning rate also increases yarn imperfections. Seed damage can also result from increasing the ginning rate, especially when the seeds are dry. High ginning rate and low seed



6.10 Continental Eagle 161 Golden Eagle Saw brush-type gin stand.

moisture cause seed damage ranging from 2 to 8% of the seed in gin stands. Thus, it is paramount to maintain the gin stand in good mechanical condition, to gin at recommended moisture levels, and not to exceed the capacity of the gin stand or other components of the system.

Roller-type gins provided the first mechanically aided means of separating lint from seed. Types of roller gins include Churka, reciprocating knife, and the rotary-knife. The ginning rate of the rotary-knife gin is about 20% of the saw-ginning rate per unit of length. Seed cotton conditioning equipment in roller gins is the same type used in saw gins. Lint cleaning in current reciprocating knife roller gins is typically done with cylinder and impact cleaners similar to those used for seed cotton as well as air-jet cleaners. Roller-type gins provided the first mechanically aided means of separating extra long staple cotton (*Gossypium barbadense*) lint from seed. The Churka gin, of unknown origin, consisted of two hard rollers that ran together at the same surface speed, pinching the fiber from the seed and producing about two pounds of lint/day. In 1840, Fones McCarthy invented a more efficient roller gin that consisted of a leather ginning roller, a stationary knife held tightly against the roller, and a reciprocating knife that pulled the seed from the lint as the lint was held by the roller and stationary knife. In the late 1950s, a rotary-knife roller gin was developed by the United States Department of Agriculture, Agricultural Research Service's Southwestern Cotton Ginning Research Laboratory, gin manufacturers, and private ginneries. This gin is currently the only roller-type gin used in the United States.

6.4.6 Lint cleaners

Lint cleaners remove leaf particles, motes, grass, and bark that remain in cotton after seed cotton cleaning, extracting, and ginning. Most gins that process machine-harvested cotton have one or more stages of lint cleaning. The lint cleaners now being marketed for saw-ginned cotton are of two general types; flow-through air type and controlled-batt saw type.

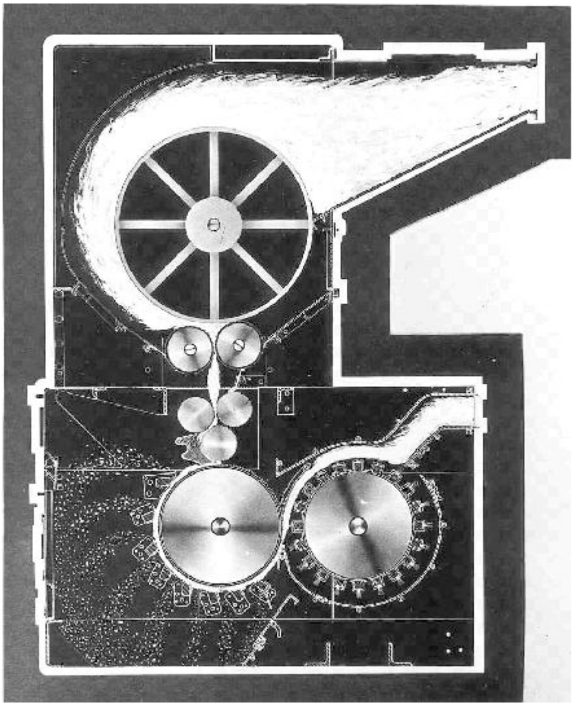
Flow-through air lint cleaner

The flow-through air lint cleaner, commercially known as the Air Jet/Super Jet®, Centrifugal Cleaner®, or Super Mote Lint Cleaner®, has no saws, brushes, or moving parts. It is usually installed immediately behind the saw or roller gin stand. Air and cotton moving through the duct change direction abruptly as they pass across a narrow trash-ejection slot. Foreign matter that is heavier than the cotton fibers and not too tightly held by fibers is ejected through the slot by inertial force. Flow-through air lint cleaners are less effective in improving the grade of cotton than saw lint cleaners because these air lint cleaners do not comb the fibers. However, air lint cleaners do remove less weight from the bale. Fiber length, fiber strength, and neps are unaffected by the air lint cleaner. This type of cleaner is commonly used in both saw and roller gins.

Controlled-batt saw lint cleaner

Lint from the gin stand or another lint cleaner is formed into a batt on a condenser screen drum. The batt is then fed through one or more sets of compression rollers, passed between a very closely fitted feed roller and feed plate or bar, and fed onto a saw cylinder. A typical saw-type lint cleaner is shown in Fig. 6.11. In addition to removing trash, lint cleaners comb and blend the cotton to produce a smooth appearance. They also degrade some desirable mill qualities, especially at low moistures.

Lint fed to the cleaning machinery at high rates will result in decreased cleaning efficiency and perhaps lower bale values. For efficient cleaning and minimum damage, feed rates should average about 750 kg/hr/m (500 lb/hr/



6.11 Typical saw-type lint cleaner.

ft) of saw-cylinder length. Lint cleaners can process 1119 to 1492 kg/hr/m (750 to 1000 lb/hr/ft) of saw with no noticeable operational problems; this rate corresponds to about 1591 kg/hr (3500 lb/hr) for a 1.7 m (66 in.) wide lint cleaner (40.6 cm or 16 in. saw cylinder) and about 3409 kg/hr (7500 lb/hr) for a 2.4 m (96 in.) wide cleaner. The higher feed rates may cause additional fiber damage and lint loss. These feed rates are also directly related to the saw diameter and saw speed. Increased saw speeds also increase fiber damage and fiber loss. Larger diameter saws such as the 61cm (24 in.) ones have higher feed rates than 30.5 or 40.6 cm (12 or 16 in.) diameter saws.

The number of grid bars in a modern lint cleaner may vary from four to nine depending on the model used. Clearance gauges are used to set the grid bars with respect to the saw cylinder. Lint cleaners have negative pressure in the waste discharge area to remove waste, improve lint cleaner efficiency, and reduce air pollution within the gin plant. Air movement across the grid bar area should average at least 33 m^3/min/m (350 ft^3/min/ft) of grid-bar length. Lint cleaning generally improves the grade classification (color, leaf, and smoothness) of the lint. However, the extent of grade improvement decreases with each succeeding cleaning. In addition, lint cleaners blend Light-Spotted cottons so that some of these pass into the White grades

(Mangialardi, 1990, 1993, 1996). Lint cleaners can also decrease the number of bales that are reduced in grade because of grass and bark content. Lint cleaners also reduce bale weights and may decrease staple length, thus affecting bale value. In some cases, the net effect of multiple stages of lint cleaning is a loss in bale sales value as well as an increase in neps and short fiber content which decreases its spinning value (Mangialardi and Anthony, 1998).

Lint cleaning for roller ginned cotton

Cylinder cleaners, textile-type beaters, impact cleaners and airjet cleaners may be used to remove motes, broken seed, fiber entanglements, and small trash not removed in seed cotton cleaning. There is no standard machinery sequence for lint cleaning roller-ginned cotton. Lint cleaning in United States plants is mostly performed by an inclined cleaner, impact cleaner and one airjet cleaner in series. The controlled-batt saw cleaner is not used in roller gins because it changes the characteristic appearance of roller ginned cotton.

6.4.7 Moisture restoration

Adding moisture before fiber/seed separation and lint cleaning will help maintain fiber length and reduce the number of fibers that break in the gin stand and lint cleaners. For example, if moisture is restored to the seed cotton to raise the fiber moisture from 4% up to 6%, staple length will be increased by 0.08 mm (1/32 in.) and short fiber content will be decreased by 2%. Adding moisture to lint that has already been ginned and lint cleaned, however, will not increase fiber length. Other benefits resulting from moisture restoration include reducing the static electricity level of the cotton, reducing the volume of the cotton required to achieve a given bale size and reducing the force required to press the bale. The resilient forces exerted on the restraining bale ties are also lower for the higher moisture cotton.

Many approaches have been used to restore moisture in cotton fiber. Moisture restoration may occur at several locations such as module feeder, feed control, dryers, above extractor feeders, moving-bed conditioners, press battery condensers, grids and other apparatus in the lint slide. There is a practical physical limit to the quantity of moisture that may be added to seed cotton. Wetting of the cotton by condensation within machinery and pipes must be prevented, or choking will result. If liquid water is present on the seed cotton mass, gin stand operation will become irregular and may cease altogether. Cotton with fiber moisture of 9% or more may be rough in appearance and will not smooth out properly when processed through the lint cleaners. Thus, the recommended fiber moisture level of 6 to 7% is based on production aspects as well as quality aspects. Lint moisture in the bale must be uniform and not exceed 7.5% at any point in the bale to avoid fiber discoloration and weight loss during storage.

One approach is to use humid air to moisten cotton. The air must be heated to carry sufficient moisture to the cotton fiber. Air can carry ten times as much water vapor at 54 °C (130 °F) (0.1118 lb/lb) as it can at 16 °C (60 °F) (0.01108 lb/lb). The air is first heated to high temperatures where it is exposed to atomized water droplets, which evaporate into the air. The evaporation process lowers the air temperature and increases the 'dew point' temperature of the air. The dew point temperature of the air must be well above the temperature of the cotton. This humid air is then blown through the cotton, which lowers the air temperature below its dew point causing fine water droplets to form on the cotton fibers throughout the cotton batt. The amount of moisture restoration with this system is limited, especially at higher ginning rates. The cotton fibers lose some of their resilience, thus reducing compressive forces required in baling.

Another approach is to atomize water and spray it directly onto the cotton. Sometimes a wetting agent is added to the water to hasten its distribution through the cotton. Most gins that use this system spray water on the cotton at the lint slide as the cotton moves by gravity from the battery condenser to the ball press. Care must be exercised to avoid wet spots in the bale, which promote bacterial and fungal growth and cause degradation of the fiber therefore this method is not recommended.

6.4.8 Packaging lint cotton

Bale packaging is the final step in processing cotton at the gin. The packaging system consists of a battery condenser, lint slide, lint feeder, tramper, bale press, bale covering, and bale tying systems. The basic tramping and pressing system may be supplemented with systems for bale conveying, weighing, and wrapping. The bale press consists of a frame, one or more hydraulic rams, and a hydraulic power system. Tying subsystems may be entirely manual, semi-automated, or fully automated. Restraining ties are usually steel wire or flat, steel straps but may also be plastic straps. Six to ten ties are typically spaced along the bale but a spirally wrapped continuous tie is sometimes used. The stress on the ties after the bale is released from the press is a function of the uniformity of the lint distribution, bale weight, bale dimensions, density to which the bale was pressed, moisture content, tie length and other factors. Bale tie strength must be matched carefully to the bale press system to prevent tie breakage and subsequent contamination and handling difficulties. In the United States, ties for gin universal density bales (227.3 kg or 500 lb confined in a 53.3 cm wide by 137.2 cm long by 76.2 cm thick (21 in. by 54 in. by 30 in.) package must have minimum breaking strengths at the joint of 9.3 kN to 17.8 kN (2100 to 4000 lb), depending on the type of tie.

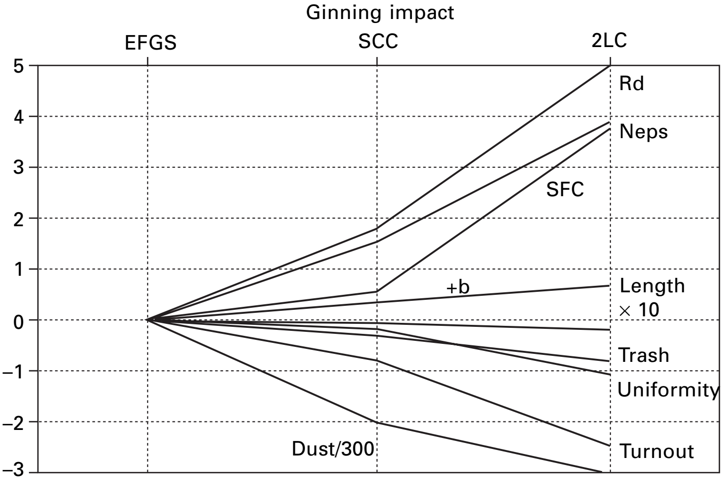
Bales should be fully covered (including openings caused by sampling), and all bale covering material should be clean, in sound condition, and of sufficient strength to adequately protect the cotton. Bales are covered in natural fibers such as cotton (preferably), burlap, and jute, and synthetics such as polypropylene and polyethylene. The material must not have salt or other corrosive materials added and must not contain sisal or other hard fiber or any other material that will contaminate or adversely affect cotton. For outside storage, bale coverings must include ultraviolet inhibitors commensurate with the anticipated storage period.

6.5 Effect of gin machinery on cotton quality

Cotton quality is affected by every production step including variety selection, cultural practices, defoliation, harvesting, storing, and ginning. Certain quality characteristics are highly influenced by genetics, while others are determined mainly by environmental conditions, cultural practices, or by harvesting and ginning practices. Problems during any step of production or processing can cause irreversible damage to fiber quality and reduce profits for the producer as well as the segments of the textile industry including spinning, weaving, dyeing, and finishing. After varietal and cultural practices are complete, fiber quality is highest the day the mature cotton boll opens. Weathering, mechanical harvesting, handling, ginning, and manufacturing can diminish the natural quality. There are many measures of the overall spinning quality of cotton fiber. The most important include strength, fiber length, short fiber content, length uniformity, maturity, fineness, trash content, color, seedcoat fragment and nep content, and stickiness.

The ginning process can significantly affect fiber length, uniformity, and the content of seedcoat fragments, trash, short fibers, and neps. The two ginning practices that have the most impact on quality are (i) the regulation of fiber moisture during ginning and cleaning, and (ii) the degree of gin cleaning used. Figure 6.9 illustrates the impact of moisture on fiber quality generally, and Fig. 6.12 illustrates the impact of cleaning on fiber quality. The extractor-feeder/gin stand shown in Fig. 6.1 and 6.2 represents the absolute minimum machinery required to produce marketable fiber. The addition of seed cotton cleaning machinery impacts some fiber quality parameters and saw-type lint cleaners impact nearly all fiber quality parameters. Large and small trash particles are removed by gin machinery. In fact, particles commonly known as ‘pepper trash’ that are typically about 500 microns in diameter are dramatically reduced by all gin processes except gin stands. Saw-type lint cleaners are especially efficient at removing small trash particles.

Choosing the degree of gin cleaning is a compromise between fiber trash content and fiber quality. Lint cleaners are much more effective in reducing the lint trash content than are seed cotton cleaners, but lint cleaners can also



6.12 Typical response of fiber parameters to seed cotton cleaning and lint cleaning machinery at 5% lint moisture. Note that EFGS = extractor-feeder and saw-type gin stand and represents the absolute minimum amount of machinery required (similar to Fig. 6.2); SCC = cylinder cleaner + stick machine + cylinder cleaner + EFGS; and 2LC = two saw-type lint cleaners + EFGS; Rd = High Volume Instrument (HVI) reflectance; neps = neps per 100 in^2 of web (a thin layer of combed fiber); SFC = short fiber content by weight (advanced fiber information system or AFIS); + b = HVI yellowness; length × 10 = HVI length times 10; trash = HVI trash; uniformity = HVI fiber length uniformity (ratio of mean length to upper half mean length); turnout = ratio of lint to seed cotton; and AFIS dust/300 = dust particles smaller than 500 microns divided by 300 for graphing purposes.

decrease fiber quality and reduce bale weight (turnout) by discarding some good fiber with the waste. Cleaning does little to change the true color of the fiber, but combing the fibers and removing trash and dust changes the perceived color. Lint cleaning can sometimes blend fibers so that fewer bales are classified as spotted or light spotted. Ginning does not affect fineness and maturity although these properties affect the amount of damage to lint during ginning and lint cleaning. Each mechanical or pneumatic device used during cleaning and ginning increases the nep content, but lint cleaners have the most pronounced influence. The number of seedcoat fragments in ginned lint is affected by the seed condition and ginning action. Yarn strength, yarn appearance, and spinning-end breakage are three important spinning quality elements. All are affected by length uniformity and, therefore, by the proportion of short or broken fibers. These three elements are usually best preserved when cotton is ginned with minimum drying and cleaning machinery.

Air-type lint cleaners remove motes (aborted ovules), green leaf, large foreign matter, seedcoat fragments and seed, and have a cleaning efficiency of about 10% by weight. Saw-type lint cleaners remove motes, small and large foreign matter, dust, seedcoat fragments and seed, and improve the perceived color. They have a cleaning efficiency of about 50% by weight. Saw-type lint cleaners also draft, comb and blend the fibers; they also increase short fiber content and neps, and decrease length as they improve market color, grade and appearance. The typical impact of gin machinery on various quality parameters is illustrated in Fig. 6.12 for reflectance, yellowness, leaf grade, high volume instrument (HVI) trash, uniformity, length, short fiber content, neps, and seedcoat fragment weight, number of seedcoat fragments, trash and dust. Note that all parameters in Fig. 6.12 are determined by machines except leaf grade.

6.6 Summary

Cotton possesses its highest fiber quality and best potential for spinning when the bolls are mature and freshly opened. The quality of baled cotton depends on many factors including variety, weather conditions, degree of weathering, cultural, harvesting and storage practices, moisture and trash content, and ginning processes. Cotton gins are responsible for converting seed cotton into bulk cottonseed and bales of lint. Gins can preserve fiber quality and improve market grade and value. Yield and market qualities such as color, leaf, micronaire, length and strength are important characteristics of fiber as well as neps, short fiber content, and seedcoat fragments.

A ginner must have two objectives: (i) to produce lint of satisfactory quality for the grower's classing and market system, and (ii) to gin the cotton with minimum reduction in fiber spinning quality so that the cotton will meet the demands of its ultimate users, the spinner and the consumer. A single 'best ginning practice' does not exist for all cottons – each lot of cotton requires careful assessment of its needs, and thus different ginning practices. Moisture content, length of storage, amount of high-moisture foreign matter, variation in moisture content throughout the stored mass, initial temperature of the seed cotton, temperature of the seed cotton during storage, weather factors during storage (temperature, relative humidity, rainfall), and protection of the cotton from rain and wet ground all affect seed and fiber quality during seed cotton storage.

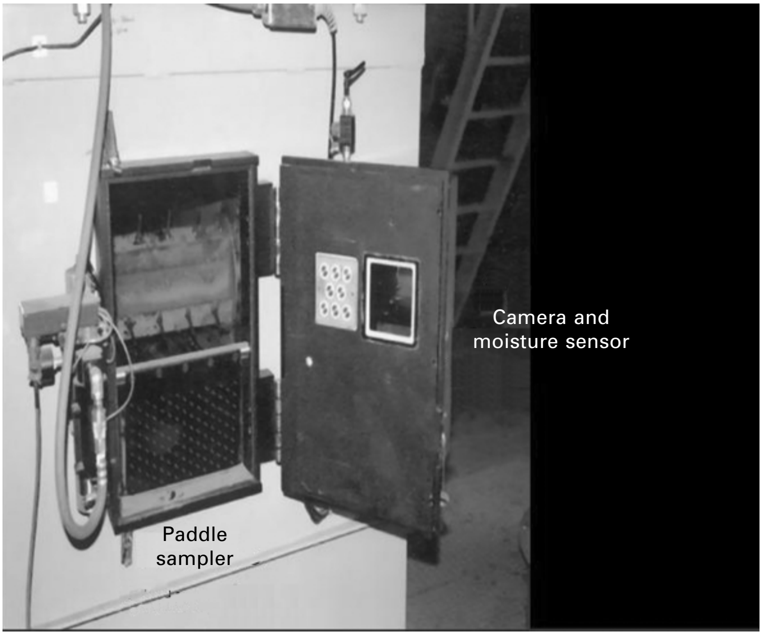
For long storage periods, moistures should be below 12%. The temperature of cotton harvested at safe storage moisture will generally not increase more than 8 °C (15 °F) during the initial five to seven days and will then level off and even cool down as storage continues. Foreign-matter levels in seed cotton before gin processing usually range from 1 to 5% for hand harvested, from 5 to 10% spindle-harvested, and from 10 to 30% for stripper-harvested cottons. A simple gin machine sequence such as a dryer, extractor-feeder and gin stand is required for clean cotton; however, a more extensive machine sequence is required for trashy cotton. The extensive sequence of gin machinery to dry and clean trashy cotton includes a dryer, cylinder cleaner, stick machine, dryer, cylinder cleaner, extractor-feeder and saw-type gin stand followed by two stages of saw-type lint cleaning. For stripper-harvested cotton, an additional extractor is required. The quality of ginned lint is directly related to the quality of the cotton before ginning. High grades will result from cotton from clean fields and lower grades will result from cotton that comes from grassy, weedy fields.

When gin machinery is used in the recommended sequence, 75 to 85% of the foreign matter is usually removed from cotton. Drying cotton at high temperatures may damage the cotton fiber. Cotton should be dried at the lowest temperature that will produce satisfactory market grades and allow satisfactory gin operation. In no case should the temperature in any portion of the drying system exceed 177 °C (350 °F) because irreversible damage may occur. Temperatures over 121 °C (250 °F) cause moderate fiber damage and should not be used if at all possible. Adding moisture before fiber/seed separation and lint cleaning will help maintain fiber length and reduce the number of fibers that break in the gin stand and lint cleaners. The ginning process can significantly affect fiber length, uniformity, and the content of seedcoat fragments, trash, short fibers, and neps. Choosing the degree of gin cleaning is a compromise between fiber trash content and fiber quality. Lint cleaners are much more effective in reducing the lint trash content than are seed cotton cleaners, but lint cleaners can also decrease fiber quality and reduce bale weight (turnout) by discarding some good fiber with the waste. The best ginning practice is simply to use the minimum machinery for a particular cotton to achieve the optimum market grade.

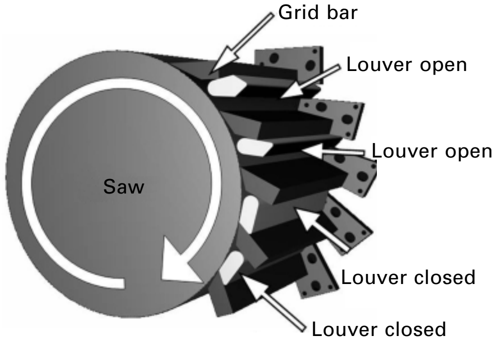
Ginners must determine the needs of their customers and select the drying and cleaning processes that meet their needs. They must ensure that farmers are aware of the impact of varieties and cultural practices on the quality of the seed cotton brought to the gin, and thus, the amount of gin processing equipment required. Gin procedures must be well planned to ensure timely and efficient processing. Operator and management personnel must be well trained and skilled in all aspects of gin operations. Gin machinery must be operated at the proper speeds and capacities, and must be well maintained. Moisture must be managed from harvesting through packaging. Cotton must not be harvested or stored at seed cotton moisture levels above 12% wet basis. Cotton should not be exposed to temperatures above 121 °C (250 °F) and must not be exposed to temperatures above 177 °C (350 °F) unless it is wet. Fiber moisture at the gin stand should be 6 to 7%, and the fiber should be packaged at less than 7.5% moisture. Bales should be packaged at the proper density and protected by high quality bale ties and bale coverings. Good gin operations use only the amount of drying, moisture restoration, and cleaning required to meet customer demands. New, proven technology must be used to process cotton as well as to monitor and control fiber quality.

6.7 Future trends

New and emerging gin technologies to reduce manpower, energy, and fiber loss as well as to improve fiber quality and fiber utilization potential will shape the future of the global cotton industry. These technologies will migrate from the more advanced cotton production areas to the less advanced and globalize the production, marketing and use of cotton. Two technologies recently developed by the United States Department of Agriculture and licensed to private industry are available globally. These are a computerized process control system that optimizes cleaning and drying called IntelliGin® (Fig. 6.13), and a prescription lint cleaner called LouverMax® (Fig. 6.14). IntelliGin® grades the cotton online at three sensing stations and optimizes the gin process, and increases net bale value about $8US per bale. The LouverMax® uses from 1 to 8 cleaning points to achieve the required cleaning and reduces the amount of good fiber lost by the lint cleaner, and increases bale weight 8 to 10 pounds.



6.13 Typical sensing station used in the IntelliGin.



6.14 Lint cleaner equipped with louvers for selectively cleaning cotton.

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7
The opening, blending, cleaning, and carding of cotton

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7.1 Introduction

When cotton and short-staple man-made fibres (MMFs) are delivered to a spinning mill, they are usually received in the form of compressed, high density bales of 1.5 m × 0.5 m × 0.5 m in dimensions, weighing 230–250 kg, and of 613 kg m^{-3} density. A typical production rate for, say, a medium size mill would be of the order of 500 kg hr^{-1}. This means that the equivalent of one bale of fibre would need to be processed every $^1/_2$ hour. Depending on the fineness, length and density of the fibre type to be converted to yarn, the bale can comprise 1.5 to 50 × 10^9 fibres (50 billion); this calculates to approximately 30 million fibres per second removed from the baled stock. The most practical way of doing this is to remove clumps or tufts of fibres from the bale and then progressively reduce the size of these tufts into smaller tufts or tuftlets ultimately reaching the state of a collection of individual fibres which can be subsequently spun to make the required yarn. Therefore, in preparing materials for spinning, the primary purpose of blowroom operations is to convert the baled fibre mass into the individual fibre state and assemble the fibres in a suitable form for subsequent processing by the intermediate processing stages to spinning. The individual fibres state is essential because these post-blowroom stages require the material to be a linear mass of disentangled fibres, so that fibres can be made to slide past each other in order to uniformly reduce the linear density of the mass. During this action fibre friction straightens and parallelises the fibres in the cross-section of the reduced linear mass prior to it being twisted to make yarn.

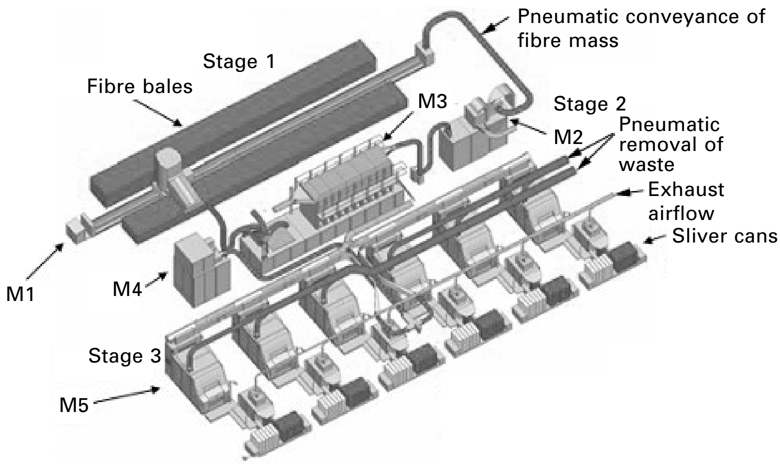
The action of breaking the baled fibre mass down into initially large and then smaller size tufts (tuflets) is termed opening (fibre opening) and the converting of small size tufts into individual fibres is called carding. With natural fibres such as cotton, the baled fibre mass will contain impurities, such as leaf, seed, trash and dust particles. It is essential that as much as possible of the impurities are removed so as to produce yarns of high quality.

Although certain of the post-blowroom processes can remove impurities, the opening and carding actions of the blowroom machines enable most of the impurities to be extracted at these early stages. We therefore refer to the term cleaning as the removal of impurities from fibre tufts during opening and carding.

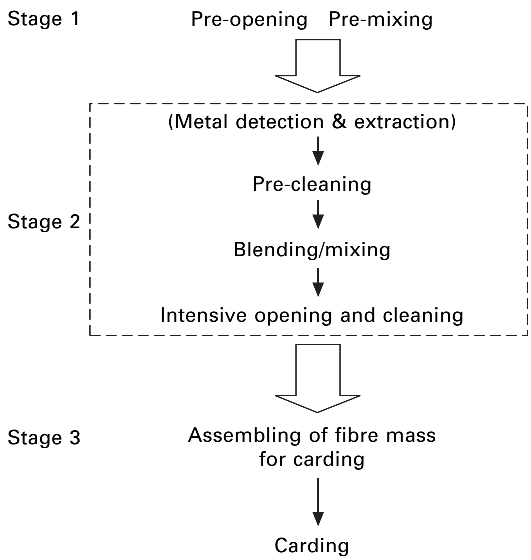
When the baled fibre mass is to be opened into small tufts a sequence of machines is used to perform this task and as they can also carry out cleaning of the tufts, the machine sequence is called an opening and cleaning line; machines making up such a line are generally referred to as opening and cleaning machines. In the progressive opening of the fibre mass, tufts from one machine are fed to the next in the series for further opening. This is achieved by airflow through pipe ducting linking the machines and is described as pneumatic transport. The tufts are effectively blown from one machine to the next in line, hence the term 'the blowroom'.

As the tufts arrive at a machine they are collected in a bin or hopper to form a new assembled mass of tufts which is then worked on by the machine. The opportunity therefore arises for tufts to be mixed or blended as they are being collected to form the assembled mass. Thus, tufts from different bales and different parts of a bale can be blended. This is an essential part of the blowroom process, since fibres at different regions of a bale will have noticeable differences in their properties, particularly natural fibres like cotton where maturity, length, strength and elongation may differ. Unless tufts are well blended, the difference in fibre properties can result in poor processing performance upstream from the blowroom, such as high end breakage rates in spinning, and in a lower quality of the resultant yarn, e.g., lower yarn strength and evenness. We speak therefore of blowroom blending as the mixing of opened fibrous tufts to produce a homogeneous mass which facilitates consistent yarn quality. The word 'facilitate' is important here, because other process factors can also cause lower yarn quality and reduced production efficiency.

Once the fibre mass is suitably opened, cleaned and blended it arrives at the carding machine and here the tufts are descretised into individual fibres which are reassembled into the form of a twistless rope of disentangled fibres, i.e. a linear mass of fibres held together largely by interfibre friction. This form of fibre mass is called a carded sliver and is coiled into large cans (card sliver cans) ready for the upstream processes. At one time the carding process was housed separately from the earlier opening and cleaning machines. Then the fibre mass was fed in the form of laps to the card. Modern mills now tend to have these machines in the same location with pneumatic transport of tufts to the cards. Figure 7.1 illustrates a typical machine sequence involving opening, cleaning, blending and carding and Fig. 7.2 gives a flowchart indicating the function of each stage.



7.1 Blowroom: opening, cleaning, blending and carding installation.



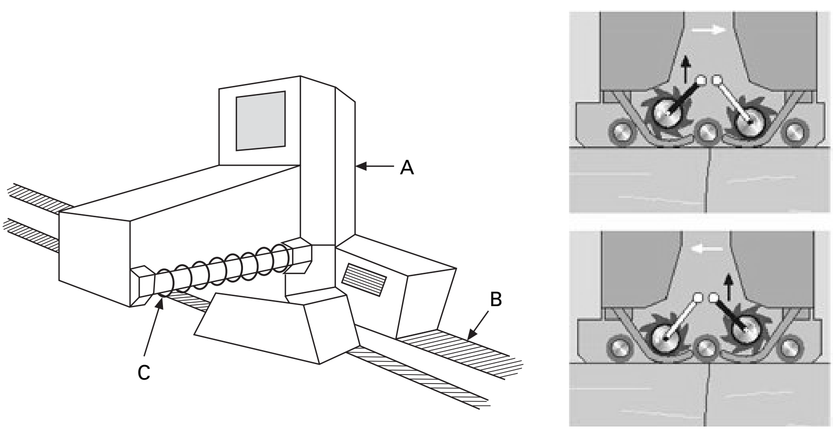
7.2 Basic sequence of blowroom operations.

Stage 1 uses a special machine (M1) for the automatic removal of tufts from lines of bales ('bale lay downs'), Stage 2 involves the opening, cleaning and blending machines (M2, M3, M4) and Stage 3 the carding machines (M5). As shown, the opening, cleaning and blending line feeds six cards, which indicates that the output from Stages 1 and 2 is much greater than the production capacity of one card. A machine throughput balance must therefore be established when planning and designing a blowroom operation.

From this overview we can now consider the basic principles involved at each stage and the production calculations that can be used to determine the appropriate number of cards for a blowroom line of a given production output. Throughout the remainder of this chapter descriptions of the blowroom machines manufactured by Trutzschler GmbH & Co. KG will be used to illustrate the main principles involved in short-staple materials preparation. These should not necessarily be considered as the author's recommendations, since there are also other manufacturers of similar equipment, and the reader may well find it of interest to visit the websites of these other companies.

7.2 Stage 1: pre-opening/pre-mixing

By considering how the fibre mass is opened up into tufts, cleaned and blended we can identify the various actions of particular blowroom machines used for material preparation. Stage 1 is largely concerned with the actions of opposing points or spikes, which is suitable for breaking the fibre mass down into large size tufts of around 70 mg. In modern short-staple yarn production mills the automatic bale opener (M1) uses this action most effectively (see Fig. 7.3). The main working parts are the swivel carriage/ tower (A) with guide arm; two lines of rotating large-tooth, saw-blade discs (B) – one at either side of the guide arm; and a guide rail and trunking (C). One line of discs rotates clockwise while the other anticlockwise giving the action of opposing points, thereby plucking tufts from the tops of a line of bales, as the carriage runs along the guide rail. The tufts are transported pneumatically into and then along the interior ducting of the guide rail, subsequently through a ducting linked to the first machine of stage 2. This plucking of tufts from each consecutive bale enables mixing at a coarse level, hence the reference to pre-mixing. Better mixing or blending of tufts occurs with small tuft sizes. Automatic bale openers can work on two lines of bale lay-down, one on each side of the guide rail, and positioned parallel



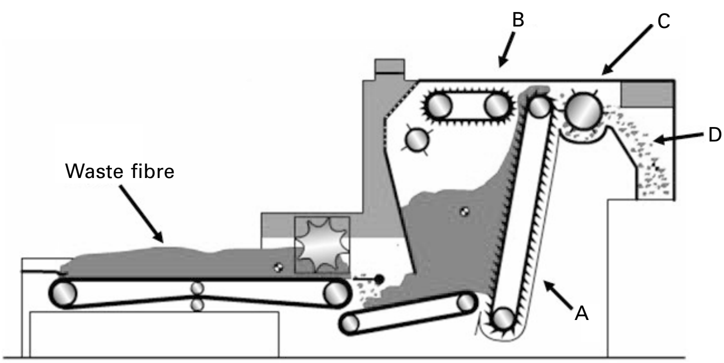
7.3 Automatic bale opener: Trutzschler Baleomat.

to the guide rail. Each line can be up to three bales wide and 100 or more bales in length. As the carriage reaches the end of a line, it swivels and starts plucking the bales in the other line. The carriage traverse can be 6–13 m per minute, giving a production rate of up to 1500 kg h^{-1}.

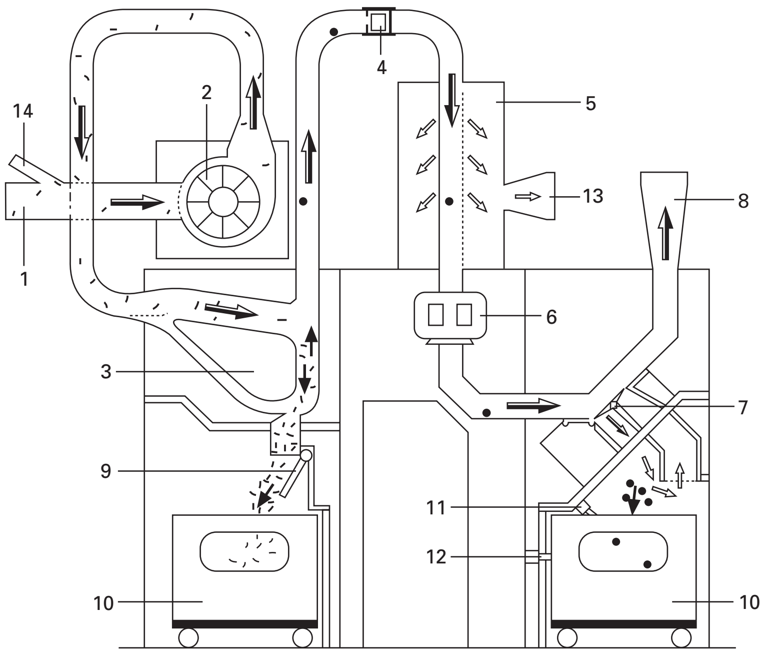
It should be evident that bales of different cotton grades or fibre types (cotton + viscose or cotton + polyester) could be positioned to make up the lines and in so doing, get a useful pre-mixing for the eventual production of 'blended yarns'. Process waste with high fibre content (usually from the intermediate process to spinning, up-stream of the blowroom) may be recycled by feeding into the process line around 5% of waste with the virgin fibre. A waste feeder is illustrated in Fig. 7.4. Here the fibrous waste is fed from the hopper by the spike lattice (A) and belt (B) to the fast rotating spike roller (C) which separates the fibre mass into tufts. Since the waste is usually made up of fibres that have previously passed through the blowroom, it is important to keep further mechanical treatment to a minimum, so as to reduce fibre breakage. The waste tufts therefore may be fed directly to the blending unit of Stage 2 provided no heavy foreign particles are contained within it.

7.3 Stage 2 heavy particle detection and extraction

The first machine in stage – 2, called the multifunctional separator, is one which separates heavy foreign particles and dust from fibre tufts delivered by the automatic bale opener and waste opener. These particles are liberated from the fibre as the mass of the bale is broken down into tufts. The tufts are of a lower density than the heavy foreign particles, and fibres forming the tufts also have a greater surface area to weigh ratio. Therefore, the airflow transporting the material through the machine can be used to effect the removal of the unwanted particles; we may refer to this as the action of air currents. There are two approaches by which the action of air currents is utilised (see Fig. 7.5).



7.4 Waste fibre feeder.



7.5 Multifunction Separator.

Tufts (1) from the automatic bale opener and tufts (14) from the waste opener are sucked into the multifunctional separator by a fan (2). The arrows indicate the flow path of the tufts. The small black dashes represent the heavy trash particles and the black dots metallic fragments embedded in some tufts. These fragments may result from damaged machine parts during the harvesting and ginning of cotton.

The first action of air currents occurs at (3) where the flow path splits into two; the material being prevented from moving along the lower path. Since the airflow rate is constant through this section of the machine, the splitting of the path means a slower flow in the upper path. The bends of 90° angle give a sudden change of direction to the airflow. The lift due to the combined airflow from both flow paths is sufficiently larger than the momentum and gravitational force on each tuft to move tufts in the changed direction. However, the airdrag is not greater than the opposing momentum and gravitational force on the more dense foreign particles. Consequently these drop from the airflow and are collected via a trap door (9) into a waste bin (10), whilst the liberated dust and trash particles remain in the airflow.

The second action of air currents occurs at (5). Here a perforated metal sheet or wire mesh enables the dust particles in the flow to be removed through (13); the dusty exhausted air is fed to a filter installation. Small pieces of metallic materials may remain trapped within some tufts, in which case these are detected by sensors at (6), and a diverter (7) (a swing flap) momentarily changes the direction of flow so that these fufts can be ejected to waste. The remaining fibre tufts subsequently exit through (8) to the opening/pre-cleaning unit.

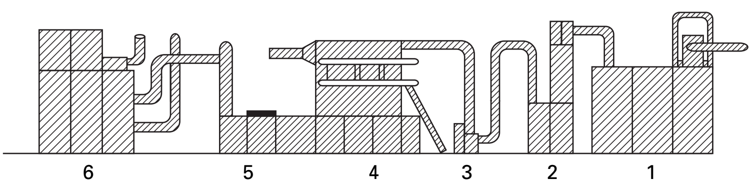
With combustible materials, there is always the possibility of tufts being ignited from sparks caused by metal particles impacting on the sides of the air trunking. Burning or smouldering tufts will need to be removed before reaching the opening/pre-cleaning stage. A detector (4) signals the diverter (7) to redirect any ignited material to the waste bin (10). A fire extinguisher (11) and heat sensor (12) are fitted safety provisions for any burning material entering the waste container. Figure 7.6 shows the remaining sequence of machines in Stage 2 following the multifunctional separator.

7.3.1 Stage 2 pre-cleaning

The opener/pre-cleaner (see Fig. 7.7) is comprised of a wire-mesh cylindrical drum, termed a condenser (1), a feed trunk (2), a cleaning compartment (3), beaters and grid bars (4), an exit suction trunking (5) and a waste removal device (6). The arrows indicate the flow of the tufts.

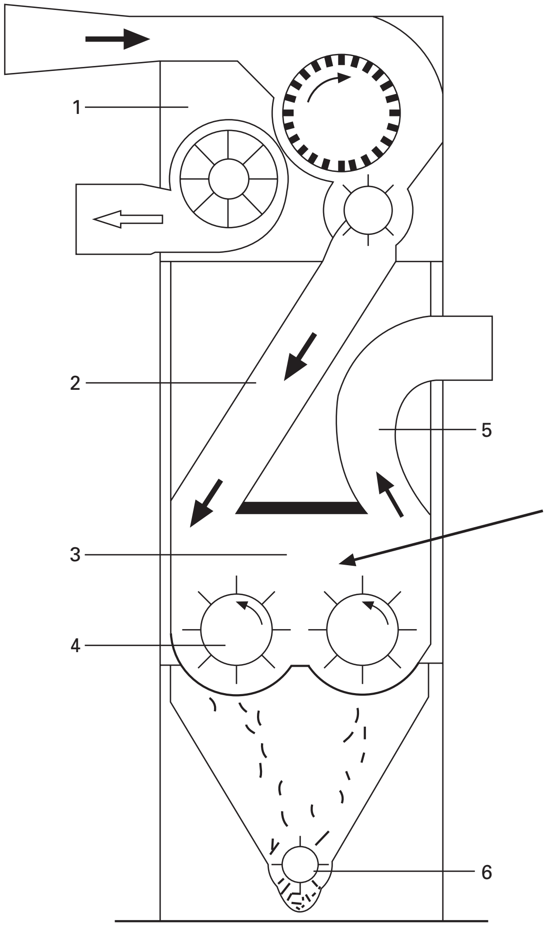
The condenser fulfils two functions. It removes dust particles in the air stream and from the surface of the tufts as they are 'condensed' onto it. Second, its rotation transports the tufts into the feed trunk, which is positioned to ensure tangential feeding to the left beater or cleaning roll. The two beaters are basically cylindrical rolls with metal rods projecting from the roller surface.

When the fibre mass of a large tuft is opened into smaller tufts (approx. 8 mg) by the beaters, fibres in one part of the mass will slide past fibres in another part. The interfibre friction will liberate dust particles attached to fibre surfaces and importantly will move trash particles to the surface of the smaller tufts. These particles cling to the surface fibres and to remove them, the tufts are thrown against (and pulled over) narrowly spaced bars (grid bars) so that the impact shakes the particles from the tufts and ejects them



1 Multifunctional separator
2 Pre-cleaner
3 Booster fan
4 Stack blender
5 Intensive opener/cleaner
6 Foreign particle separator

7.6 Sequence of machines comprising Stage 2.

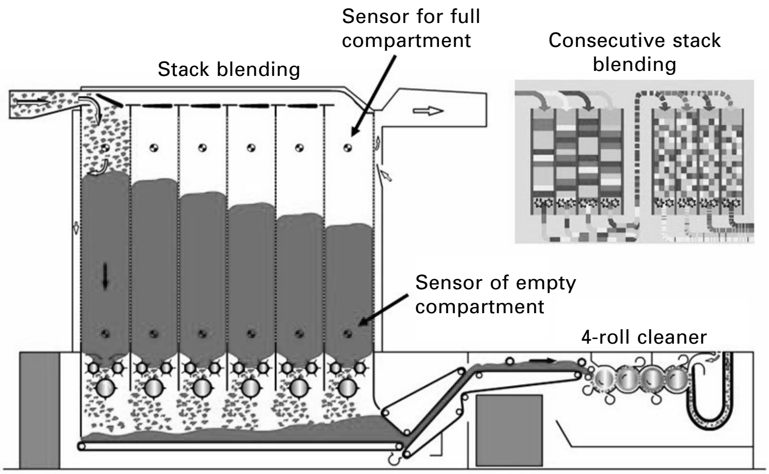


7.7 Opener/pre-cleaner.

through the gaps of the grid bars. This 'beater and grid bars' technique is a commonly employed pre-cleaning action. A booster fan ((3) in Fig. 7.6) transports the pre-cleaned tufts to a stack blender ((4) in Fig. 7.6).

7.3.2 Stage 2: Blending/mixing

The operation of a stack blender is depicted in Fig. 7.8. The basic principle of stack blending is to fill, sequentially, a series of vertical compartments in a storage bin (providing stacks of tufts), and then to remove layers from consecutive stacks in a manner that sandwiches the layers, thereby dispersing and mixing tufts, say, from the first traverse of the bale lay down with tufts from subsequent traverses. The figure shows a stack blender of six vertical bins, referred to as a six fold mixer; a four fold mixer would comprise four vertical bins, and so on up to a ten fold mixer.



7.8 Stack blending with intensive opening and cleaning.

As the figure illustrates, whilst fibre tufts are being deposited into the bins, previously accumulated tufts are dropped simultaneously onto a moving belt. With the movement of the belt towards the exit of the blender, the drops from the first bin forms the first layer that receives the deposits from the second bin, which forms the second layer, and this in turn receives the third deposited layer from the third bin. This sequences of deposition eventually forms a sixth layer accumulation that is continuously fed to an intensive opener and cleaner (the four-roller cleaner). The top left of Fig. 7.8 illustrates that significant benefits may be obtained with consecutive stack blending. There are three important reasons for blending.

1. *Reduction of the production cost.* Production cost = raw material cost + conversion cost, the latter accounting for capital, labour, space, maintenance, etc. The raw material element can account for around 50% of the production cost. Where appropriate it may be useful to blend different grades of a fibre type, e.g. cotton, to obtain a reduced cost per kg.
2. *Product development.* Often this aspect involves blending cotton with man-made fibres (mmfs), such as cotton/polyester blends for easy care fabrics, acrylic/cotton blends for increased bulk and handle in, say, sportswear. Commonly, blending of mmfs and cotton is undertaken downstream of the blowroom. However blowroom blending is favoured by some mills to provide a better intimacy of blend.
3. *Improvement in processing performance and/or upgrading yarn quality.* Often when lower grade cottons are being processed good blending can be critical to the downstream process efficiency and the resultant yarn quality, in terms of irregularity, strength and hairiness. A fibre of given properties will require a minimum twist to spin. Thus, variation in properties

can cause variation in the yarn twist and thereby add to the variation in yarn strength. Tension fluctuation in spinning and post spinning processes can therefore result in high end breakage rates of yarns made from inadequately blended fibre stock. Poor blending can also lead to dyeing faults in piece-dye fabrics. A well blended fibre stock will ensure uniformity of properties throughout a batch of material being spun.

As we have seen, blending starts at automatic bale opening, and therefore the number of bales constituting the bale lay down is important; the maximum possible would be preferred but would be limited by practical constraints such as floor space and operational logistics.

The proportions of each constituent of a fibre blend can be estimated from:

$$W_b = w_1 + w_2 + w_3 \ldots + w_n = \sum w_i \qquad 7.1$$

$$p_1 = \frac{w_1}{W_b} \quad \text{or} \quad p_i = \frac{w_i}{W_b} \qquad 7.2$$

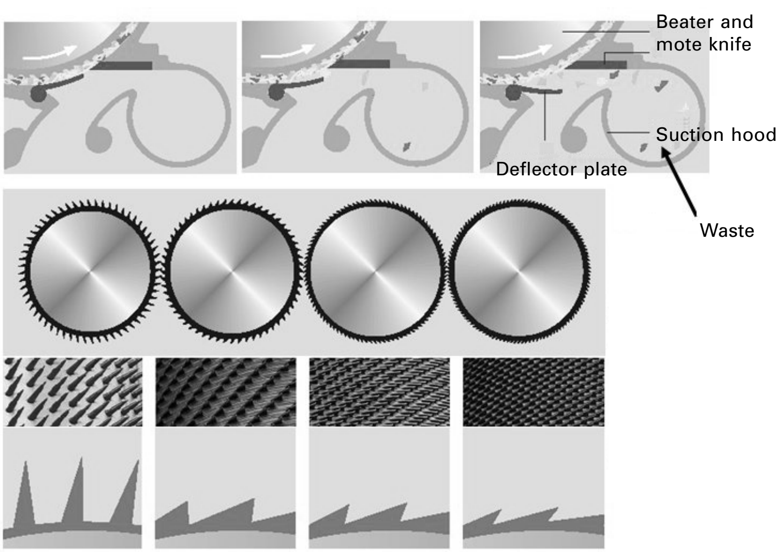
where W_b is the total mass, and w_i and p_i are the individual mass contributions and blend fractions of the fibre components for $i = 1$ to n components. In preparing to blend different cotton grades, or mmf/cotton blend, it is useful to estimate the average fibre characteristics of the blend that will influence yarn properties and spinning performance, in particular the mean length, fineness and strength. Table 7.1 gives the relevant equations and Lee and Kin[1] describe the application of these equations in linear programming for the formulation of cotton blends.

Table 7.1 Formulation of fibre blends

Fibre characteristics	Blend equation
Fineness:	
Diameter (μ)	$d_m^2 = \Sigma p_i d_i^2$ where d_m – mean of the blend, p_i and d_i – the proportion and mean diameter for each blend component for i = 1 to n components
Count (mtex)	$f_m = 100/[\Sigma q_i / f_i]$ where f_m – mean of the blend, q_i and f_i – the percentage and mean count for each blend component for i = 1 to n components
Length	$L_m = \Sigma p_i L_i$ where L_m – mean of the blend, p_i and L_i – the proportion and mean length for each blend component for i = 1 to n components
Strength	$S_m = \Sigma p_i S_i$ where S_m – mean of the blend, p_i and S_i – the proportion and mean strength for each blend component for i = 1 to n components

7.3.3 Stage 2: intensive opening and cleaning

The four-roll cleaner employs the intensive opening action of feed roller(s) and beater combination coupled with the cleaning action of beater and mote knife. As depicted in Fig. 7.8 a pair of feed rollers supply the fibre mass of blended tufts to the first of four rolls or beaters covered in sharp points. The arrows indicate the direction of rotation of each beater. The first beater divides the tufts into smaller sizes, freeing trash particles, and transports the mass onwards, the fibre mass reaching the second, third and ultimately the fourth beater. Each successive beater has an increased surface speed and more closely spaced points. Also, each beater is positioned closer to the one it follows. These three factors facilitate effective opening of tufts and freeing of trash particles. Located around the periphery of each beater are deflector plates with mote knives and attached suction hoods for waste particle removal. Each location is referred to as a cleaning point. The deflector plate is positioned close to the beater surface so that as tufts pass by, trash entrained in the flow can be ejected by the action of centrifugal forces near the edge of the mote knives, then deflected by the plate and removed by the continuous air suction (see Fig. 7.9). The permanent suction results also in the removal of dust particles. It can be seen from the figure that the position of the deflector plate determines the ejection of the trash particles. For cotton of low trash content the deflector plate would be positioned to give a narrower opening than in the case of dirtier cottons, the aim being to keep the fibre content of the waste to a minimum. It is important to note that the objective of these

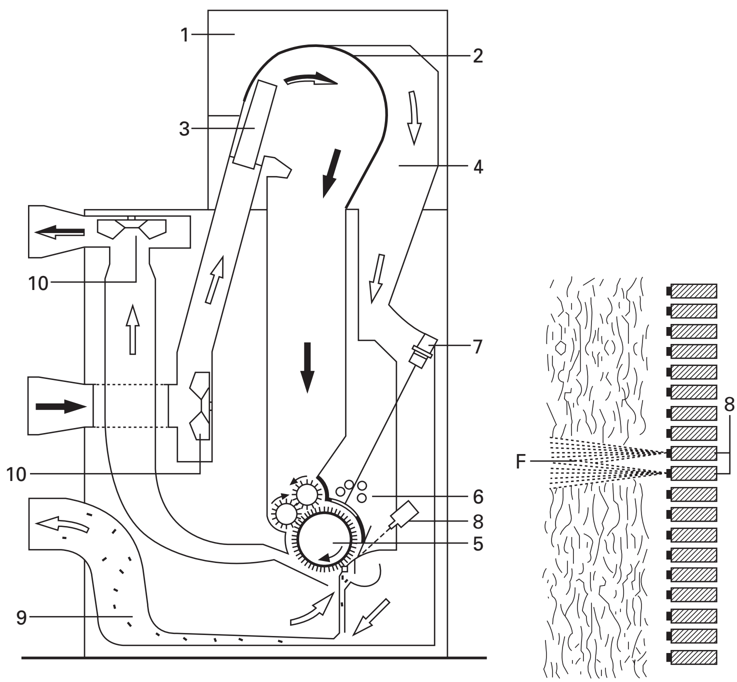


7.9 Intensive cleaning action.

cleaning systems is the intensive, but gentle opening of the fibre tufts in order to minimise fibre damage.

Gentle opening is achieved by having the first beater clothed in pins angled ca. 10° from the vertical, and the remaining beaters having saw-tooth clothing, the tooth angle increasing from roller to roller (e.g. 15°, 30°, 40°). The teeth density (number of points per cm^2) should also progressively increase from beater 1 to 4, depending on fineness of the fibre being produced. Importantly, the beater speeds should progressively increase from beater 1 to 4 (for example 300, 500, 800, 1200, $rmin^{-1}$). Hence, the mean tuft size is decreased (approximate figures) from 1 mg by the first beater to 0.7 mg, 0.5 mg and 0.1 mg by the second, third and fourth beaters, respectively. It is only the fourth beater that reaches a sufficiently high surface speed at which the finest trash particles are ejected.

The final cleaning machine in Stage 2, is the foreign particle separator, indicated as M4 in Fig. 7.1. Foreign particles often include pigment coloured polypropylene bale straps, which get broken down into fine fibre fragments during carding. This results in yarns produced being rejected owing to material contamination. At this part of the blowroom the aim is to significantly reduce the dust still present within the mass flow, but critically also, to detect and remove particle contamination of the fibre mass. Figure 7.10 illustrates how this is achieved.



7.10 Foreign particle separator.

The white arrows indicate the direction of the airflow through the machine, and the black arrows depict the fibre mass flow. The dedusting section (1) is screened by a large perforated metal sheet (2). Distribution flaps (3) spread the tufts over the surface area of (2) and the dust released is sucked away via (4). The tufts fall into a reserve chute and the mass of material is fed by a pair of sawtooth rollers to a beater (5) covered in fine pins. The tufts, when caught by the beater, become lightly and uniformly spread over the beater surface. Four fluorescent lamps (6) give high but uniform illumination of the beater surface. Two digital cameras continuously scan the beater surface. On detection of a contaminated part of the fibre mass (F) a bank of compressed air nozzles (8) are selectively activated to blow the contaminated part of the fibre mass from the beater surface into a waste suction unit (9). The fibre mass is therefore screened to be free of material contaminants. The tufts are transported through the machine by airflow generated from two integrated fans (10), and the fan at the exit blows the screened tufts through the trunking to the carding machines of Stage 2.

7.3.4 Estimation of the effectiveness of opening and cleaning systems

Intensity of opening, I

To assess the opening action of a beater we refer to its intensity of opening, I. This can be defined as the amount of fibrous mass in mg per one striker of a beater for a preset production rate and beater speed.[2] Thus,

$$I = \frac{P \cdot 10^6}{60 n_b N} \qquad 7.3$$

where I = intensity of opening (mg) P = production rate (kg hr^{-1}); n_b = beater speed (rmin^{-1}); N = number of strikers.

The intensity of opening is an estimate of the tuft size produced by a given beater and from the I value we can get an approximation of the number of fibres, n_f, comprising a tuft produced by a given beater.

$$n_f = \frac{I \cdot 10^5}{L_f \cdot T_f} \qquad 7.4$$

where L_f = average fibre length (cm); T_f = average fibre linear density (millitex). An alternative to tuft size is the number of blows per kg, N_k.

$$N_k = \frac{1}{P}[60 \cdot n_b \cdot N] \qquad 7.5$$

Although the I or N_k value gives an indication of the degree of treatment, in that the more blows per kg of material the smaller the tuft size and the more trash likely to be removed, the calculation does not take account of the effect of the space settings of beater to feed roller, beater to grid, grid spacing, and beater to deflector plate.

The mechanical removal of trash and dirt particles is always accompanied by some loss of fibre; with cotton cleaning the amount of fibre in the waste is referred to as the lint content. Usually this is composed of short lengths of broken fibres but poor processing can cause the loss of fibres of much longer lengths and/or a high level of fibre breakage. The objective is to optimise the machine settings, i.e., beater speed, production rate and gap settings of the working components to minimise the percentage lint and useable fibre length in the waste.

Openness value, OV

The more effectively the material is opened, the better the chances of trash removal and the lower the fibre content of the waste. The opening action primarily does two things. It reduces the fibre mass into small tufts, as described earlier, but it also loosens the tightness of packing of the fibres within each tuft, thereby reducing the tuft density or increasing its specific volume; in common parlance we could refer to the tufts being more 'fluffed up' which describes their visual appearance. The openness value (OV) is a measure of how 'fluffed up' the fibre mass has become on passing through a beater system, i.e., the effectiveness of the degree of opening. Since we are concerned with changes in tuft density, and to take account of different fibre densities, OV is defined as the product of the specific volume of the fibre mass and the specific gravity (SG) of the constituent fibres (or for a blend of fibres the sum of the product of their relative proportions and their SGs).[2]

Szaloki[2] describes a simple method of measuring the specific volume for cotton and short-staple mmfs. A sample of the fibrous mass is used to fill a 4000 ml Pyrex beaker. A Plexiglas disc, weighing 200 g, with air-escape holes and of a slightly smaller diameter than that of the beaker interior is placed on top of the sample in the beaker. After a settlement time of 15–20 seconds the compressed volume is noted, the sample weighed and the specific volume in units of $cm^3\ g^{-1}$ calculated. Eight to ten measured samples are usually required for a 95% confidence level in the resulting data. Measured values show a typical OV for the fibre mass in a bale of cotton at the beginning of an opening and cleaning line to be around 51 $cm^3 g^{-1}$, whilst at the end of the line the OV can be greater than 140 $cm^3\ g^{-1}$.

Cleaning efficiency (CE) and effective cleaning (EC)

The cleaning efficiency (CE) is the percentage of the impurities removed from the fibre mass. Hence,

$$CE = 100 \frac{[W_{IN} - W_O]}{W_{IN}} \quad 7.6$$

where W_{IN} and W_O are the mass values of the impurities in the feedstock and the processed material, respectively at the input and output to a machine or a sequence of machines, and CE is the cleaning efficiency.

As referred to earlier, some unavoidable fibre loss occurs during mechanical cleaning. When considering this fibre loss we can refer to the effective cleaning (EC) of a machine or a sequence of machines as

$$EC = 100 \frac{[W_T - W_F]}{W_T} \quad 7.7$$

W_T = mass of waste; W_F = mass fibre in the waste.

7.4 Stage 3: carding

7.4.1 Basic principle of carding

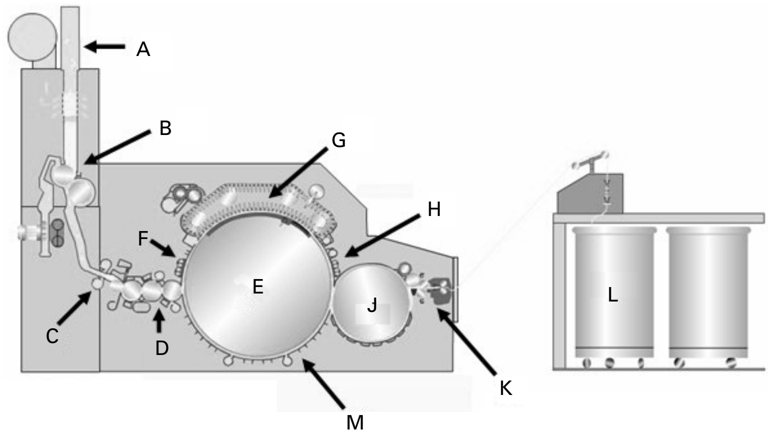
Carding involves:

- dividing tufts into smaller sizes, termed tuflets
- separating each tuftlet into individual fibres to form a filmy web, by working the tuftlets between closely spaced surfaces covered in sharp opposing points
- consolidating the web into a continuous length having the form of an untwisted rope, called a card sliver
- removing trash, fibre fragments, very short fibres and neps during the reduction of tufts into tuftlets and tuftlets into individual fibres.

7.4.2 Key features and operation of the revolving flat card

Figure 7.11 illustrates the main working components of a revolving flat card and Table 7.2 gives typical operational speeds and settings. The carding machine is comprised of four sub-systems or four zones.

- Zone I: the feed arrangement; commonly referred to as the chute feed, it comprises an inlet chute, A, linked to the outlet of Stage 2 (i.e. the trunking connecting the foreign particles separator); a feed roller and pin covered beater, B; and a pair of air outlet combs, C.
- Zone II: the taker-in and fibre mass transfer; this consists of a feed roller and spring-loaded feed plate, three beaters, D, called a triple taker-in system, and a fixed-flats cleaning system, F.
- Zone III: the carding zone; this includes the carding cylinder with its



7.11 The revolving flat card.

Table 7.2 Example of dimensions and relative settings of revolving flat card

Component	Diameter (mm)	Teeth density (ppcm^{-2})	Speed (r min^{-1})	Draft	Approximate settings (μm)
Taker-in (3rd beater)	229 over wire 248	7–8	800	1000	Taker-in/ cylinder 25
Cylinder	1270 over wire 1289	62–100	300	2.08 25	Cylinder/flats
Flats	44.5 × 1016	90–100	101.6 mm per minute		
No. of teeth	106–110				
Doffer	686 over wire 705	100	16–40	15–35 × slower than cylinder	Cylinder/doffer doffer 12.5

peripheral surface clothed with saw-tooth wire, E, and a set of revolving flats, G, each has rigid wire points projecting from its surface and angled to oppose the saw-tooth wire angle of the cylinder clothing.

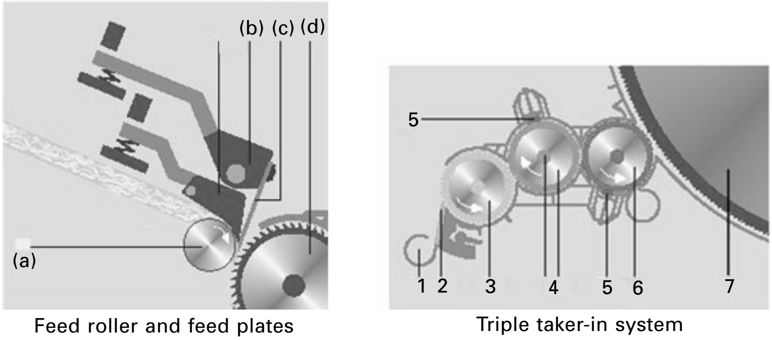
- Zone IV: the fibre mass transfer, the card web formation and consolidation; this includes a second fixed-flats cleaning system, H; a second cylinder, J, called a doffer, clothed with saw-tooth wire; a web doffing unit, K, and a sliver delivery and automatic sliver-can changing system, L. The angle of tooth of the doffer wire clothing opposes that of the cylinder.

Zone I

There are differing designs of chute feed but their basic principles of operation are similar. As can be seen in Fig. 7.11 there is an upper and a lower chute, (A and C) separated by a feed roller and beater (B), and a pair of air outlet combs positioned at the end of the lower chute. Each chute has air-escape holes and a pressure sensor fitted to control a pre-set compacted volume of tufts in the chute. The upper chute receives tufts from a distribution ducting linked to Stage 2 and the transporting air is exhausted through the air-escape holes. The feed roller and beater remove the material at a slower rate than the incoming tufts, enabling tufts to build up in the top chute. As the tufts build up and cover the air-escape holes, the pressure sensor detects the associated increased air pressure in the chute and the tuft inlet is closed off. As tufts build up in the top chute, the beater feeds the tufts to the bottom chute. Here, the tufts are compacted into a batt (i.e. a thick blanket of tufts) by permanent air suction through the pair of air-outlet combs connected to a fan. The air-outlet combs are positioned only a few centimetres from the feed rollers of Zone II, and therefore the batt is formed at the inlet to the feed rollers. The rate of removal of the compacted material by the feed rollers is slower than the tuft feed from the beater, so a pressure switch is used to control the stop-start motion of the upper feed rollers at B.

Zone II

Figure 7.12 shows the main components of Zone II. The batt of tufts is nipped between a feed roller (a) and the bottom of two feed plates (b). Attached to the top feed plate are ten spring loaded feelers (c) each 100 mm in width and in close contact with the batt fringe, up to the first of the triple licker-in (d). Each feeler automatically adjusts to the thickness of that part of the batt with which it is in contact. The feelers are electronically linked to a control unit which adjusts the motor drive to the feed rollers; the arrangement



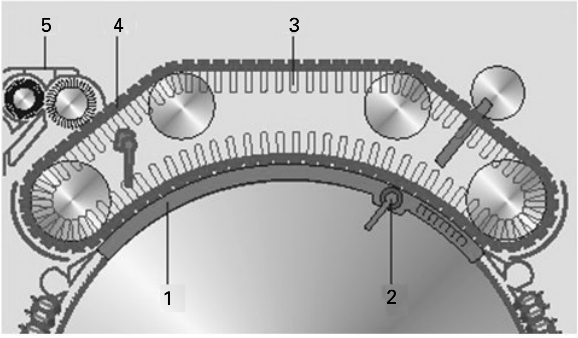
7.12 Main components of Zone II.

is called an autoleveller. This means that if there is a variation in the batt thickness (and therefore the fibre mass) across the width of the feed, this will be detected and the speed of the feed roller adjusted (i.e. slowed for increased thickness, speeded up for a thinner section) to allow the taker-in roller (d) to continuously remove a consistent fibre mass from the fringe of the batt during carding.

Figure 7.12 also shows the arrangement of the triple licker-in (3, 4 and 6) can be seen. The arrows indicate the direction of rotation of each licker-in beater. The objective of the triple licker-in is similar to the four-roll cleaner described above, but here the tufts are converted into very small tufts (i.e. tuftlets) and some individual fibres. That is to say, a higher degree of 'gentle' opening, achieved by progressively increased beater speeds (up to say 1200 $r min^{-1}$) as well as having finer and a higher density of pins on the first beater, followed by progressively finer and a higher density of saw-tooth wire clothing on the subsequent beaters. The result is tuftlet sizes of around 0.05 mg produced by the first beater; 0.01 mg and 0.005 mg by the second and third; the latter may be referred to as micro-tuftlets. As shown in Fig. 7.12, there are located around the periphery of each beater, deflector plates with mote knifes and attached suction hoods for waste particle removal, i.e., a series of cleaning points. To assist the opening action of the beaters on the tuftlets and thereby the freeing of trapped fine trash particles, two plates (5) – termed 'combing segments or carding plates' – fitted with a saw-tooth wire clothing are positioned so that the angle of the wire clothing opposes the rotating surfaces of the beaters.

The surface speed of the cylinder (7) in Zone 3 is usually twice the surface speed of the third beater (6), and the saw-tooth wire clothing on the cylinder is of a greater working angle and a higher teeth density. The cylinder rotates in a clockwise direction to strip the tufts from the third beater, but simultaneously reduces the tuft sizes to around 0.001 mg. The stripping action is usually described as 'point-of-tooth' to 'back-of-tooth'. That is, the point of a saw tooth on the cylinder (7) moving faster and past the back of a saw tooth on the slower rotating third beater, thus stripping tuftlets from the latter (6).

The micro-tuftlets on the cylinder saw-tooth clothing now moves with the rotation of the cylinder and meet the fixed flats cleaning system F (see Fig. 7.11). These are called the back fixed flats and incorporated in the fixed flats unit is a separator knife edge and suction unit, which has a similar purpose to a mote knife for removing dust and trash particles. They also tend to orientate and elongate the fibres of the micro-tuftlets along the direction of cylinder rotation.[3] This facilitates the individualisation of the fibres during the carding action in Zone III.



7.13 The carding zone.

Zone III

As the micro-tuftlets on the cylinder are brought into the inlet region (1) of the carding zone (see Fig. 7.13) they are caught by the ridge wire points of the flats. The opposing angles of the rigid wire clothing on the slow-moving flats and the saw-tooth wire clothing on the fast-moving cylinder result in the micro-tuftlets being separated into individual fibres, as the fibre mass moves towards the outlet region, 2, of Zone III. Thus, this point-of-tooth to point-of-tooth gives the carding action required to individualise the fibres. Not all micro-tuflets caught by the flats are separated into individual fibres; some parts of a micro-tuftlet can become embedded in the rigid wire of the flats and then move with the flats out of the carding zone, i.e., from 2 to 3. On reaching 4 the embedded mass is stripped from the flats by a brush roller unit, 5, and removed as waste – called flat strip waste.

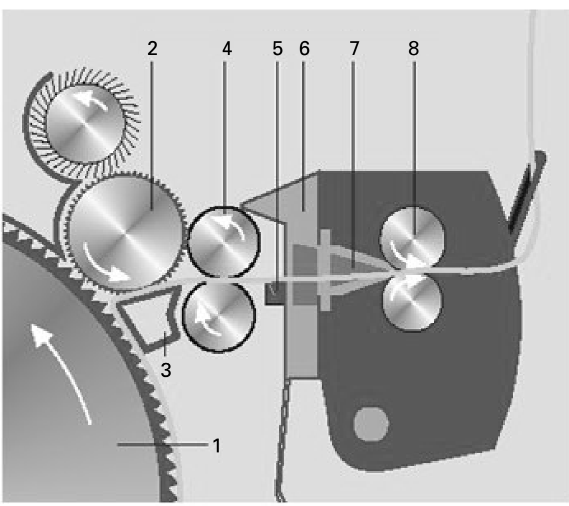
During carding, the motion of the cylinder clothing generates air turbulence that, along with mechanical forces, causes the trailing ends of fibres attached to the teeth of the cylinder clothing to vibrate rapidly and shake loose dust, trash particles and neps still remaining among the fibres. The fibre mass embedded in the flats acts as a filter, and much of these impurities are deposited into it to be later removed as part of the flat strips.

A nep is a small entangled knot of fibres (or of one fibre). Neps are often formed in the ginning process during removal of the cotton fibre from the cotton seed and are unwanted as part of the cotton mass characteristics. It is essential to remove these neps during opening, cleaning and, particularly, carding. This is because neps degrade the appearance of cotton yarns and the resulting fabric, and are usually associated with lower yarn strength, poorer spinning performance and a more irregular yarn. The appearance of dyed or printed fabrics is negatively influenced by the presence of neps, as neps often comprise immature fibres, which do not absorb dye, and reflect light differently from mature fibres and therefore appear as spots or 'flecks' on finished fabrics. Such fabrics are downgraded or rejected, as there are no cost-effective means of covering or removing the neps once they are present in the fabric.

Zone IV

In the outlet region of Zone III, the individual fibres attached to the cylinder clothing collectively appear as a very lightweight web on the cylinder surface. This web moves with the cylinder rotation and comes into contact with the front fixed flats cleaning system, H (Fig. 7.11), which further extracts neps and fine trash particles. After the cleaning system, the web reaches the doffer clothing and this removes the fibres from the cylinder. Thus, the point-of-tooth to point-of-tooth of the cylinder and doffer wires gives a stripping action. This cylinder-doffer area is called the transfer zone, as the objective is for fibres to be transferred from the cylinder to the doffer. Since the surface speed of the cylinder is much faster than the doffer (see Table 7.2) there is a build up of fibres on the doffer, forming a thicker, heavier web of fibres (the doffer web) than that on the cylinder. The rotation of the doffer brings this web to the front of the card where it is removed (as the card web) by a wire-covered stripping roller (see Fig. 7.14) and passed through a pair of pressure rollers before being condensed into a sliver and wound into a sliver can (see Fig. 7.11). The pressure rollers are used to crush trash particles such as seed coat fragments that still may be present, attached to fibres in the web; the crushed particles would then be removed during subsequent processing of the sliver.

Not all the fibres are stripped on first contact with the doffer; some remain on the cylinder for several cylinder rotations before being removed. The



7.14 Sliver formation.

cylinder under screen, M (Fig. 7.11), controls the boundary air layer at the cylinder surface to prevent the un-doffed fibres being ejected from the cylinder clothing during their motion from the doffer/cylinder area to the taker-in/cylinder area. There appears to be an optimum number of times fibres go through the transfer zone before being stripped by the doffer; too short or too long a dwell time on the cylinder impairs the quality of the card web.[4] The fibre layer remaining on the cylinder is referred to as the recycling layer and on passing the third beater of the taker-in, this layer will therefore receive a deposited layer of microtufts. The combination of the two layers is referred to as the cylinder load. After the carding action the cylinder load will be missing a proportion removed by the flats; that remaining on the cylinder should be in the individual fibre state, and as this is what is operated on by the doffer, it may be termed the operational layer. The amount of fibre transferred from the cylinder load to the doffer is dependent on the fibre transfer coefficient. Factors determining the transfer coefficient include the cylinder and doffer speeds, type of saw-tooth wire, the set gap between the two rolls and the type of fibre being carded. Detailed consideration of these issues form part of the more advanced theory of carding and the reader is referred to reference 6.

Despite the fact that not all fibres are removed from the cylinder on their first pass through the transfer zone, there is continuity of mass flow within a few minutes of running, i.e., the rate of batt feed to the first taker-in equals the sum of the rate of waste accumulation and sliver production rate. Strictly speaking, the assumption is made that the moisture content of the fibres remains constant throughout the process and that the amount dust particles and fly (i.e fibre fragments) which cannot be collected is negligibly small.

Drafts equations

Consider now the surface speeds of the main components moving the fibre mass through the card, which eventually forms the sliver that is coiled into the can. We can for simplicity ignore the speed of the flats because this only governs the rate of removal of the flat strips from the carding zone. Based on the above description of the operating principles,

$$V_f << V_t < V_c > V_d < V_s < V_{cr} = V_a \; V_{sc} \qquad 7.8$$

V_f – feed roller, V_t – taker-in (i.e. speed of the third beater), V_c – cylinder, V_d – doffer, V_s – stripping roller, V_{cr} – crushing rolls, V_{ca} – calender rollers, V_{sc} – coiler rollers (Units: m min^{-1}).

The relation of these surface speeds shows that the fibre mass is subjected to a sequence of drafts as it moves through the card. This means that although there is conservation of mass, so that in a given period of time the total mass of materials fed into the card emerges from it, the fibre mass is nevertheless thinned out. This sequence of drafts therefore results in the mass per unit length of the sliver being much smaller than the mass per unit length of the batt fed into the card. The sequence of drafts is:

$$D_{ft} = V_t / V_f;\ D_{tc} = V_c / V_t;\ D_{cd} = V_d / V_c;\ D_{ds} = V_s / V_d;$$
$$D_{scr} = V_{cr} / V_s;\ D_{crc} = V_{ca} / V_{cr};\ D_{csc} = V_{sc} / V_{ca} \qquad 7.9$$

All drafts are > 1 except D_{cd}. The following are sufficiently close to unity to be ignored D_{ds}, D_{scr}, D_{crc} and D_{csc}. The total draft for the card is, then, given by:

$$D_{TM} = D_{ft} \cdot D_{tc} \cdot D_{cd} = V_d / V_f \qquad 7.10$$

It should be evident that the width of doffer web or card web equals the width of the batt feed, and that in consolidating the doffer web into a sliver, the mass per unit length of the sliver equals the mass per unit length of the doffer web, ignoring drafts D_{ds}, D_{scr}, D_{crc} and D_{csc}. The ratio of the values of the input and output mass per unit length gives

$$D_{TF} = M_L / S_L \qquad 7.11$$

M_L – the mass per unit length (in g m^{-1}) of the batt, and S_L – sliver count in ktex. Since eqn 7.11 deals only with the fibre that forms the sliver, we can relate D_{TM} and D_{TF} by subtracting the percentage waste, W, from M_L removed during carding. Hence,

$$D_{TM} = D_{TF}\,(1 - 0.01W) \qquad 7.12$$

we may refer to D_{TM} and D_{TF} as the total mechanical draft and the total fibre draft.

The carding of fibres will generate heat, which may alter the moisture content of fibres. Therefore, in determining W from measurements of M_L and S_L the effect of moisture regain must be controlled by conditioning the fibre mass in a standard atmosphere.[5]

Production equation

As described earlier, the last pair of rollers that moves the fibre mass are the coiler rollers which place the sliver into the sliver-can. Therefore V_{sc} is the production speed. Hence the production rate (P_C) in kg hr^{-1} is given by

$$P_C = 60 \cdot V_{sc} \cdot S_L \cdot 10^{-3} \qquad 7.13$$

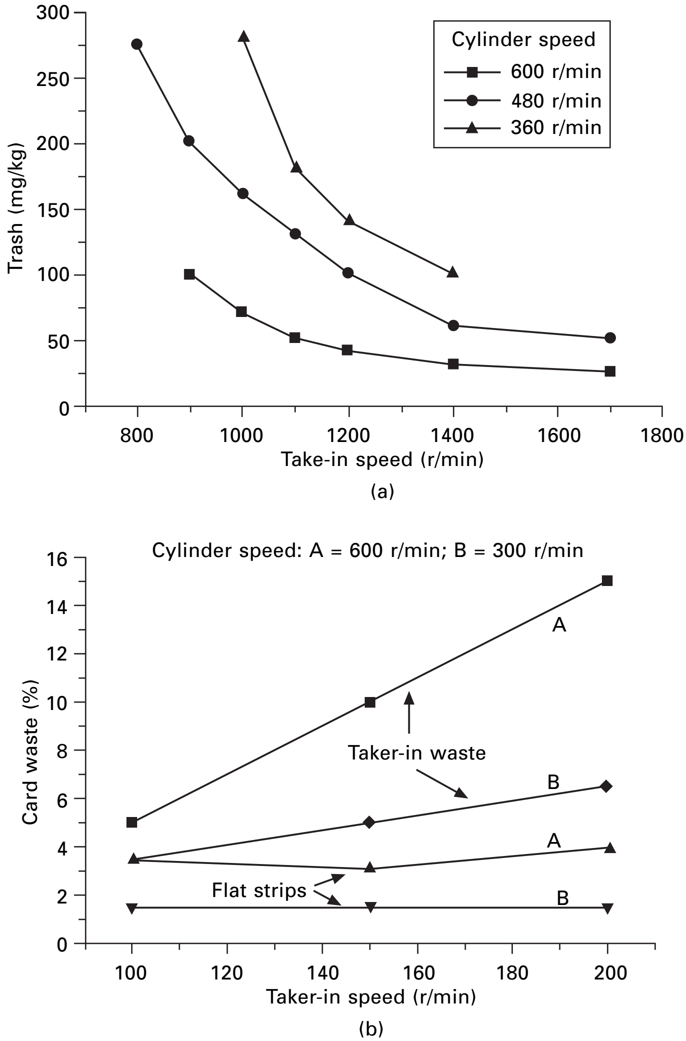
This is usually much lower than the fibre mass flow from Stage 2. For example, in processing a cotton with not too high a trash content, on average the production rate for the opening and cleaning line would be 500 kgh^{-1}, whilst the production rate of the card would be below 100 kgh^{-1}. In certain situations, production rates of 30 to 50 kgh^{-1} are used commercially. The reason for this concerns the opening up of the fibre feed into suitable tuft sizes for the carding action. Equation 7.4 is applicable to the opening part of the card and with all other factors remaining constant, tuft size is therefore largely dependent on the production rate and a modest rate will give small tufts. To obtain small tufts at very high production rates would mean increasing the beater speed, also the number of points on the beater surface may be increased. The difficulty is that increased beater speed may result in fibre breakage. This is therefore a limitation to the speed that would be suitable. Since the production rate of a card cannot match the blowroom output, several cards must be used, linked to the blowroom in such a way that there is a uniform feed of the fibre mass to each card (see Fig. 7.1).

7.5 Sliver quality and quality control

The quality of a yarn is determined primarily in the processes prior to spinning, and card sliver quality parameters are fundamental to the resultant yarn quality. In carding technology parameters used as measures of card sliver quality are the trash and dust content (or the cleaning efficiency), the amount of neps and short fibre content due to fibre breakage, and the level of irregularity of the sliver. Yarn quality is directly related to these parameters. Also of importance, in respect of yarn quality and spinning performance, are how well the micro-tuftlets have been separated into individual fibres (i.e. the degree of fibre individualisation) and the shapes the fibres adopt in the sliver, i.e., trailing hooks, leading hooks, both ends hooked, etc.[6] These, however, are not easily measured characteristics and therefore in general practice they are not used for monitoring quality.

7.5.1 Trash and dust content

With cotton fibres a low level of neps and trash particles in the sliver is a major objective[7] particularly as the impurity content of card slivers will increase almost linearly with carding production rate.[8] As explained earlier, the licker-in, the fixed and revolving flats, along with the cylinder, play important roles in the removal of trash particles and neps. Since the trash is embedded in the tufts comprising the batt, how well the licker-in opens the fibre mass will largely determine how effectively trash particles are removed from the flow of fibres through the card. Although there are a number of devices fitted around the surface of the taker-in to improve cleaning, the impurities must be removed with a minimum of fibre loss and for this the taker-in speed is the controlling factor. Figure 7.15(a) shows how for different cylinder speeds the impurity level in the sliver decreases, but the under card waste increases, with licker-in speed. Increasing the speed



7.15 Trash content and card waste with increased taker-in speed.

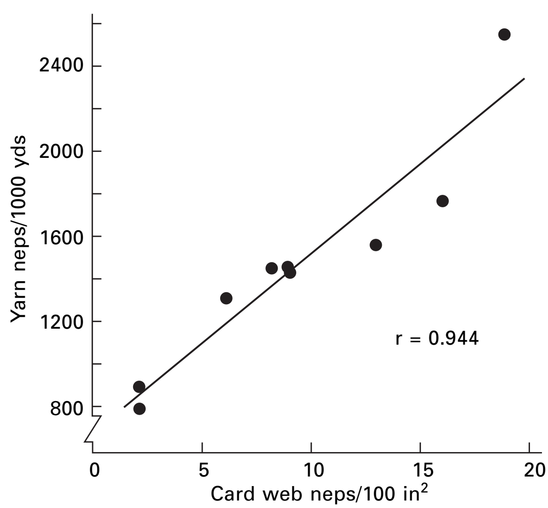
above 1500 r/min gives negligible improvement on sliver cleanliness but can lead to fibre breakage and increased waste.

The removal of neps and trash improves with carding intensity, so the cylinder and flats speeds are important factors, and Fig. 7.15(b) shows that over the range of 300–600 r/min, high cylinder speeds will reduce trash content by greater than 50%, depending on taker-in speed, but may also cause more fibre breakage than high taker-in speeds, i.e., increasing card waste. Increased flats speed will reduce the sliver impurity but increase the flat strip waste. Close flat settings give a more intensive cylinder-flat interaction with the tuflets, and at the front fixed flats cleaning system, reduces neps and fine trash particles, referred to as pepper trash. Fibre breakage is evidently an important quality parameter. Consequently, reduced trash and nep count on the one hand and reduced fibre damage on the other are conflicting requirements.

The overall carding system has a cleaning efficiency of 95% (this is calculated using eq. 7.6) which is much higher than the 45% for the opening and cleaning lines (i.e. Stage-2). Taking the carding zones individually, the cleaning efficiency of the licker-in on its own approximates to 30%, the carding segments give 30% and the cylinder/flats 90%. The cylinder/flats carding action therefore gives the highest cleaning effect. Carding efficiency is better the higher the number of points, the closer the settings and the higher the cylinder speed; the limitation on the values of these parameters will be fibre breakage.

7.5.2 Neps

Figure 7.16 shows there to be a high correlation between neps in a card web and in the resulting yarn. Therefore, a sliver of low nep content is a pre-requisite for producing a good quality yarn. Earlier it was explained that a nep is one or more fibres occurring in a tangled and unorganised mass.[9] Whilst this is a useful general definition, in cotton processing there are various types of neps. Imperfections that have been identified as neps in spun yarns may be classified into the four categories L to H given in Table 7.3[10,11] The table also gives typical figures for the relative proportions of each category determined with the use of an 'inspection stop' fitted to the USTER® yarn irregularity tester.[10] The number of neps per gram of sliver can be measured by an instrument known as the AFIS system.[13,14] Also the



7.16 Relation between neps propensity in cotton yarn and card web.

Table 7.3 Nep classification for cotton fibres

Nep class	Class abbreviation	Description	Percentage of total (%)
Loose fibre neps (may also be referred to as knops or burls)	L	A discrete entanglement of fibres larger than 1 mm, which can be disentangled	28
Knot fibre nep	K	A discrete tightly knotted or highly entangled small (less than 1 mm) group of fibres or a single fibre, which cannot be disentangled	25
Trash nep (not applicable to man-made fibres)	T	Leaf, stem, VM particles fragments at the core of an entanglement of a small group of fibres	44 (T+ H) Unidentified = 2%
Husk nep (only in cottons)	H	Seed coat fragments at core of the entanglement of a small group of fibres or with fibres attached to them	

nep content of the card web can be counted manually or by online measurement with a digital camera as a sensor fitted to the card.[15] Such measurements can be used in monitoring nep level in the card sliver to be spun into a yarn.

Neps usually migrate to the yarn surface during the spinning process and therefore result in poor yarn and fabric appearance; and as mentioned earlier, they prevent a uniform appearance of dyed or printed cloth, giving instead spotty looking fabrics of lower market value.[16] In spinning, large neps may restrict twist propagation, which for fine yarn counts can result in unacceptably high end breakage rates; thus large neps may limit the fineness of count which could be spun. H neps pose particular problems in certain spinning systems, especially in rotor spinning where they account for up to 30% of thread breaks.[17] Neps generally are more conspicuous in finer-count yarns, because of the diameter ratios. Such counts are often used for high-quality fabrics, and therefore the level of neps in the processed fibre mass reaching the spinning stage must be kept as low as possible.

Neps are usually formed during ginning, and along with remnants of dirt, husk and trash particles in the opened mass, should be removed by mechanical opening and cleaning processes, particularly at the card. However, depending on fibre properties, machine settings and operating speeds, the L and K type neps can be formed during opening, cleaning and carding, thereby reducing the amount that is removed. This is because such neps result from broken fibres or from the rolling up of fibres between too closely spaced surfaces. When a fibre breaks the release of tension can cause the shorter length to recoil and roll up into a loose knot, which subsequently tightens with further mechanical action by the two closely spaced machine surfaces processing the fibre mass.

The type of particulate impurity in the baled fibre mass can therefore influence the nep level. Particles that are difficult to remove from tufts may require very intensive beater action, leading to fibre damage and a high nep level to be generated, and consequently greater sliver neppiness. Studies[18] have shown that taker-in speeds below 700 min^{-1} have little influence on generating neps at the card, but above this value the nep count in the card web can increase significantly with speed. Generally, however, this increase with speed is applicable only to low micronaire or immature cottons; for coarser cottons high taker-in speed does not generate neps.[19]

The production rate employed in carding has a negative effect on nep removal, this is particularly so when processing low micronaire cottons. It is likely that with increased production speed, the higher cylinder load results in a lower subdivision of neps entering the carding zone (Zone III Fig. 7.13) and in increased fibre breakage, thereby forming new neps.

The cylinder-doffer interaction gives an important carding effect as well as a stripping action, and the intensification of the carding action here will produce a cleaner less neppy web.[18] A reduction in doffer surface speed increases the carding action and was found to reduce the nep level. With regard to wire specifications, the smaller the land area of tooth, the sharper will be the wire points and therefore the lower the nep level, since the wire points can better penetrate neps to separate the fibres. Reduced neppiness also occurs when the working angle of the doffer is smaller than the cylinder. The smaller doffer-wire angle gives a better transfer coefficient and thereby less fibre in the recycling layer on the cylinder; thus, a reduced cylinder load and reduced potential for fibre breakage. The density of the wire points of the card clothing, especially the cylinder clothing, is an important factor in reducing the nep level of the card web.[20] The point density of card wire clothing is governed by the spacing between rows of teeth, and the wider the spacing the greater the chance for neps to become lodged between rows of teeth and, in the case of the cylinder, escape the carding action. However, as the point density increases, the possibility of fibre breakage increases, consequently an optimum specification has to be reached depending on production rate and fibre type.

Husk and trash neps are most effectively removed by the carding action and the combined actions of knife-edge and applied suction at the fixed flats. However, some escape removal and these are then subjected to the effect of the crush rolls, which dislodge them from their attachment to fibres. They are subsequently removed in the downstream processes.

Although cotton stickiness in carding, i.e., honeydew, is not a nep-forming characteristic it is a recurring problem that can have a disrupting effect on production and a degrading one on quality. Cottons contaminated with honeydew are difficult to card because of the severe sticking and build up of fibres on working components, particularly the crush rolls where the result is frequent breakage of the card web. Stickiness is largely associated with freshly cropped cotton and can become less problematic when the honeydew cotton is stored for 3–6 months.[21] The honeydew cotton may then be processed by blending with uncontaminated fibre, but a suitable blend proportion has to be determined by trials. A dust control additive or over-spray[21] may be applied to the stored cotton and this generally alleviates the effects of stickiness during carding and in downstream processing. The additive on the cotton continuously coats the surfaces of the working components with a thin film of lubricant to prevent the honeydew from gaining a purchase on the surfaces.

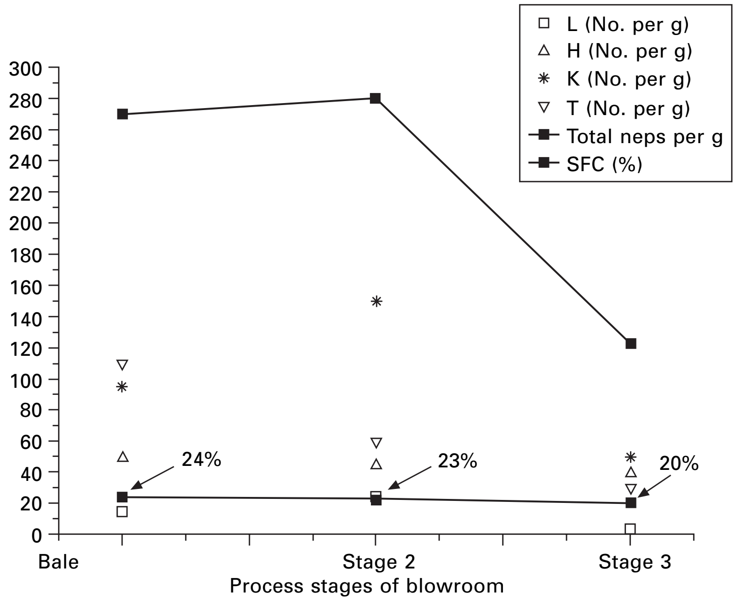
7.5.3 Short fibre content (SFC)

In spinning, the presence of short fibres can result in yarn breaks and poor yarn quality. It is important that during opening, cleaning and carding, fibre breakage is kept to a minimum. It was explained above that nep formation is closely linked to fibre breakage. It is therefore not surprising to find that a typical SFC profile for the process stages from cotton bale to sliver can be similar to a typical nep propensity profile (see Fig. 7.17).

Cotton bolls have very few short fibres. A significant amount of fibre breaking occurs in the harvesting and ginning of cottons, which results in the baled fibre mass having an SFC of around 24%. Mechanical opening and cleaning can increase the %SFC and the total nep level, but the levels are usually reduced in the card sliver because most of the short fibres and neps are caught in the flat-strip waste.

7.5.4 Sliver irregularity

The variation of the thickness of a yarn along its length and of the measured yarn count are important yarn characteristics to the uniform appearance of woven and knitted fabric surfaces. The variation of the card sliver thickness is a contributing factor to both yarn thickness and yarn count variation. The terms used in referring to thickness variations along the length of the sliver and yarn are ‘levelness’, ‘evenness’, ‘regularity’, ‘unevenness’ or ‘irregularity’.

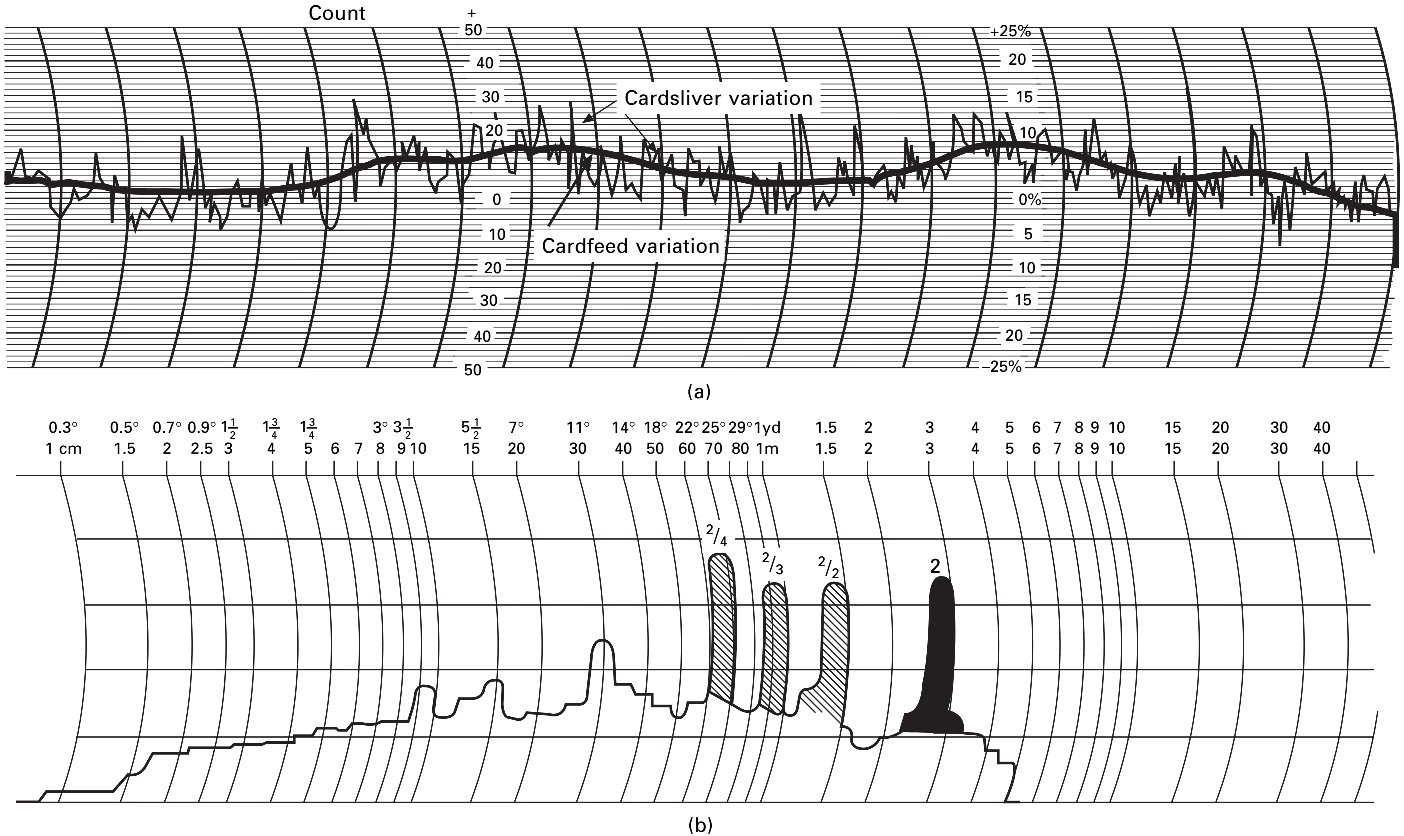


7.17 Changes in nep and SFC cotton fibre processing.

The latter will be used here since it gives the correct mental image of a linear assembly of fibres in which the number of fibres in the cross-section is not uniform along its length. Thus, the variation in thickness along a measured length of a card sliver is directly related to the variation of the number of fibres in the cross-section throughout that length. The variation in mass per unit length can therefore be taken as a measure of the irregularity.

There are several ways by which the variation in mass per unit length can be determined, but the most widely used instrument for doing so is the Zellweger Uster Irregularity tester.[5] This is based on a capacitance method where a sample length of the material is made to run between a parallel plate capacitor approximately 1–2 cm long, depending on the type of sample, i.e., sliver, yarn, etc.; a 2 cm capacitor would be used for slivers and a 1 cm for yarns. The changes in capacitance reflect the mass variations between successive 1 cm or 2 cm lengths along the sample length, and if plotted on a chart would look similar to Fig. 7.18(a). This shows a random waveform for a card sliver, in which the peak values, or amplitudes, are the actual measurements. The coefficient of variation of the measurements, the CV%, may then be stated as the irregularity value for the sampled length of the measured card sliver. This measure of mass variation is commonly called the Uster Irregularity or Uster CV%.* The CV%, however, is only a useful

*In some older publications U% values are given – called the Uster values. The U% is the percentage mean deviation (PMD). CV% = 1.25U%.



7.18 Irregularity trace and spectrograph of card sliver.

indicator of quality provided no machine faults or processing errors occur periodically to add significantly to the measured value.

Owing to such faults, particular values of amplitude may reoccur within the random waveform. These values are denoted as periodic faults and the distance between a particular reoccurring amplitude within the random waveform gives a measure of the periodic wavelength related to the fault.

Although there are steps that can be taken in post-carding processes to reduce a high CV% of a card sliver, little can be done post-carding to correct periodic faults. Therefore, periodic faults of sizeable amplitudes are detrimental to yarn quality and are very likely to result in seconds-quality fabrics. The reader should note that periodic faults can also occur at process stages after carding, and therefore it is essential to identify the process at which they do occur so that the problem can be rectified.

A graph of the periodic amplitudes plotted against their wavelength is used to highlight significant periodic faults. This wavelength spectrum is called a spectrograph or spectrogram and Fig. 7.18(b) shows an example of the spectrogram relating to the irregularity chart of Fig. 7.18(a) for a card sliver. The irregularity chart shows several periodic amplitudes amongst the random waveform, and the spectrogram depicts the amplitudes along the ordinate and the wavelengths along the abscissa. The pronounced amplitudes are the significant periodic faults. Periodic faults may be classified according to their wavelength, using the fibre length as a unit length.[22]

- 1 to 10 times the fibre length: short-term variation
- 10 to 100 times the fibre length: medium-term variation
- 100 to 1000 times the fibre length: long-term variation.

The classification is important since it can be used to trace the source of a periodic fault. For example, in the chart of Fig. 7.18(a) it can be seen that the centre line drawn through the random waveform also varies. This is a medium-term variation and indicates an inconsistency in the sliver count, which is attributable to variation in the feed to the first beater of the taker-in. The reader wishing for detailed information on the tracing of periodic faults should consult references 23–7.

Short term irregularity

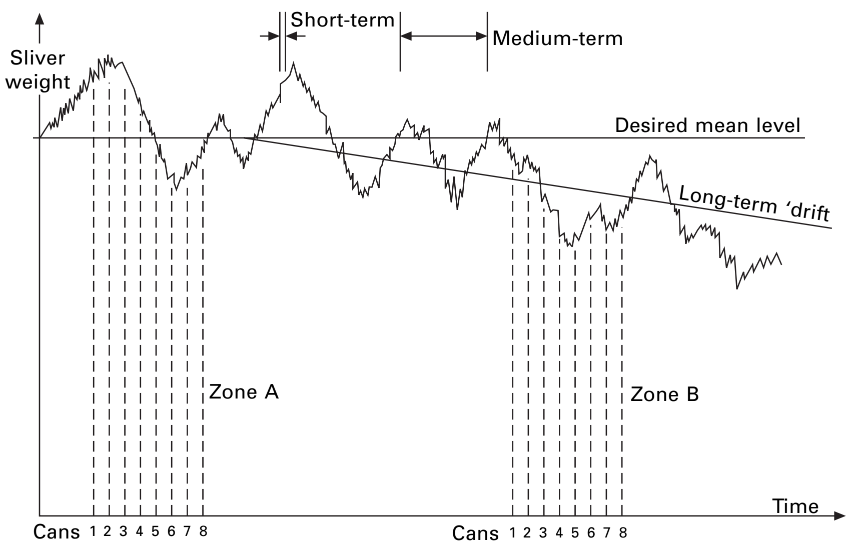
The Uster CV% of a sliver is a measure of the short-term irregularity of the sliver and is not therefore a useful predictive indicator for the Uster CV% of the yarn[28] This is because the short-term irregularity for a yarn is more dependent on the short-term variations introduced during post-carding processes in which there is attenuation of the sliver count in order to obtain the yarn count. However, the yarn resulting from the further processing of a sliver is usually checked for count variation by measuring 100 m yarn lengths; such would have originated from short lengths of the sliver. Thus the sliver Uster CV% is important to the measured count variation within, say, a given yarn package.

Medium and long-term irregularity

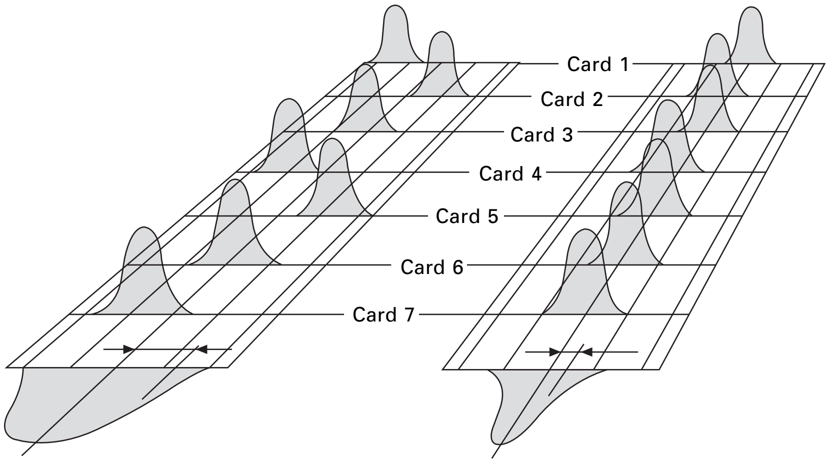
Figure 7.19 illustrates the medium- to longer-term variability of a sliver, that is to say the irregularity of a sliver length that comprises a full can of sliver and the variation between cans of sliver. The Uster CV% is not a measure of this variability. The CV% of sliver count measurements, made at random intervals during carding, is the appropriate indicator of such variations.

The importance of monitoring and controlling medium- and long-term variability can be seen from Fig. 7.20. In the processes following carding, the short- and medium-term irregularities can be significantly reduced. However, these processes cannot readily correct for the long-term drift of the sliver count. The problem is particularly important where many cards are needed to match the production of the opening and cleaning line of Stage 2.

The long-term drift associated with each card can result in unacceptable sliver count variations. Thus, at any given moment during production, the mean sliver counts of each card may give a statistically widespread distribution for the carding process (see Fig. 7.20). To overcome this difficulty autolevellers are usually fitted to the cards. As the name implies, autolevellers automatically



7.19 CV% of sliver count: short-, medium- and long-term irregularities.

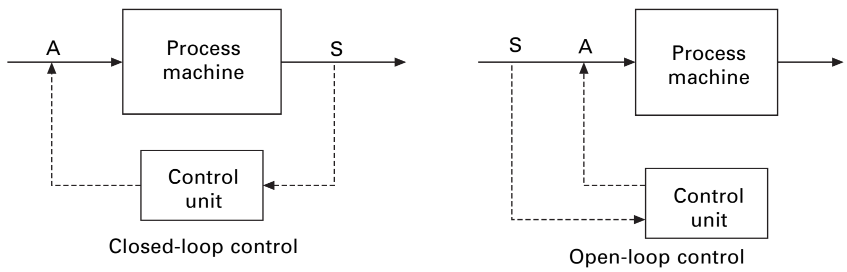


7.20 Count variations within and between cards.

level or reduce large changes in the medium- and long-term irregularity of the sliver.

Autolevelling at the card

The principles of autolevelling are based on the fundamentals of control theory which is beyond the scope of this chapter. However, the reader wishing to study the theoretical aspects of autolevelling should find reference 29 informative. Essentially, there are two methods of autolevelling that are used at the card. The basis of one system is for a sensor to electronically monitor the sliver irregularity and a control unit to interpret the electronic data in terms of variations in the sliver count from the preset count required. Then, according to the size of any unacceptable differences and whether these are greater or less than the preset value, modify the draft of the card by slowing or increasing the feed roller speed to ensure that there is only a minimum (negligible) deviation from the preset value. The time elapsed between changing the feed roller speed and detecting its effect in the output sliver, is the response time of the carding process or the lag time due to the process. With the second method, the batt thickness at the feed roller is constantly monitored. When deviating from a preset value, the speed of the feed roller is deliberately changed with the intention of maintaining a minimum variation of the card sliver count. The first method is referred to as closed-loop autolevelling and the second as open loop autolevelling. Figure 7.21 depicts the main features of these two types of control system; S and A represent the locations of the sensors and actuators, the dotted lines the signal path and the solid lines the material flow.

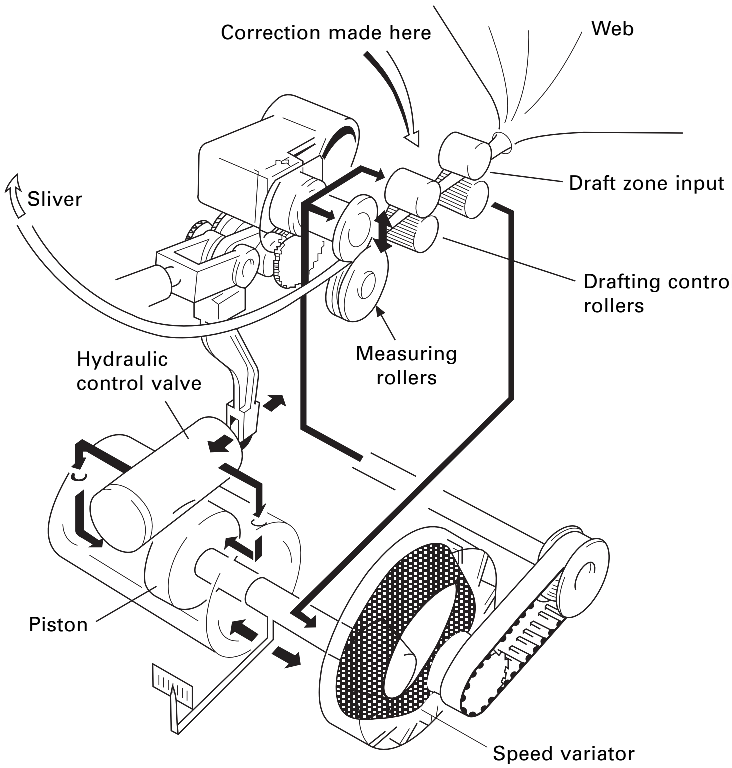


7.21 Closed-loop and open-loop control systems.

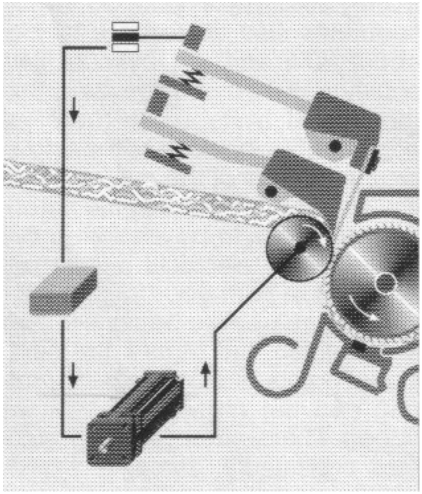
The open-loop system results in a quicker response time to the deliberate changes since the lag time of the carding process is avoided. However, there is no feedback from the output to ensure that corrections made achieve minimum variation of the output characteristics. Most autolevelling systems on cards employ the closed-loop principle. However, because of the slow response time of the carding process, these closed-loop systems are called long-term autolevellers.

Various types of sensors may be used to monitor the sliver irregularity,[30] but the tongue and groove device is probably the most popular, and is considered to be very simple and reliable. This basically consists of a grooved bottom roller through which the sliver passes whilst under compression by a top roller that fits the groove. Variation in the sliver thickness causes the top roller to rise and fall thereby monitoring the sliver irregularity. The movement of the top roller is converted to an electronic signal, which is fed to the control unit. Figure 7.22 illustrates the tongue and groove system and also shows the use of two pairs of rollers to provide a quicker response time for the control of short-term sliver irregularity, i.e., a short-term autoleveller. The two pairs of rollers are used to apply a small draft of up to 1.5 on the output sliver. These rollers precede the tongue and groove sensor. The very small movements of the top measuring roller are amplified by a low friction lever arrangement that in turn moves a hydraulic valve to vary the rate and direction of oil flow to a piston. The piston operates mechanically a speed variator which increases or decreases the speed of the draft control rollers. The speed of the coiler rollers depositing the sliver into sliver cans is also varied to ensure no uncontrolled changes to the sliver count.

Open-loop systems, as indicated earlier, are fitted to the feed device of the card. The sensor used either monitors thickness of the batt or mass per unit area. This is done prior to the measured portion of the batt being fed forward by the feed roller, and the necessary change to the feed roller speed is regulated to increase or reduce the feed rate. The thickness may be monitored as illustrated in Fig. 7.23. Pressure sensors are fitted at the front of the feed plate where the plate and feed roller forms a wedge to progressively compress and nip the batt; changes in the batt thickness are therefore readily detected.



7.22 Tongue and groove device fitted for short-term closed-loop autolevelling at card.



7.23 Open-loop autoleveller on short-staple card.

In general autolevellers may be used to correct fluctuations in the monitored fibre mass of up to +/– 30% and minimise deviations to within +/– 1–2%, based on the mass of five-metre lengths of sliver.

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8
Cotton spinning technology

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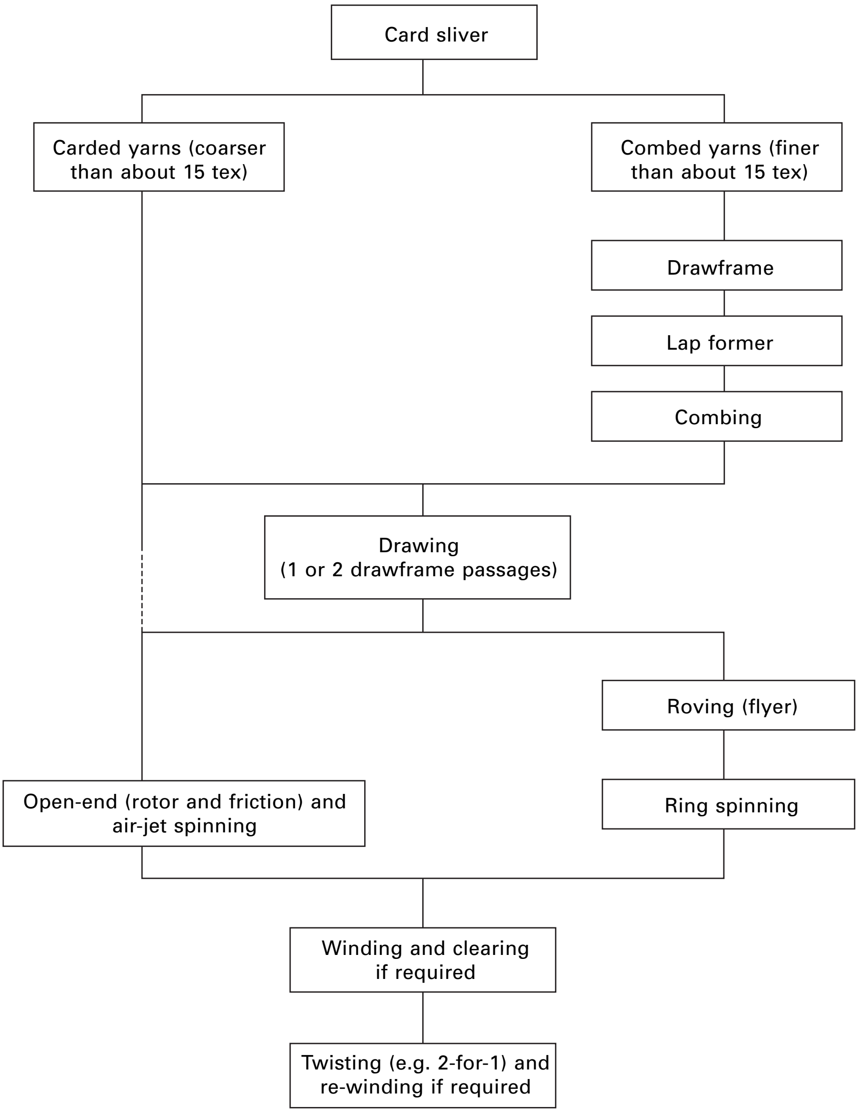
8.1 Introduction

In 2005, approximately 62% of all textile fibres were processed into spun yarns (short and long staple), 8% into non-wovens and 30% into filament yarns, short- staple spinning (up to about 50 mm) accounting for over 80% of all staple yarns spun, with cotton accounting for almost 70% of this. This chapter covers the various processes and technologies involved in the conversion of a cotton card sliver into yarn on a package suitable for subsequent fabric manufacturing. This is often referred to as the yarn manufacturing stage of the textile pipeline and as the 'cotton or short-staple system'.

Yarn manufacturing in essence involves the following actions and objectives:

- sliver attenuation (drafting)
- sliver evening (doubling, autolevelling)
- fibre aligning and straightening
- fibre blending
- short fibre removal
- removal of foreign particles (also dust) and neps
- twist insertion
- winding
  - clearing (fault removal)
  - waxing/lubrication (knitting yarns).

Ultimately the purpose of the preparatory processes and spinning is to convert into a yarn, as cost effectively as possible and with a minimum of waste, a relatively coarse cotton sliver, in which the fibres are individualised but fairly randomly arranged and also not always all that well blended and which contains undesirable short fibres, fibre hooks and foreign particles. The intention is to produce a yarn in which the fibres are as straight, orderly arranged and well aligned (parallel) as possible and which is as even as possible, both in appearance and composition, with the minimum number of imperfections, faults, trash, protruding hairs and short fibres. The yarn should also be on a package which is suitable for the subsequent fabric manufacturing processes. In essence, two routes may be followed, the one for producing carded yarn and the other for producing combed yarn, the latter involving the additional process of combing (Fig. 8.1).



8.1 Typical cotton flow chart.

Of particular importance in all of the above is good fibre control and minimisation of waste. The above are achieved during the following processing stages which will now be discussed:

- drawing
- combing (combed yarn)
- spinning
- winding.

For more in-depth information, the reader is referred to various textbooks and reviews.[1–16]

8.2 Preparation for spinning

8.2.1 Drawing

General

Drawing, on a drawframe, represents the first process (called a drawframe passage) applied to the card sliver (containing some 30,000 fibres in its cross-section), with the intention to reduce (attenuate) the sliver linear density until the desired linear density for spinning (some 100 fibres in the yarn cross-section) is achieved. The drawframe operation can also be either linked to, or integrated with, the card, with coiler delivery speeds approaching 500 m/min being possible in such cases, higher drafts (2 to 2.5) improving fibre orientation (alignment). The process of sliver attenuation, is called drafting. Commonly two drawframe passages (single or twin delivery) occur between carding and spinning. Oxtoby[4] defines 'drawing' as a series of operations using drafting and doubling, with the machines which work together for this purpose being referred to as the 'drawing set'. Nevertheless, the terms drawing and drafting are often used interchangeably. Drawing therefore involves the processes of drafting and doubling, with good fibre control being of the essence throughout. Doubling refers to the action of combining two or more slivers during a process, such as drawing, doubling taking place at the input to the drawing stage. Lateral fibre blending and evening (autolevelling) also take place during the drawing process. Individual drives and sensors enable 'self-learning' and 'self-adjusting' drawing processes, with expert systems facilitating the detection of faults and the optimum setting and operation of drawframes.

In general, two drafting stages are applied to the card sliver on the drawframe, the first referred to as the 'breaker drafting' or 'break-draft' and the second as final (or main) draft. From the cans, the slivers pass, via the power creel, to the drawing zone, it being important that the slivers are not stretched or damaged in the process. Sliver output speeds are as high as 1000 m/min, or even higher, coiling, for example, into rectangular cans which can accommodate up to 65% (30 kg) more sliver. The fibre waste is around 0.5 to 1.0%.

The reversal of the slivers, which automatically occurs during each processing stage, from card sliver to spinning, assists in the randomisation of the fibre ends, and the correct direction of fibre hooks. Two drawframe passages are commonly applied after carding, the first being referred to as 'breaker drawing' and the second as 'finisher drawing'. In general, the fibres in the card sliver are not very well aligned (i.e. not very parallel) and one of the consequences of the drafting which takes place during the drawing process is that the fibres become better aligned and straighter. Furthermore, the card sliver is not very even along its length, and this is overcome by combining doubling (as well as autolevelling) with the drafting process.

Drafting

Drafting will be discussed here in its wider context, i.e., not only with respect to drawing but also with respect to those processes subsequent to drawing. It is possible to spin yarn directly from either a drawframe or card sliver, and this is in fact accomplished in certain high draft sliver spinning systems (drafts above 120) and often in rotor spinning. Nevertheless, it is difficult to produce even ring-spun yarn, particularly fine yarn, in such a way, the reasons being that it requires a very uniform input sliver and a very precise control of the feed sliver as well as very precise drafting and fibre control, since very high drafts are involved and the beneficial effects of sliver feed reversal and doubling are eliminated. Good drafting is difficult to achieve under such high draft conditions, there generally being an optimum draft, and the total draft necessary to achieve the required sliver and yarn linear densities is normally accomplished by drafting in stages. The sequence of processes, called drawing, is required to gradually and in a controlled manner, through a process of drafting, reduce the sliver linear density while controlling the movement and alignment of the fibres. Drafting takes place by:[3]

- fibre straightening (decrimping)
- fibre elongation
- fibre sliding (relative movement).

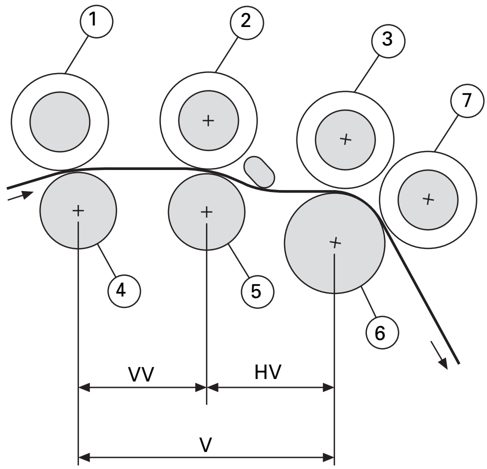
The latter effects the greatest change in sliver linear density.

The first drafting zone, referred to as 'break-draft', is very low, of the order of 1.1 to 1.4, while the second, the main or final draft, is much higher, the total draft being the product of the two, generally ranging from about 6 to 30, the optimum often being determined by trial and error. The total draft (d_t) is the product of the draft (d_i) in the consecutive drawing zones as follows: $d_t = d_1, \times d_2 \times \ldots . d_i$. It needs to be remembered, however, that, because of the doubling employed during drawing, the reduction in sliver linear density will not correspond to that calculated simply by using d_t, but will be the ratio of the total doubling and the total draft. The break-draft helps lessen the inter-fibre cohesion and frictional forces (due to fibre set, crimp and migration), thereby facilitating the fibres sliding past each other during the subsequent drafting.

Uncontrolled, or poorly controlled, fibre movement within the drafting zone leads to random irregularities in the output sliver, often referred to as drafting waves, the wavelengths of which depend upon the draft applied and fibre length. Drafting generally introduces its own unevenness, increasing sliver unevenness to varying extents, good drafting requiring effective fibre speed control, particularly that of the short fibres floating between the nips of the front and back rollers. In general, this can be achieved by means of aprons, roller surfaces, condensers, pressure arms (bars) and as short an uncontrolled distance between the aprons and the delivery rollers beneficially affecting the ultimate yarn quality. Aprons represent one of the most effective and popular means of controlling the movement of the floating fibres (i.e. those fibres not gripped by either the front or back rollers) within the drafting zones, retarding the premature acceleration of such fibres. Apron wear is accelerated by high drafts and sliver linear density, aprons therefore rarely being used in the drawing processes or in the break-draft zone preceding the roving and ring-spinning stages.

Essentially, the reduction in sliver linear density, during the drawing process, is achieved by what is termed roller drafting (Fig. 8.2), in which a front set of rollers runs at a higher speed than the back set of rollers, the ratio of the surface speeds of the two sets of rollers determining the degree of drafting. Generally the fibres gripped by the front, faster moving, rollers in the drafting zone need to transmit forces (frictional) to the fibres in contact with them, but which are not gripped by the front rollers, and in most cases also not by the back, slower moving, rollers. Only by means of such forces can these fibres (floating fibres) move forward. The forces imparted in such a way are crucial in achieving uniform and controlled fibre movement and drafting within the drafting zone. There are different arrangements of the rollers in the drafting zone, such as three over three (three top and three bottom rollers), three over four or four over three (Fig. 8.2) or four.

The best roller drafting is generally achieved when the input sliver comprises parallel fibres and has a minimum proportion of short fibres, the fibres can move independently (individually) and be controlled during the drafting processes, lower drafts generally also being beneficial within this context. In as much as the above conditions are met and combined with doubling (to be discussed below), the cross-sectional uniformity of the sliver will be ensured. More detailed information on roller drafting is available.[8] An essential requirement in drafting a sliver, during the drawing process, is that the fibres



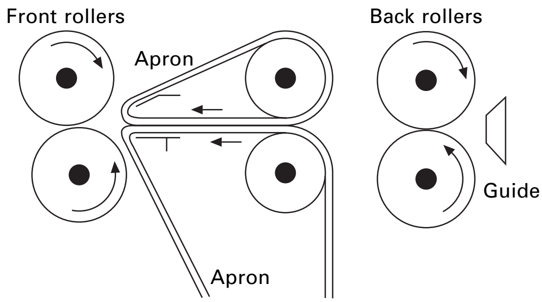
8.2 Roller drafting arrangement in the drawframe (source: Maschinenfabrik Rieter AG).

and their movement, are controlled as well as possible, thereby achieving maximum uniformity of the sliver material. In cotton drawing, control of the short and floating fibres is exercised by direct pressure and/or twist, the latter only being used during the roving and spinning operations.

Direct pressure control uses lateral pressure, generally on a twistless fibre assembly, to increase inter-fibre friction, but still allowing fibre slipping, this often being termed 'slip drafting'. Ways of achieving this include:

- carriers and tumblers
- apron and tumblers
- double aprons
- pressure-bar

Twist control is only applied during the drafting (or roving) for spinning and works on the principle that longitudinal tension applied to a twisted assembly generates inward radial pressure. Twist redistribution (running) helps to distribute the draft so that thicker sliver areas are drafted more than thinner areas, thereby improving the sliver evenness. Nevertheless, to prevent drastic twist redistribution (twist 'running' to thinner places) some direct pressure is also applied, for example by carriers and tumblers, or more popularly, by either single or double aprons, generally the latter in the case of the roving (speed-frame) and spinning processes (Fig. 8.3).[1] On the drawframe, a combination of rollers (e.g. four over four or four over three) and a pressure bar is used to draft and control the fibres (Fig. 8.2). Fibre control is generally achieved by, as far as possible, keeping the fibre in contact with the roller surfaces and by using a 'pressure bar', which produces a low pressure on the fibre assembly within the drafting zone.



8.3 Apron-drafting, used in roving and spinning (source: Grosberg and Iype[1]).

Doubling

As already mentioned, doubling is used primarily to improve sliver evenness, doubling tending to 'average out' irregularities (unevenness), the irregularity (CV of linear density) being reduced by a factor of $\sqrt{1/d}$, where d is the number of doublings. The combined actions of doubling and drafting also substantially improve the mixing (blending) of the fibres and this is often used to blend different fibres, such as cotton and polyester. Although more intimate blending is achieved by blending fibres prior to, and during, the carding process, blending during the subsequent processes, notably drawing, is often preferred, for convenience and the fact that different fibres being blended often require different treatment prior to, and during, carding. Nevertheless, in the case of pure cotton yarn, the blending of different cottons almost without exception takes place prior to, and during, carding, the subsequent drawing processes further improving the intimacy of blending.

The number of doublings and draft applied determine the linear density of the output sliver and these are selected in such a way that the desired sliver linear density, evenness and fibre alignment are attained. Frequently, six to eight slivers, each from a different can or container, are combined (doubled) during drawing, with a draft equal to, or greater than, this number, to produce the output drawframe sliver of the same, or lower, linear density as that of one of the input slivers, but which is considerably more regular and in which the fibres are better blended, more parallel and straighter.

Ratch

The distance between the nip of the front rollers and that of the back (prior set of) rollers is referred to as the ratch and needs to be carefully selected in relation to the fibre length characteristics of the material being processed. Too low (or short) a ratch leads to many fibres being simultaneously gripped by both sets of rollers and possibly broken, while too great (long) a ratch leads to excessive floating fibres and poor fibre control. Although the nominal, or theoretical, ratch is easy to calculate the actual or effective ratch is more complicated to derive, depending upon a number of factors, such as the sliver thickness (linear density), inter fibre-frictional forces and cohesion.

Drafting irregularities (waves)

Because floating fibres, are not positively controlled by either the front or back rollers, these fibres being acted upon, and movement imparted, by frictional forces resulting from contact with adjacent fibres, perfect drafting is not possible, and drafting irregularities (waves), largely random in nature, are formed, with wavelengths varying from about half to twice the mean wavelength, the latter being about twice the maximum fibre length.

Mechanical defects

In contrast to drafting irregularities (drafting waves), which are largely random, mechanical defects tend to introduce periodic (regularly occurring) faults: If the operating surfaces of the various rollers, gears and other circular elements, directly or indirectly involved in the drafting process, are not perfectly circular or eccentric, unevenness in the output sliver or yarn will result, generally in the form of a periodic unevenness in linear density, the wavelength of which is determined by roller/gear circumference, gear ratios and draft. Eccentric and fluted rollers and eccentric and worn gear wheels represent typical mechanical defects.

Drafting force

The force required to draft a sliver, termed the drafting force, depends upon the friction and cohesion of the fibres, which in turn are greatly influenced by any lubricants (finish) or chemical treatments, notably dyeing and bleaching, applied to the fibres. Drafting force is also greatly dependent upon sliver specific factors, such as fibre entanglement, fibre crimp, fibre fineness, fibre alignments packing factor, fibre hooks and twists.[17] The drafting force is also affected by draft ratio, drafting speed and roller setting, being approximately inversely related to ratch and draft, except for relatively low drafts (1.2 to 1.6) where a maximum occurs in the drafting force vs. draft. Drafting force also increases with sliver thickness and bulk density. Sliver and yarn evenness and spinning performance are all related to drafting force and its variation, the best quality yarns generally being produced with a relatively high break drafting force.[7]

Individual drives (motors) and sensor technologies enable a self-learning and a self-adjusting drafting process, draft optimisation taking place automatically by determining the break draft to produce the maximum break drafting force and then adjusting the main draft to keep the total draft required constant.[7] Variations in drafting force are also reflected in the degree of stretching of the sliver which introduces further unevenness. Stick-slip drafting takes place at low drafts, around 1.15 to 1.4 for sliver and between 1.3 and 1.7 for roving, where the drafting force is too low to cause a permanent change in the relative positions of the fibres.[3]

Fibre hooks

Carding produces fibre hooks, the presence of which in a sliver adversely affect fibre extent, drafting efficiency and material evenness, such hooks causing the fibre to behave as if it was much shorter. Klein[3] mentioned that some 50% of the fibres in the card sliver have trailing hooks, 15% have leading hooks, 15% have double hooks and less than 20% have no hooks. The trailing hooks in the card sliver leaving the card, becoming leading hooks as the sliver enters the next machine. During the drafting process, a leading hook is unlikely to be straightened, the fibre behaving as if it is a shorter fibre, equal in length to the 'extent' of the hooked fibre, the effect being accentuated at high drafts. In contrast to this, trailing hooks are generally straightened during drafting when the fibres are accelerated, higher drafts improving hook removal. Fibres with hooks at both ends are difficult to straighten. A greater drafting force is required when drafting a majority of trailing hooks,[4] the effect increasing with increasing draft, it being preferable to have a majority of trailing hooks when high drafts are involved, such as during spinning. Combing is an effective means of removing hooks, more particularly leading hooks, it therefore being preferable to present leading hooks to the comb, which is achieved by an even number of machines (e.g. one drawframe and one lap winder) between the card and the comb. It is preferable to present trailing hooks to the ring frame (achieved by an odd number of machines between the card and the ringframe), the orientation of the fibre hooks presented to the rotor spinning machine being of little consequence.

Autolevelling

Although doubling improves the sliver evenness, an autolevelling system is often fitted to the drawframe, to further improve the sliver evenness. The open-loop auto-levelling system for drawframes, introduced towards the end of the 1970s greatly improved the quality of slivers and yarns. The autoleveller measures the sliver linear density, or cross-section, on a continuous (on-line) basis, comparing it to the predetermined level, producing a signal proportional to any deviation which is then used to change the draft (usually the main draft as opposed to the break draft) so as to correct for the deviation. Systems used to measure the sliver linear density include tongue-and-groove, pneumatic trumpet, optical and capacitive. Such systems can be located at either the input (open-loop) or output (closed-loop), or both, of the drawframe, these often being linked to computers for monitoring the state and performance of the drawframe, thereby enabling corrective action to be taken at the precise position in the sliver which needs to be corrected. The autoleveller drawframe is often used as the finisher passage in the drawing stages or as a single passage after the comber.

Open-loop autolevellers are largely aimed at correcting short- and medium-term deviations, measuring the sliver at the input side, i.e., at a point prior to where corrective action (appropriate draft change) takes place, a time delay being used to delay the draft change until the deviation in sliver reaches the point where correction occurs. Closed-loop autolevellers correct medium- and long-term deviations, measuring the sliver after the point at which correction has taken place. Combined open- and closed-loop autolevellers, which correct short, medium and long-term variations are also available.

8.3 Combing

Combing is used when high-quality fine cotton yarns (finer than approximately 15 tex) are required, improving the fibre straightening and alignment and removing short fibres, fibre hooks and any remaining neps and trash particles, thereby enabling finer, stronger, smoother and more uniform yarn to be produced. Usually one, (sometimes two) drawframe passages are used prior to combing so as to straighten and orientate the fibre hooks, thereby enabling optimum combing performance. The waste material removed during combing is referred to as noil (or sometimes as comber waste), the percentage noil, which normally falls between about 5 and 15%, being calculated as follows:

$$\frac{\text{mass of noil}}{\text{mass of (noil + comb sliver)}} \times 100 \qquad 8.1$$

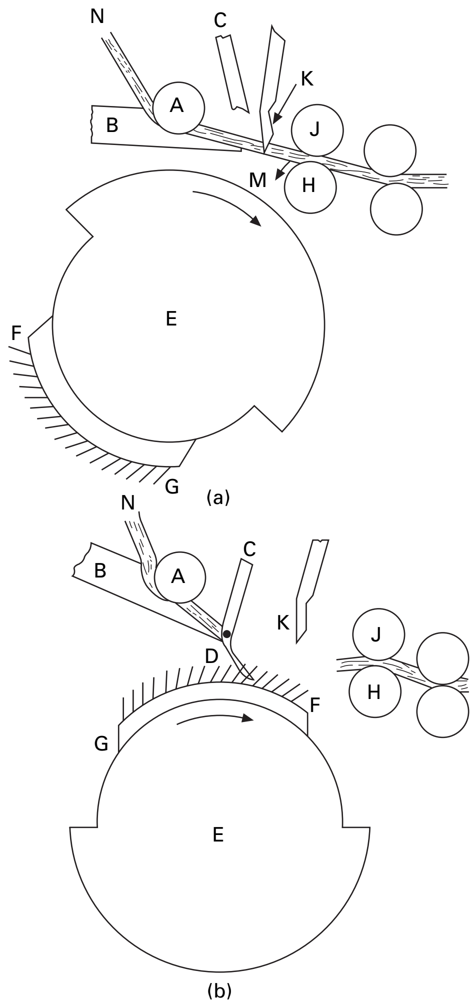
In preparation for combing, a number of drawframe slivers, are combined in a 'lap winder' to produce a comber lap consisting of a closely spaced sheet of slivers wound onto a cylindrical holder. The speed of the lap winder exceeds 100 m/min, with a draft of between two and four, the high doubling combined with the low draft result in a considerable improvement in the evenness of the lap. The correct tension is also required during the winding of the lap, too low a tension results in a soft lap, requiring more storage space and which is also prone to damage during subsequent handling and transport, while too high a tension makes it difficult to unwind the lap at the comber, particularly the last few layers, sometimes leading to 'split laps'.

The lap forms the input to the comber. Essentially the lap is combed and drafted into fibre webs, which are layered at the comber table to form a sandwich, which is drafted to form the combed sliver, the latter being coiled into a can ready for the next stage, called 'finisher' drawing, using a conventional drawframe, with single or twin delivery and autolevelling. The combing machine can have some eight combing heads. Comb production rates of up to 70 kg/hr, and nip speeds of up to 450 per min are not uncommon, with automatic lap change and transport and batt piecing and a self-cleaning top comb.

Combing essentially entails the following actions (Fig. 8.4):[4]

- Feeding: fibres are fed so that a projecting fringe of fibres, held by nip jaws, are presented to the combing pins.
- Initial combing: the above fringe is combed by pins, which remove short fibres not held, the longer 'held' fibres are straightened, with some fibre breakage possible, broken fibre segments also being removed. The resulting fringe consists of aligned fibres and no entangled or short fibres.
- Final combing and drawing-off: the projecting fringe is gripped and drawn through the pins, thereby eliminating any remaining entangled and short fibres.
- Sliver formation: the combed fibre fringes are overlapped to form a continuous sliver.
- Noil removal: the short fibres, trash and imperfections are removed from the pins, by a rotating brush, with centrifugal forces releasing the noil from the brush, the noil being transferred pneumatically to a container.

Since combing involves a number of doublings, the combed sliver is correspondingly much more even than the input drawframe slivers. In addition the fibres are considerably more parallel, and there is a much reduced proportion of short fibres, fibre hooks and imperfections, such as neps and trash particles. Nevertheless, the sliver delivered by the combing head can have a periodic unevenness, with a wavelength between some 33 and 46 mm, due to the overlapping of successive fibre tufts. Combing head slivers are fed into the comb drawbox as doubling where they are drafted to produce slivers between about 3 and 6 ktex in linear density. One or two drawframe passages (commonly six doublings and a draft of six in each case), more often one, followed by the roving operation, are applied subsequent to combing when producing combed ring-spun yarn. Sliver condensing funnels, (e.g. off-set to one side), attention to fibre alignment and tuft-overlap distance, together with reversal of draft direction, all contribute to optimising sliver levelness. The efficiency of combing is influenced by the number of hooks and the direction in which they are fed to the comb, slivers fed to the comb with a majority of leading hooks being preferred, resulting in less noil and better hook removal, although at low detachment settings the reverse may hold.

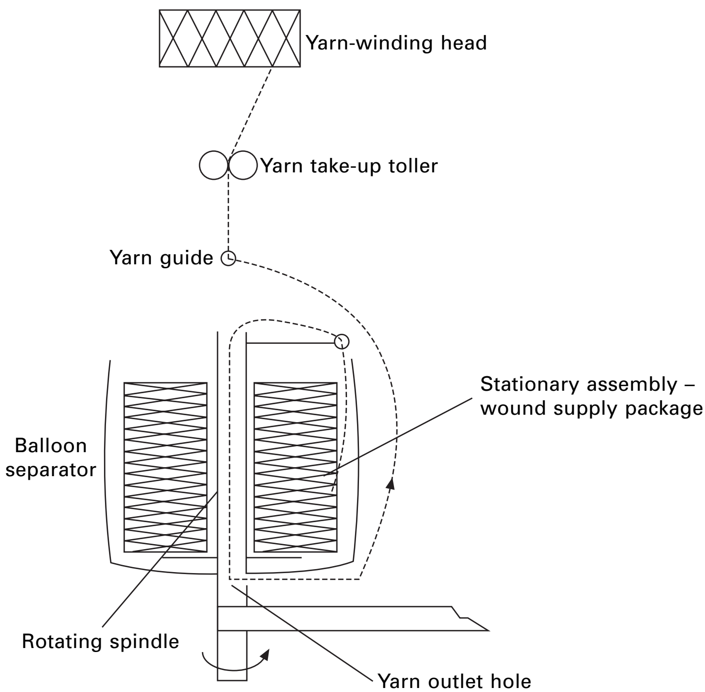


8.4 Cotton comb cycle of operations (side elevations) (a) feeding, final combing, and drawing-off (b) initial combing. A, feed roller; B, feed plate and lower nipper; C, upper nipper; D, fibre fringe initially combed ; E, cylinder; F, first row of pins; G, last row of pins; H, bottom detaching roller; J, top detaching roller; K, top comb pins; L, detached fringe of fibres; M, trailing end of previous fringe; N, continuous lap feed (source: Oxtoby).[4]

8.4 Roving

For carded yarns, typically two drawframe passages precede the roving operation, while for combed yarn, one drawframe passage precedes combing and one succeeds combing. Roving production, on a machine termed a speed frame or flyer, is the final process prior to ring-spinning, it is popularly carried out using an apron drafting system and then inserting a low level of twist into the roving in order to impart sufficient cohesion and condensing to the roving to facilitate uniform and controlled drafting during ring-spinning, particularly during the pre-drafting stage. Simple roller drafting was used in some systems up to 50 years ago but due to its relatively poor fibre control, it was replaced by the apron drafting system (Fig. 8.3) which provides far better fibre control, due to the aprons exerting a very light pressure on the fibres, until they reach the nip of the front rollers. This has become widely adopted as the drafting system in both the roving and ring-spinning operations. Drafts range between three and 16, with the roving linear density typically between 300 and 600 tex, the drafted twisted strand is wound onto a bobbin using a flyer-and bobbin arrangement (see Fig. 8.5),[1] one turn of twist being inserted with each rotation of the flyer, the latter also protecting the roving from balloon formation and air currents. The bobbin has a higher surface speed than the flyer which winds the twisted roving onto the bobbin. Automatic (integrated) bobbin doffing, followed by bobbin loading and transport, is now a reality. Flyer speeds of over 1500 revs/min are possible.

The required roving twist level may be calculated as follows[4]: twist (turns/m) = K $tex^{-2/3}$ ± 15%, where K varies from about 2000 for extra long-staple



8.5 The twisted-roving (flyer) system (source: Grosberg and Iype).[1]

cotton (e.g. Sea Island) to about 7000 for short-staple cotton. The twist can also be estimated by the following equation:

$$\text{twist (turns/m)} = \frac{1710 - 17.3l}{\sqrt{\text{tex}}} \quad 8.2$$

where l = staple length (mm) and tex = linear density (g/1000 m) of the roving.

8.5 Spinning

8.5.1 Introduction

Spinning can be divided into the following three basic operations:

1. Attenuation (drafting) of the roving or sliver to the required linear density
2. Imparting cohesion to the fibrous strand, usually by twist insertion
3. winding the yarn onto an appropriate package.

Spinning systems presently employed include ring (including the compact and 'two- strand' systems), rotor (open-end), self-twist, friction (also open-end), air-jet, twistless and wrap-spinning, with the first mentioned two systems by far the most important for cotton spinning, together accounting for far over 90% of the cotton yarn produced globally. In 2003 there were some 175 million ring spindles and 8 million o-e rotors in place worldwide (source ICIS 2003, C. Schindler, ITMF, Zurich). One rotor spindle is generally taken to equal five or more ring spindles in terms of yarn production capacity.

Ring-spinning accounts for some 70% of global long and short staple yarn production, rotor spinning for some 23% and air-jet vortex for some 3% (Source ICIS 2003, C. Schindler, ITMF, Zurich). The main reason for the dominance of ring-spinning (which is well over 100 years old) over other spinning systems is the superior quality, notably strength and evenness, of ring-spun yarns over those produced by other systems. Very fine ring yarns can also be spun (even as fine as 2 tex), the spinning limits being about 35 fibres in the yarn cross-section for combed yarns and 75 fibres in the cross-section for carded yarns. Second in importance, and increasing its share of cotton yarn spinning, is the rotor (open-end) spinning system. Spinning systems which are of little importance to cotton and not discussed here include the following: Solospun, Self-twist, PLYFil. The reader is referred to references 1, 2, 5 and 6 for information on these systems. Tables (8.1, 8.2 and 8.3) compare the different spinning processes.

8.5.2 Ring spinning

Because of its versatility in terms of yarn linear density and fibre type and also the superior quality and character of the yarn it produces, as a result of

Table 8.1 Comparison of spinning processes

Spinning system	Actual twist-insertion rate per minute*	System limited by:		Delivery speed m/min
		Twist-insertion rate*	Drafting and fibre-transport speed*	
Ring	15,000–25,000	Yes	No	20–30
Wrap	25,000–35,000	Yes	No	20–100
Rotor	80,000–150,000	Yes	Partly	100–300
Air-jet	150,000–250,000	No	Yes	150–450
Friction	200,000–300,000	No	Yes	150–400

* Based upon Stalder[18]

good fibre control, orientation and alignment (extent) during spinning and in the yarn, ring spinning (Fig. 8.6)[20] remains by far the most popular system for spinning, particularly for fine yarns. Its main disadvantage is the yarn production rate due to limitations in spindle speed (productivity), due to high power consumption, traveller wear and heat generation and yarn tension. It is necessary to rotate the yarn package (tube, bobbin or cop), approximately once for each turn of twist inserted, this consuming a great deal of power (approximately 74% required to overcome 'skin friction' drag and 25% to overcome yarn wind-on tension[21]), even for small packages. Smaller rings, higher spindle speeds, automatic doffing, compact spinning, on-line monitoring, linked winding and very hard rings and travellers (e.g. ceramic) all play a role in ring spinning maintaining its popularity. According to Oxtoby,[4] about 85% of the total power requirements of a ring-frame is consumed in driving the spindles (depending on yarn density, package size, spindle speed, etc.) the balance being consumed by the drafting and other mechanisms.

The following factors are the main influences on spinning conditions:[4]

- ring diameter (affects package size, yarn tension, traveller and spindle speeds, power consumption, capital costs, floorspace and doffing costs)
- balloon height (affects power consumption, capital cost, floorspace, doffing costs, balloon collapse – longest balloon height without balloon collapse is the most economical)
- spindle speed
- traveller mass.

The limitations in the speed of the traveller on the ring (around 45 m/s maximum) are due to excessive wear and heat being generated by the traveller at high speeds, as well as by the yarn tension and tension peaks generated during spinning, created by the balloon and traveller friction, exceeding the yarn breaking strength. The maximum spindle speed is normally around 25,000 revs/min and yarn production around 40 m/min, with drafts ranging from about ten to 80. Reducing the balloon size and traveller friction can

Table 8.2 A general comparison of yarns spun by different spinning systems*

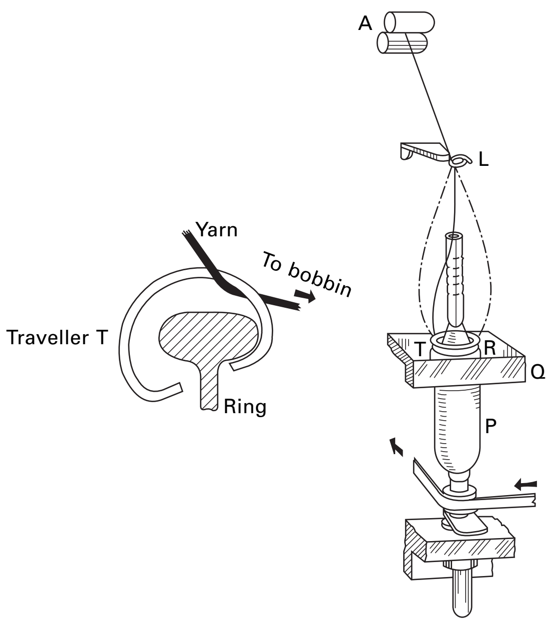
Property	Ring-spun yarn	Rotor-spun yarn	Friction-spun yarn	Air-jet-spun yarn
Tensile strength	Good	Lower than ring-spun yarn	Lower than ring- and rotor-spun yarn	Good
Evenness	Good	Very good to good	Satisfactory	Good
Imperfections	–	–	Fairly high	–
Hairiness	High	–	High	–
Snarling tendency	High	Low	Hign	Low
Stiffness	Low	Higher than ring-spun yar	Similar to rotor-spun yarn	High
Shrinkage	–	–	–	High
Twist structure	Homogeneous across the length and cross-section	Homogeneous except for the presence of systematically formed wrapper fibres	Inhomogeneous, with ring-spun-yarn appearance in the absence of systematically formed wrapper fibres	Inhomogeneous, along the length with untwisted core fibre bound in by the sheath fibres
Fibre extent and orientation	–	–	Poorer than ring- and rotor-spun yarn	–

* From Klein[5,6]

Table 8.3 Order of importance of fibre properties for different spinning systems[19]

Order of importance	Ring	Rotor (open-end)	Air-jet	Friction
1	Length and length uniformity	Strength	Fineness	Strength
2	Strength	Fineness	Cleanliness*	Strength
3	Fineness	Length and length uniformity	Strength	Fineness
4		Cleanliness*	Length and length uniformity	Length and length uniformity
5			Fineness	Cleanliness*

* Trash, dust, etc.



8.6 The ringframe (source: Booth).[20]

reduce the latter limitation. The tension on the yarn can be controlled by the traveller, largely depending upon the frictional resistance of the traveller against the ring, which in turn is largely determined by the rotational speed. Requirements of the traveller include good heat dissipation, sufficient thread space, matching of traveller size and shape to the ring flange and good sliding properties.[4]

The yarn tension (S) may be approximated as follows:[22]

$$S \approx \frac{\mu_L}{\sin \alpha} \left[\frac{m_L v_L^2}{d_R} \right] \qquad 8.3$$

where μ_L = coefficient of friction between ring and traveller, m_L = traveller mass, α = angle between yarn from traveller to cop (tube) and a straight line from traveller to spindle axis, v_L = traveller circumferential speed, and d_R = ring diameter. The term in brackets represents the centrifugal force.

Yarn spinning tension is also affected by the length and diameter of the balloon, the use of balloon control or suppression devices (e.g. rings, and spindle attachments) enabling the yarn tensions in the balloon to be reduced by reducing the balloon, thereby allowing spinning speeds and/or package sizes to be increased and power consumption to be reduced, traveller speeds as high as 45 m/s (or even 50 m/s) becoming possible when, for example, using sintered rings and nylon travellers. Rotating rings were explored as another way to overcome traveller speed and yarn tension limitations but they have not yet found wide application.

The input into the ring-frame can be twistless (rubbed) or twisted (flyer) rovings although in the case of cotton, it is virtually always the latter. Double apron drafting, optimum draft typically between 30 and 40 (break-draft around 1.2), in some cases even as high as 60 for combed yarn,[23] is generally used in modern ring-frames, except in some of the high draft spinning systems, the drafting procedure and yarn formation determining the quality and structure of the yarn. Decreasing the width of the fibre ribbon at the exit of the drafting system has been found to improve yarn quality and also to make higher drafts feasible[23] (see section 8.5.4).

Spinning production and cost are related to the level of twist inserted, which in turn is related to spinning efficiency (end breakage rate) and yarn properties (notably tensile, bulk, hairiness and stiffness). The minimum twist required to produce acceptable spinning performance and yarn properties is normally selected. Inserting twist into the yarn causes a reduction in the yarn length, referred to as twist contraction, which is typically around 4% for a 20 tex cotton yarn, but which depends upon the twist level. End breaks are caused either by the yarn spinning tension exceeding the yarn strength, more particularly that of the yarn weak places, or by flaws, such as neps, vegetable matter and short fibres, in the input material. Krifa and Ethridge[24] have reviewed research on cotton spinnability and developed a new spinning potential definition which captures critical aspects of spinning performance and yarn quality. It is generally held that surface fibres have the same angle of inclination to the yarn axis when yarns have the same twist factor (e.g. turns/cm $\sqrt{\text{tex}}$), and that such yarns therefore have a similar geometry. Typical twist factors for ring-spun cotton yarns are given in Table 8.4.[3]

Table 8.4 Typical twist factors (αtex)[3*]

Fibre length	Short	Medium	Long
Knitting	–	2400–2875	2010–2500
Weft	3150–3650	2875–3350	2400–2875
Semi-warp	3550–3830	3350–3650	2875–3260
Warp	3830–4790	3650–4300	3260–3750

Source: Klein[3]

* α_{tex} = turns/m $\sqrt{tex}$

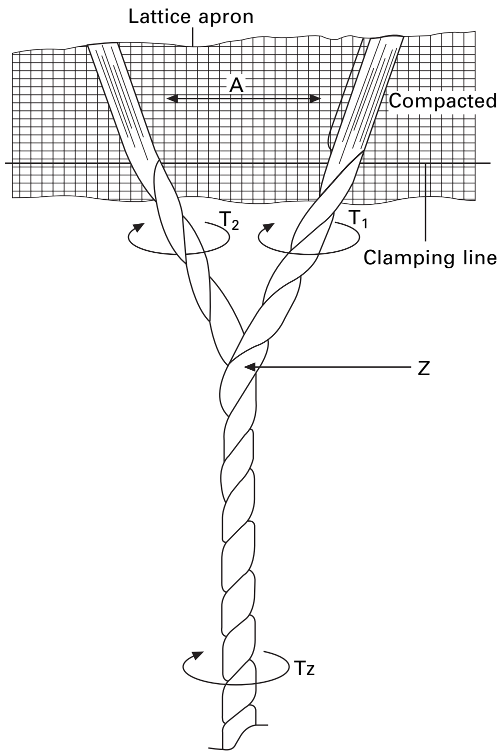
$$\alpha_e = \frac{\alpha_{tex}}{958}$$

Modern ring-frames can incorporate push-button draft and twist changes, automatic doffing (also without underwinding), sliver/roving stop motions, thread break indicators, electronic speed and package building programs, and automatic piecing, on-line monitoring, data collection, ring cleaning and can also be linked to the winders, with a cop steamer stage between spinning and winding.[9] For good spinning performance, the atmospheric conditions, particularly relative humidity (RH), in the spinning room need to be maintained within the optimum range (e.g. 40% to 50% RH), too high an RH leading to roller lapping while too low a level (below 40% RH) leading to excessive fibre fly and static.

8.5.3 Two-strand spinning (twin-spun)

Considerable efforts have been directed towards eliminating two-folding (plying and sizing) in the production of weaving yarns, the ultimate aim being to produce as fine a yarn as possible on the spinning frame which can be woven without resorting to either two-plying (folding) or sizing. In the main, two approaches have been followed, namely, 'two-strand' spinning (e.g. Sirospun, EliTwist and Solospun) and 'compact' (condensed) spinning, the latter being mainly used for cotton.

Two-strand spinning, also referred to as spin-twist or double-rove spinning, involves two rovings being fed separately to the same double apron drafting system, each strand receiving some twist before they are combined at the convergence point after the front rollers. The Sirospun system uses, for example, a mechanical break-out device and automatic repiecening to prevent spinning when one strand breaks. It is also possible to include a filament, (flat, stretch or textured). Spinning limits are about 35 fibres per strand cross-section. With the EliTwist® system (Fig. 8.7),[26] yarns with resultant linear densities from R60 tex/2 (Ne 20/2) to R8 tex/2 (Ne 140/2) can be spun.

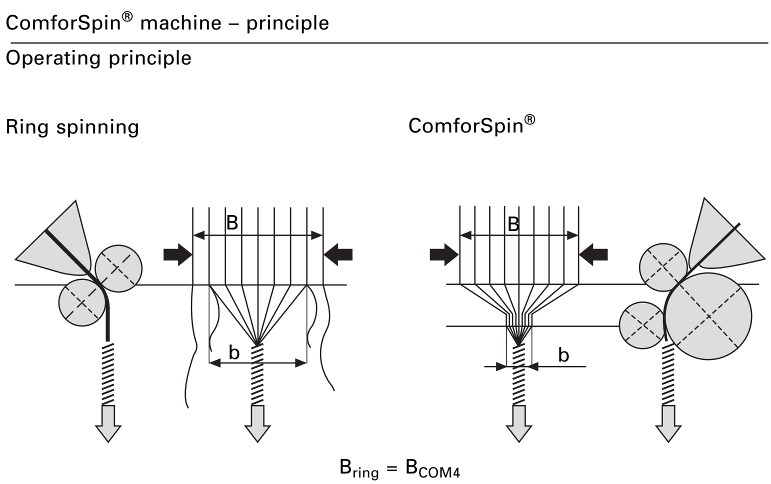


8.7 Two-strand spinning EliTwist (source: Ramasubbu, Spindelfabrik Suessen GmbH).

8.5.4 Compact (condensed) and related spinning systems

Following upon the two-strand spinning developments, further work was undertaken to produce ring-spun singles yarns with superior properties (notably tensile, hairiness, abrasion and pilling). Considerable success has been achieved and compact spinning systems were commercially introduced in the 1990s, in some cases enabling combed yarns to be replaced by carded yarns and two-ply yarns by single yarns. Compact spinning has caused a revival in ring spinning, and compact yarns fetch a premium price. Examples of compact/condensed spinning systems include the EliTe spinning system of Suessen, ComforSpin® (Com4)® of Rieter, CompACT[3] of Zinser and RoCoS of Rotorcraft.

The width of the fibre ribbon (±4 mm) in the drafting zone is wider than that of the spinning triangle, resulting in the fibres at the edge not being integrated into the yarn core or else not being properly integrated. The fibre ribbon emerging from the front rollers of the spinning machine is twisted to form a yarn, forming a 'spinning triangle' in the process. During twist insertion, the fibres in the spinning triangle are not fully integrated into the yarn. The width of the spinning triangle (fibre beard) has been shown to be related to the spinning tension, and therefore also to fibre migration, as well as to the hairiness and imperfect integration of the fibres into the yarn.[26] Considerable effort has therefore been directed towards narrowing (compacting or condensing) the spinning triangle (fibre beard) at the exit of the front rollers. Most of the resulting systems, referred to as compact or condensed spinning, involve a condensed, narrow spinning triangle at the front roller nip (Fig. 8.8)[27] and better control of the fibres at the exit of the front roller nip and their integration (binding) into the yarn, eliminating peripheral fibres. This has been done by introducing an intermediate (condensing) zone (pneumatic or mechanical) between the front roller delivery and the yarn formation (twist insertion) point in which the fibrous ribbon width and spinning triangle are reduced. This gives improved spinning efficiencies (50% less end breakages), fibre binding and alignment, smoothness, lustre, hairiness (≈ 20–70% lower), tensile properties (≈ 10–15% better) and compactness in the yarn, less fibre waste and fly as well as reduced levels of spinning end-breakages (50%), size (≈ 30–50% less, or sometimes even dispensed with) and twist (≈ 10–25% lower). The condensing systems used to accomplish this, and which are generally easily attached to, and dismantled from, the spinning frame, mostly involve pneumatics (vacuum suction), applied, for example, to a perforated front roller, lattice or apron. This has enabled higher optimum drafts to be achieved, even as high as 80 for coarse yarns.[23] Although the low yarn hairiness (particularly longer hairs) leads to increased traveller wear, this has been overcome by new coatings. Compact core-spun yarns are also produced using the compact spinning technique.

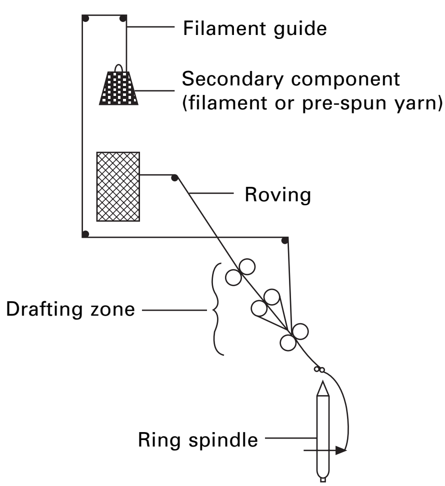


8.8 Compact spinning (Maschinenfabrik Rieter AG).[27]

8.5.6 Bicomponent spinning

Bicomponent yarns, also referred to as bound yarns, have a niche market, these generally combining pre-spun continuous filament yarns (sometimes even staple yarns) with staple fibres to provide improved properties, such as stretch (e.g. Lycra), abrasion and strength. The filament yarn can either be covered by the cotton sheath (i.e. be in the core of the yarn) or be wrapped around the outside of the yarn, the former being the more common, except in the case of wrapper yarns which are produced in a different way as discussed later in this chapter.

Bicomponent spinning (see Fig. 8.9)[28] normally involves twisting together either a filament (sometimes water soluble) and a conventionally drafted staple (cotton) strand during the spinning operation, and is particularly attractive for the cost-effective production of superior yarns which can, for example, be woven or knitted without any further operations (i.e. eliminating plying, sizing and steaming). It also enables coarser fibres to be spun into finer yarns, reduces spinning end breakages, allows higher winding speeds and enables yarn and fabric properties to be engineered by suitable selection of the two components and the way in which they are combined. On the negative side, the filament is expensive and bicomponent yarns are generally not pure cotton or torque-balanced and produce fabrics which are generally more streaky and air permeable and have more conspicuous joints. A suitable type of 'break-out device' can be used to prevent the production of a single component yarn should one of the components break.



8.9 Bicomponent spinning (source: IWS Wool Profiles).[28]

8.5.7 Rotor (open-end) spinning

Rotor spinning, generally referred to as open-end (OE) spinning, since there is a definite break (discontinuity or open end) in the fibre flow prior to yarn formation, was commercially introduced during the late 1960s and is second only to ring spinning in terms of short staple yarn production. It has reached the stage where it is now classed, together with ring-spinning, as 'conventional' spinning. It can produce yarn within the range of approximately 10 tex to 600 tex, more often 15 to 100 tex, with delivery speeds as high as 300 m/min or even higher, although its economics become less favourable at the finer end of the scale. The main disadvantages of rotor-spun yarns compared with ring-spun yarns are their lower strength and the presence of wrapper fibres which adversely affect their handle. The spinning limits are also lower, generally taken to be between 100 and 120 fibres in the yarn cross-section.

Brandis[29] calculated the theoretical spinning limits of rotor spinning as well as the centrifugal forces (F) acting on the end of the yarn using the following formula:

$$F = 1.25 \times 10^{-6} \times \frac{n^2 D^2}{g} \times \text{linear density (tex)} \qquad 8.4$$

where n = rotor speed (rev/min), D = rotor diameter (m), and g = acceleration due to gravity (m/s^2).

The frictional forces are taken into consideration by introducing a systems constant, which represents the ratio (S) between the theoretical and actual draw-off forces. The ratio depends upon many factors, such as fibre type, rotor speed, and whether it is a biaxial or coaxial spinning system. The effective draw-off force (Fe in gf) obeys the following equation:

$$Fe = 1.25 \times 10^{-6} \times \frac{n^2 D^2}{g} \times \text{linear density (tex)} \times S$$

Brandis[29] arrives at an equation (called the Krupp formula) for the maximum attainable speed (n_{max}) in rotor-spinning where the yarn strength is assumed to equal the draw-off force. The equation is simplified to:

$$n_{max} = \frac{2700}{D} \sqrt{\frac{B}{S}} \text{ (rev/min)}$$

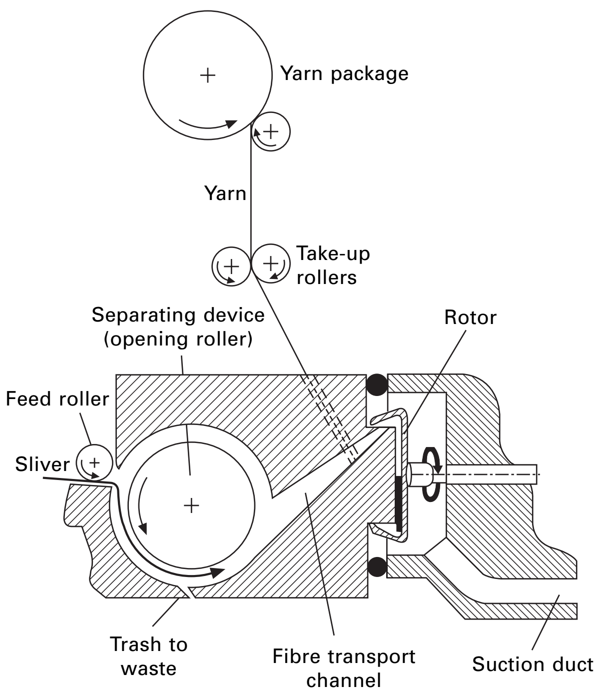
where D = rotor diameter (m). Assuming the following typical values: D = 0.04 m, B = 12 km (or gf/tex), and S = 1.5, we have n_{max} = 190,000 rev/min.

The rotor spinning machine can be supplied with either card sliver or drawframe sliver (after one or two drawframe passages, the second with autolevelling) or even in some cases with a comb sliver. Recently, the card and drawframe functions have been integrated to produce sliver well suited to rotor spinning. In essence, a feed roller feeds the sliver to the surface of the revolving opening roller (Fig. 8.10), covered in pins (or teeth) which pluck the individual fibres from the leading edge of the sliver.[30] These fibres are carried pneumatically down the fibre transport tube and deposited into the specially designed groove of the rotor (often specially coated with wear resistant coatings), which is rotating at a very high speed, rotor diameters typically varying between 28 and 56 mm.

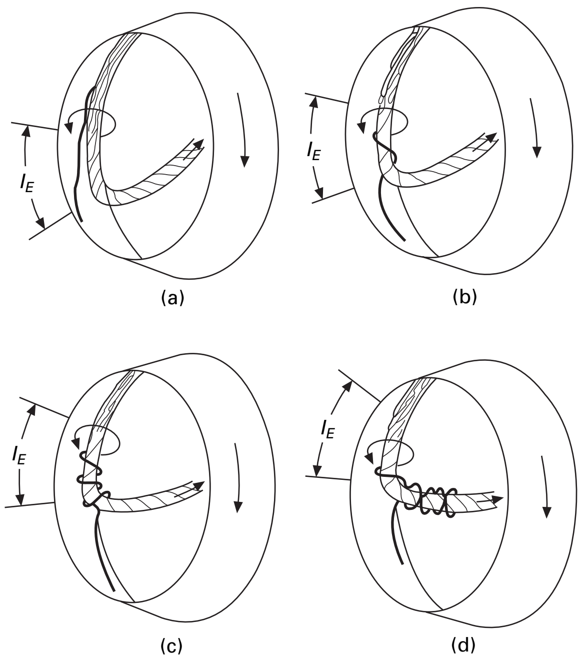
The yarn formed rotates around its own axis and is withdrawn through a specially designed navel (doffing tube) one turn of twist being inserted per rotor revolution, twist running from the rotating yarn to the fibres lying in the rotor groove (Fig. 8.10). The twist inserted can be calculated as follows:

$$\text{Turns/m} = \frac{\text{rotor speed (revs/min)}}{\text{yarn delivery speed (m/min)}} \qquad 8.7$$

The twist levels in rotor yarns are generally higher than those used in the corresponding ring-spun yarns. The yarn is wound directly onto a package (cone) which can be either parallel sided or inclined (conical), the length and



8.10 Open-end rotor spinning (source: Kwasniak and Peterson, *J. Text. Inst.* 88, (1/3), 174.



8.11 Wrapper fibres (source: Lünenschloss and Kampen).[31]

evenness of the yarn being monitored in the process. Yarns destined for knitting can also be waxed at this stage. The yarn structure comprises:

- a core, similar to ring spun yarns,
- a sheath of fibres wrapped around the core and
- wrapper fibres (Fig. 8.11)[31] wrapped tightly around the yarn almost at right angles to the yarn axis, these represent one of the main drawbacks of rotor-spun yarns.

The core of the yarn is largely responsible for its strength, the sheath largely determines the yarn bulk and handle, while the frequency of wrapper fibres affects the yarn handle (harshness).

Drafts are normally of the order of 100 to 200, but could be as high as 400 (higher drafts having some benefits in terms of yarn quality), with rotor speeds ranging from about 40,000 revs/min to 150,000 revs/min, being inversely related to the rotor diameter, the limiting speed being regarded as about 180,000 revs/min.[32] The yarn properties are affected by[33] rotor groove shape (angle, radius, depth), rotor diameter, rotor speed, doffing tube (navel) properties and rotor wall inclination and friction. The navel material generally consists of high quality ceramic. Efficient and automatic rotor cleaning and yarn piecing are both critically important, input sliver relatively free of dust and trash is also important.

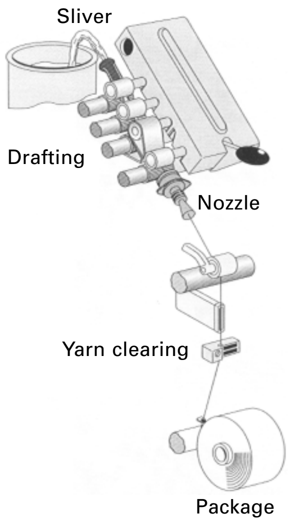
Automation (rotor cleaning, piecing and doffing) has reached high levels in rotor spinning, with on-line yarn quality monitoring (including long-term yarn linear density variations) and fault classifying and clearing, using optical or capacitance systems, as well as waxing taking place during spinning. Yarn packages of up to 6 kg, suitable for subsequent fabric manufacturing, (e.g. 4°20 conical packages) can be produced directly on the rotor spinning machine. Systems, such as the Schlafhorst Corolab optical monitoring system, enable unwanted faults, including foreign fibres, to be monitored classified and removed. Core-spun and elastic core-spun yarns (e.g. core entered through the rotor shaft) yarns as well as fancy yarns (e.g. by intermittent changing of sliver intake speed) are also produced on rotor spinning machines.

8.5.8 Air-jet spinning

Air-jet spinning, also termed Vortex spinning, introduced in the 1980s, produces yarn typically in linear densities from about 5 tex to 40 tex, at speeds of up to 400 m/min or even higher. The processes prior to air-jet spinning are similar to those used for rotor-spinning, although combing is more often used in preparation since dust and trash can obstruct the spinning jets. The yarn more closely resembles, but is weaker than, ring-spun yarns. Air storage (accumulator) systems are not suitable at such high speeds and the yarn storage system of the machine is similar to that of a weaving machine yarn storage feeder, which is self threading, and constantly stores and discharges yarn.[7]

Drawframe sliver (often combed) is supplied to the air-jet spinner, with twist being inserted to the fibres, largely on the yarn surface, by the vortex created in one or two air-jet nozzles, generally only one when spinning 100% cotton, the yarn structure therefore consisting of a core of largely parallel fibres and a sheath of wrapped (twisted) fibres. The Muratec (Murata) true twist air jet (vortex) spinning process (MVS), introduced in 1997, has proved to be the most successful for the spinning of pure cotton yarns, a highly productive core-spinning version having also been introduced. The Muratec MVS system (Fig. 8.12[34]) uses a four-line roller drafting system with a unique guide (spindle), a needle holder and a single air nozzle to impart true (real) twist to the yarn.

Combing is generally advisable for spinning fine cotton air-jet yarns, generally higher fibre loss, mainly short fibres, occurs during air-jet spinning than during ring-spinning Zeng *et al.*[35] have reported on factors which affect the twist inserted during air-jet spinning, this being a function of nozzle pressure, flow rate, jet orifice angle and diameter, also using neural networks to predict yarn tenacity.[36]



8.12 Murata vortex spinning (source: Murata (Muratec)).[34]

8.5.9 Friction spinning

Although cotton, either in 100% or in blends with other fibres, is spun on the friction spinning system, the percentage is very low. The reason for this is largely to be found in the lower quality, strength in particular, of friction spun cotton yarns compared with ring- and rotor-spun yarns due to the lower efficiency of the yarn structure (relative low orientation, extent and packing of fibres), as well as in the fact that the fibre feed speed is too high and yarn tensile force too low for fibre binding at the yarn end.[37] Friction spun yarn are weaker and more twist lively than other yarns, although plying can reduce these drawbacks. Ishtiaque *et al.*[5] have thoroughly reviewed published literature on friction spinning. The spinning limits for friction spinning cotton are around 100 to 120 fibres in the yarn cross-section,[38] although the manufacturers recommend 150 for the DREF-3 in order to avoid frequent end-breaks.

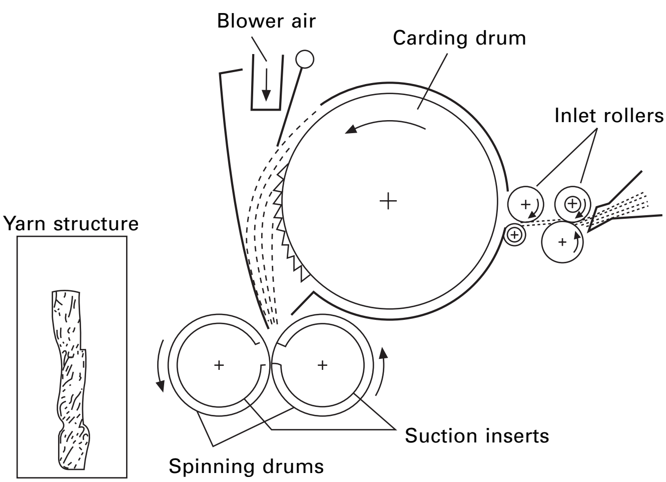
In friction spinning, twist is inserted into the yarn by a rolling action due to frictional forces generated between, for example, two perforated rollers and the yarn surface, it being relatively easy to produce core-spun yarns by introducing a filament yarn which is then wrapped by a sheath of staple fibres. Friction spinning can also be classified under the broad category of 'open-end spinning', since the sliver feed is 'broken' (i.e. discontinuous) prior to yarn formation (twist insertion). The latter takes place as a result of frictional forces, produced aero-dynamically, acting on the fibres within the spinning zone. Examples of friction spinning systems are the DREF (Fehrer AG) and Masterspinner (Platt-Saco-Lowell).

Friction spinning, is very versatile in terms of the fibres it can process, involving the following operations:[5]

- Opening and individualisation of the fibres (10–120 mm long) from the sliver(s) (e.g. by a carding drum)
- re-assembling of fibres (e.g. in the nip of two perforated rollers)
- twisting of the fibre assembly (e.g. by the drum surfaces)
- withdrawal of the resultant yarn
- winding of yarn.

One example of friction spinning is shown in Fig. 8.13,[30] where the fibres are fed to perforated rollers, the fibres being held by suction acting through the perforations in the rollers. The friction generated between the fibres and the rotating roller surfaces consolidates and inserts twist, into the fibre assembly, forming a yarn which is then withdrawn and wound onto a package. Although the improved DREF-5 was developed for the spinning of relatively fine yarns (15 to 40 tex), friction spinning is still largely used in producing coarse yarns (40 tex and coarser) for industrial applications, accounting for a very high proportion of spun yarn (mostly non-cotton) used in the production of technical textiles.

Commercially, the most successful friction-spinning machines are the DREF (DREF-2, DREF-3, DREF-5, DREF-2000 and DREF 3000) machines from the Austrian machine manufacturer, Dr Ernst Fehrer AG Textilmaschinenfabrik, core-spinning also being possible. The DREF-2000 machine was exhibited at the 1999 ITMA exhibition, it being able to produce either S- or Z-twist yarn without any mechanical alterations to the spinning machine.



8.13 Open-end friction spinning (source: Ishida).[30]

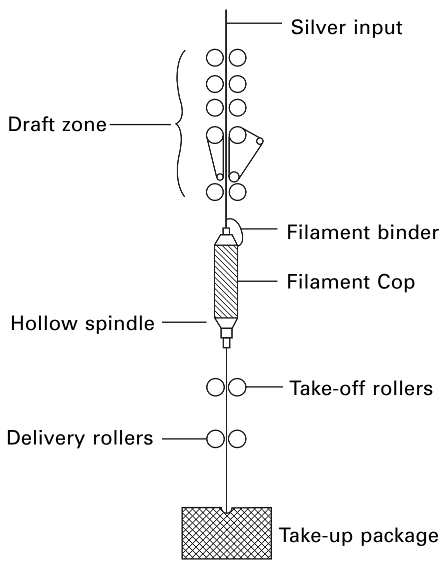
8.5.10 Wrap (hollow spindle) spinning

Hollow spindle wrap-spinning (Fig. 8.14)[28] shown at the 1975 Milan ITMA in which continuous filament yarn, usually a fine one, on a hollow spindle, is wrapped around an untwisted staple core (the latter accounting for typically 80 to 95% of the yarn composition) which has passed through a double apron drafting system. One revolution of the hollow spindle inserts one turn (wrap or twist) of the filament around the staple core.

In plain yarns, the number of wraps required per unit length is generally very similar to the number of turns (twists) per unit length used for the equivalent ring-spun yarns. Yarn delivery speeds of 200 m/min and linear densities between about 20 tex and 500 tex are possible. The economics tend to favour wrap-spinning for yarns coarser than about 50 tex. Such yarn is not twist lively and has a soft handle, the yarn being more suitable for coarse count knitting than for weaving. Wrap-spun yarns tend to be less hairy and bulky and equal to, or better, in strength and evenness and can be spun finer than the ring yarn equivalent. Spinning limits generally lie between about 40 and 70 fibres in the yarn cross-section. The fine filament wrapper is expensive, however, representing a serious constraint.

8.5.11 Fibre migration

Fibre migration, more correctly lateral fibre migration, popularly refers to the radial movement of a fibre within the yarn cross-section. Fibre migration



8.14 Wrap spinning (source: IWS Wool Profiles).[28]

(variable helix angle at different positions along the fibre length) determines the yarn structure and properties and can be characterised by:[4]

- mean fibre radial position
- migration amplitude
- mean migration intensity (i.e. rate of change of radial position).

Relatively highly tensioned fibres, or fibre segments, move (migrate) towards the yarn core or centre, while relatively low-tensioned fibres or fibre segments move towards the outer layers or surface of the yarn. Similarly, coarse or stiff fibres migrate towards the yarn surface while fine or flexible fibres migrate towards the yarn core. Also, as a consequence of the above, longer fibres tend to migrate towards the yarn core and shorter fibres towards the yarn surface.

8.6 Spinning limits and yarn irregularity

The raw material (fibre) represents between 50 and 75% of the cost of producing a cotton yarn, various studies having shown that fibre fineness is one of the most important fibre properties in terms of spinning performance and limits and yarn quality. This is largely because of its effect on the number of fibres in the yarn cross-section when yarn linear density (count) is constant. Equally, if not more, important, is mean fibre length, followed by fibre strength, length distribution (CV and short fibres), fibre friction and cohesion (see Table 8.4). For cotton ring spinning, spinning limits are normally taken to be about 50 fibres (average for carded and combed yarns) in the yarn cross-section although commercial spinning limits are often higher. Generally around 40 to 50 end breaks per 1000 spindle hours represent the maximum acceptable limits for commercial spinning of cotton.

The average number of fibres (n) in the yarn cross-section can be calculated as follows:

$$n = \frac{1000 \times \text{yarn linear density (tex)}}{\text{Fibre fineness (mtex)}} \qquad 8.8$$

According to Martindale,[39] the limiting (or ideal) yarn irregularity (CV_L), assuming completely random distribution of fibres, can be calculated as follows:

$$CV_L\,(\%) = 100\sqrt{\frac{\left\{1 + 4\left(\frac{CV_D}{100}\right)^2\right\}}{n}} \qquad 8.9$$

where CV_D is the coefficient of variation of fibre diameter.

An irregularity index (I), for yarns and slivers, is also often used to provide a measure of the yarn unevenness relative to the fibre used. I can be calculated as follows:

$$I = \frac{CV(\%)}{CV_L} \qquad 8.10$$

For cotton this becomes:

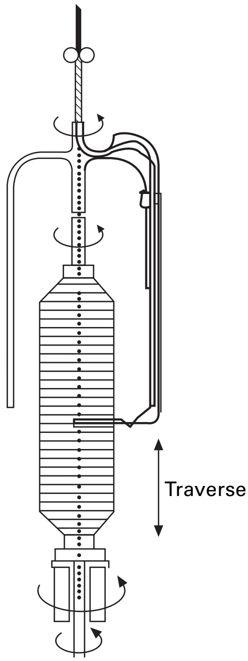
$$I = \frac{CV(\%)\sqrt{n}}{106} \qquad 8.11$$

where CV(%) = actual or measured yarn or sliver irregularity and n = the number of fibres in the yarn (or sliver) cross-section, calculated according to, e.g., equ 8.8.

8.7 Yarn twisting (folding)

Yarn twisting or folding is normally applied to improve yarn evenness (CV) (by a factor of $\frac{1}{\sqrt{N}}$, where N is the number of yarns folded), strength, extension and abrasion resistance and to reduce twist liveliness (torque) by balanced twist, hairiness and fibre shedding (fly) and to produce speciality (fancy) yarns. Balanced twist is normally achieved when the plying (folding) twist is approximately two-thirds that of the singles yarn twist, and in the opposite direction.

The twisting operation, also referred to as plying or folding, is the process whereby two (sometimes more) yarns are twisted to form a two-ply (or multi-ply) yarn. Traditionally, this was done on a ring-frame (ring-twister) but today it is almost exclusively carried out on a two-for-one twisting machine (Fig. 8.15),[1] three-for-one twisting systems having also been developed. Assembly winding is used to assemble two ends of yarn on one package in preparation for two-for-one twisting. It is particularly important to ensure that the two yarns are wound at the same tension. The assembly wound package remains stationary, the yarn passing through a guide mounted on a rotating arm which can freely rotate, through the hollow rotating spindle, then through an eyelet (outlet hole) and from there via a yarn guide and yarn take-up rollers to the yarn winding head. One revolution of the spindle inserts one turn of twist into the yarn while the rotating eyelet simultaneously inserts a turn of twist in the yarn in the balloon. Thus two turns are inserted per spindle revolution. Spindle speeds as high as 13,500 revs/min and delivery speeds up to 60 m/min are possible, the unit can be with or without balloon control. Lorenz[40] has reviewed yarn twisting.



8.15 Two-for-one twisting (source: Grosberg and Iype[1]).

8.8 Winding, clearing and lubrication

Winding, re-winding as it is sometimes called, is aimed at transferring the yarn from the spinning packages (referred to as tubes, cops or bobbins), which normally hold relatively short lengths of yarn, into packages (cones, cheeses, etc.) which can hold considerably longer lengths of yarn more suitable for the subsequent processes, such as yarn preparation, weaving, knitting, package dyeing, etc. The winding process also provides an opportunity for unwanted yarn faults (e.g. slubs and thin or weak places, foreign fibres, trash, etc.) to be classified and removed (i.e. yarn clearing) and the yarn to be lubricated. The latter is often referred to as waxing in the case of knitting since it entails the use of a solid wax disc for lubricating the yarn. Clearers may be either of the capacitance or optical types or even a combination of these.

Splicing, for example, pneumatic (the most popular), thermal (mostly for wool and wool blends) and injection (small quantities of water), is widely used today, giving joints of acceptable strength (over 90% of the yarn strength) and appearance. On-line monitoring of winding is carried out, mainly to provide exact length measurement and control, yarn path and winding speed control as well as to provide the necessary management information. On-line monitoring of yarn quality and tension, as well as tension regulating have also been introduced.

Automation (package changing, yarn jointing, etc.), higher speeds (up to 2000 m/min) and yarn monitoring and clearing systems characterise modern winders, as well as electronic monitoring systems which enable simulation of the yarn appearance on a wrapping board or in a woven or knitted fabric. Automatic linkages between spinning machines and winders, together with in-line steaming (setting) of yarn, are also increasingly being used. Maintaining yarn tension also enables twist-lively (i.e. unsteamed) yarn to be wound.

8.9 Yarn steaming (setting)

Yarn is steamed (heat set) in an autoclave after spinning so as to reduce or eliminate the twist liveliness (torque) and snarling tendency of the yarn and thereby facilitate the subsequent winding and twisting (folding) of the yarn and to avoid fabric distortion (e.g. spirality in knitted fabric). In-line steaming on conveyers has also been introduced while some modern winders enable twist-lively yarn to be wound. Different steaming conditions can be employed to achieve the desired effect but it is important to regulate the setting temperature and time, particularly the former, in order to avoid fibre yellowing and damage and ensure consistency of steaming conditions. Longer steaming times, rather than higher temperatures, are preferred if the setting effect is not adequate.

8.10 Conclusions

It is likely that within the near future, developments in spinning preparation and spinning will be incremental rather than revolutionary. Developments are likely to include further increases in production speeds as well as in the linking, integration and automation of production processes. ‘Intelligent’ and on-line monitoring and control, using expert and other advanced software systems, are also expected to feature increasingly. Although ring spinning, followed in importance by rotor spinning, is expected to continue its dominant role within the foreseeable future, unconventional spinning systems, such as air-jet and friction, are likely to be improved so that better quality cotton and cotton blend yarns can be spun, particularly in terms of the yarn structure and quality.

8.11 References

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9
Cotton knitting technology

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9.1 The development of knitting technology

Hand knitting is the foundation stone of today's mechanical and electronic stitch formation. In 1589, W. Lee invented the mechanical stitch formation technique on the stocking frame. His frame was able to knit 16 stitches at the same time. This technique is still used for today's modern machines. In 1758, J. Strutt invented the double knit technique, which consists of vertically arranged needles between the horizontal needles. In 1798, M. Decroix, developed the circular knitting technique. In 1847, M. Townsend invented the latch needle, making stitch formation easier and increasing production speed. In 1878, D. Griswold invented the circular knitting machine, which can produce rib and plain fabric in any desired distribution by vertical cylinder and horizontal dial needles. In 1910, the interlock fabric was developed by the firm R. W. Scott and then in 1918, the first double cylinder, small circular knitting machine with double hook needle was developed by the firm Wildt. In the 1920s, mechanical needle selection devices such as punched tapes and pattern wheels began to be widely used. In the 1960s, the era of electronics began and the first electronic needle selection with film-tape was demonstrated by the firm Morat at ITMA, Hannover, in 1963.[1,2]

In the 1990s, the four needle bed technique with the flat knitting technology by Shima-Seiki started to be widely used, making it possible to produce a garment from a flat knitting machine without any sewing operation. The Mayer & Cie firm demonstrated that it is possible to make an intarsia technique on a circular knitting machine (Intarsianit) which has three or six times greater production capacity than a conventional flat knitting machine. With warp knitting technology, apart from conventional needle selection, it is now possible to individually select needles by the Piezo Jacquard system.[2]

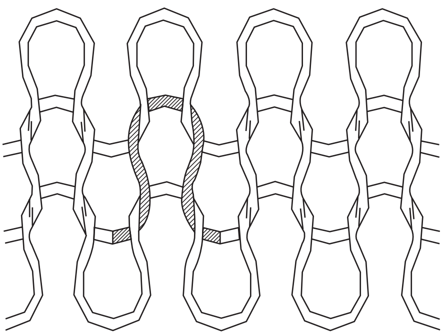
9.2 Terms used in knitting technology

9.2.1 Terms used in weft knitting technology

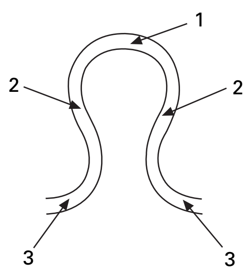
Stitch: stitch is the smallest unit in knitted fabric. A knitted fabric surface is formed by repeating it, side to side and one on top of the other (see Fig. 9.1). It consists of loop head, loop leg and loop feet (see Fig. 9.2).

Plain stitch: this is the technical face side of stitch where loop legs are above the neighbour stitch and loop head is below the neighbour stitch (see Fig. 9.3).

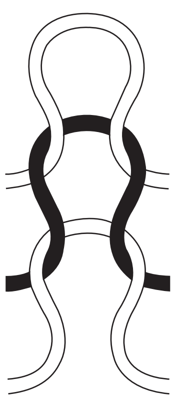
Purl stitch (reverse stitch): this is the technical reverse of the stitch where loop legs are below the neighbour stitch and the loop head is above the neighbour stitch (see Fig. 9.4). The reverse of a plain stitch (see Fig. 9.3) is the purl sititch (see Fig. 9.4).



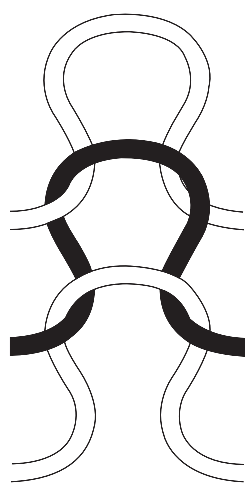
9.1 Knitted fabric surface.



9.2 Loop. 1. loophead; 2. loop leg; 3. loop feet.

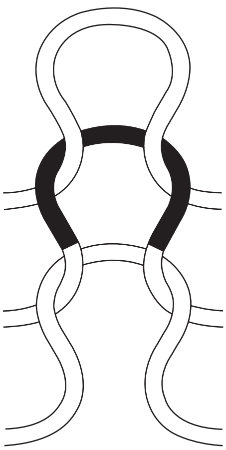


9.3 Plain stitch.

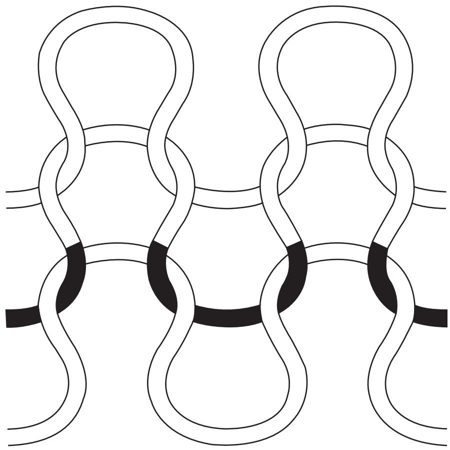


9.4 Purl stitch.

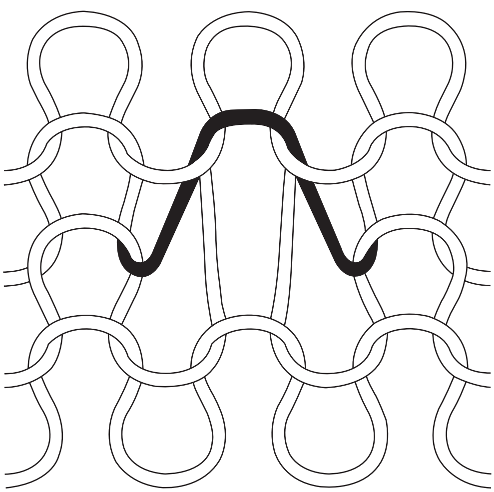
Needle loop: this is the part of the stitch which is composed of loop head and loop leg (see Fig. 9.5).
Sinker loop: this is the part of the stitch which is composed of loop feet belonging to neighbouring stitches (see Fig. 9.6).
Tuck stitch: this is the stitch which has the reverse V shape. The loop head of a tuck stitch together with the previous loop head are held by the feet of the following stitch (see Fig. 9.7). Normally, a tuck stitch with more than four successive tucks on the same needle should not be used due to high yarn tension and needle damage (not more than six adjacent tucks due to freely floating and snagging). The tuck stitch reduces the lengthwise elasticity of the fabric and the fabric length, while it increases the



9.5 Needle loop.

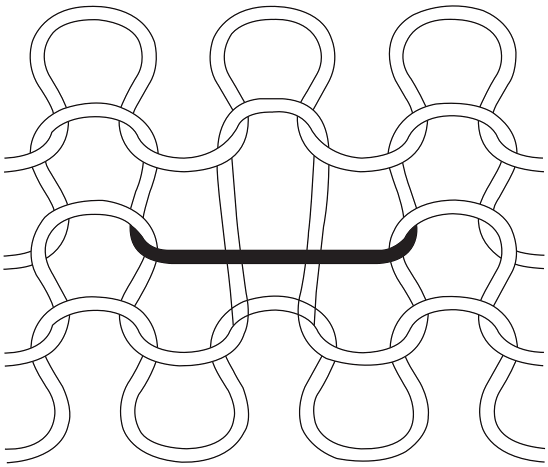


9.6 Sinker loop.

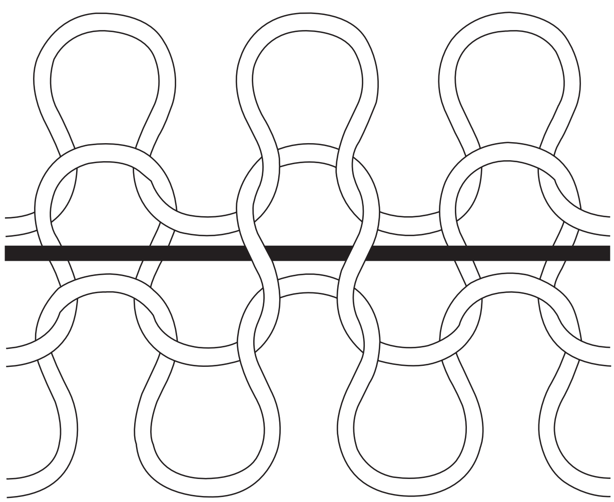


9.7 Tuck stitch.

widthwise elasticity and width of the fabric. It also increases the fabric thickness and needs theoretically less yarn.
Float stitch: this is the yarn length which extends over stitches in the horizontal direction and is limited by a tuck stitch or a knit stitch (see Fig. 9.8). Structures having float stitches tend to be narrower and have less width-wise elasticity. Float stitch of more than four successive float stiches in the vertical direction of the fabric or more than six adjacent float stiches in the horizontal direction of the fabric should not be used otherwise the knitting process is not possible due to yarn breakage or stitch ravel.
Weft: this is the yarn length which lies between plain and purl stitch in the horizontal direction (see Fig. 9.9).

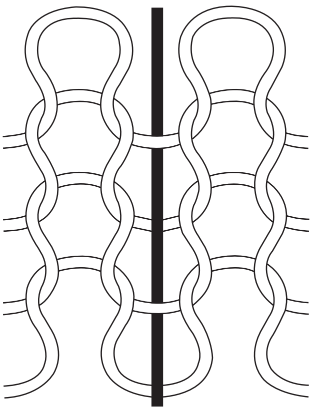


9.8 Float stitch.

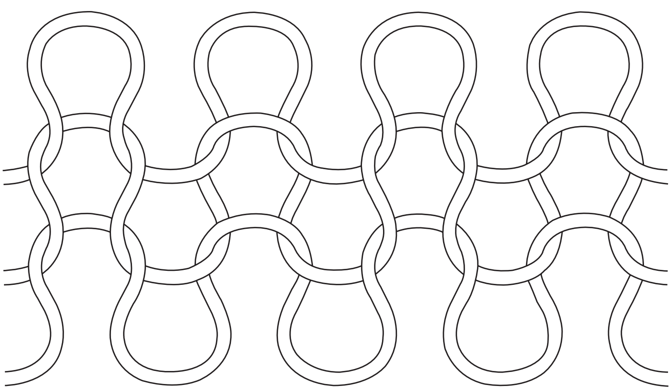


9.9 Weft.

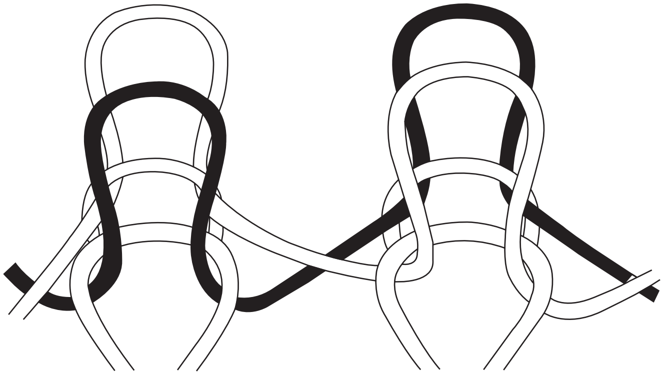
Filler: this is the yarn length which lies between successive sinker loops in the vertical direction (see Fig. 9.10).
Single jersey fabric: this is a fabric structure produced using a single needle bed. It can contain knit, tuck and float stitch structures in the fabric. One side of the fabric displays only plain stitch, while the other side of the fabric displays only purl (reverse) stitch (see Figs 9.1, 9.7, 9.8).
Double jersey fabric: this is the fabric structure which is produced by using a double needle bed. It can contain knit, tuck and float stitches in the fabric stucture. Both sides of the fabric (face and back) can display both plain and purl (reverse) stitches. While the plain stitch is produced at one needle bed, the purl stitch is produced at the other needle bed (see Figs 9.11, 9.12, 9.13).
Course: this is a horizontal row of stitches produced by adjacent needles during the same knitting cycle (see Fig. 9.14).



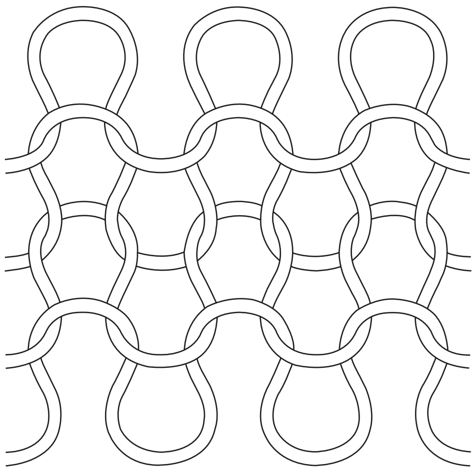
9.10 Filler.



9.11 Rib fabric 1 × 1.

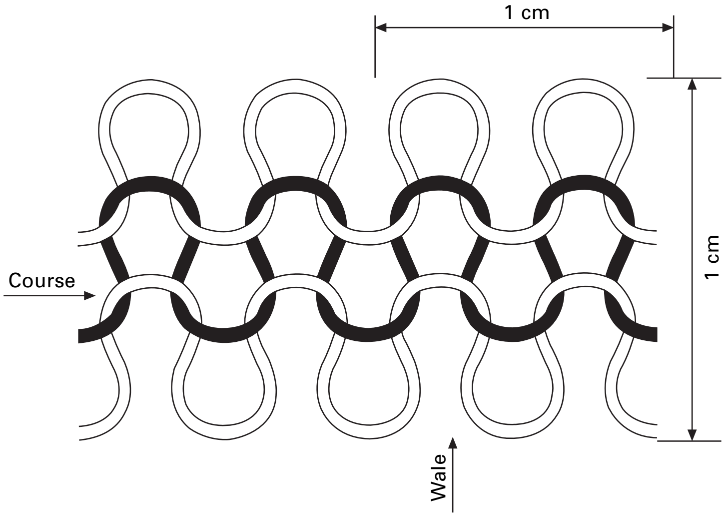


9.12 Interlock fabric 1 × 1.



9.13 Purl fabric 1 × 1.

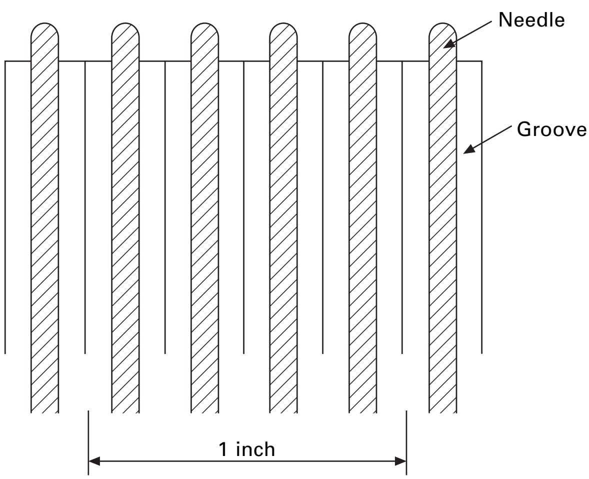
Wale: this is a vertical column of stitches produced by same needle at the successive knitting cycles (see Fig. 9.14).
Number of courses per centimetre of fabric length (course density): this is the number of horizontal rows composed of stitches per unit length of fabric in the lengthwise direction (generally, one cm fabric length is taken). Figure 9.14 has a course density of 3.
Number of wales per centimetre of fabric width (wale density): this is the number of vertical columns composed of stitches per unit length of fabric through the fabric width (generally, 1 cm of fabric is taken). Figure 9.14, has a wale density of 2.
Stitch density: this is a product of course density and wale density. It gives a total number of stitches in a square area of fabric. Stitch density tends to give more accurate measurement for fabric dimensions compared



9.14 Course and wale.

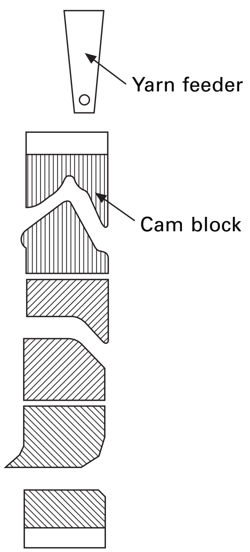
to course density and wale density, due to the fact that the adverse effect of tension on the course and wale densities may be eliminated. In Fig. 9.14, the stitch density is 6.

Machine gauge: this is the number of needles per unit length of needle bed (generally, the number of needles in one inch length on the needle bed). For a given machine diameter or width, coarser machine gauges tend to knit narrower fabrics and have fewer feeders (fewer cams) due to fewer needles on the machine and a larger knitting cam, respectively. In Fig. 9.15, the machine gauge is 4.



9.15 Illustration of machine gauge.

Machine pitch: This is the distance between two neighbouring needles.
Cam system (knitting system): one cam together with one feeder forms a cam system or knitting system for weft knitting technology (see Fig. 9.16).
Feeder density: this is the number of feeders through which yarn is fed, per inch diameter of circular knitting machine. For example, a circular knitting machine with 90 feeders and a diameter of 30 inches has a feeder density of 3.
Stitch (loop) length: this is the yarn length used in one stitch. It is generally calculated by dividing the course length, which is the yarn length used in one course, into the number of needles used in that course length. Loop length is very important in determining the fabric dimension, since fabric parameters such as course density, wale density and fabric weight are affected by the loop length.
Tightness factor (cover factor): the tightness factor indicates the looseness of a knitted fabric, i.e., increase in tightness factor results in tighter fabrics. It is defined as the ratio of the area covered by the yarn in one loop to the area occupied by that loop. Tightness factor ranges between 10 and 20 for most weft knitted structures, the most suitable for plain knitted fabrics is around 14–15. A simplified formula can be used to calculate it ($\sqrt{\text{Tex}}/l$, where Tex is the yarn linear density and l is the stitch length in centimetres).



9.16 Cam system (knitting system).

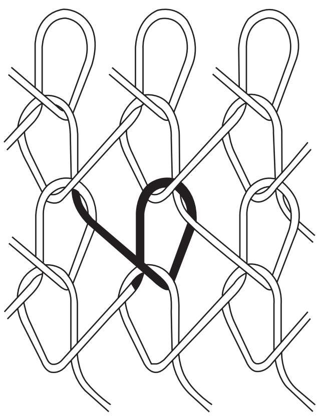
9.2.2 Terms used in warp knitting technology

Overlap: Fig. 9.17 shows a stitch in a warp knitted fabric. Overlap refers to the section of stitch in the warp knitted fabric. The yarn that is wrapped around the needle hook is called the overlap (see Fig. 9.18). Overlap is rarely taken across two needle hooks.

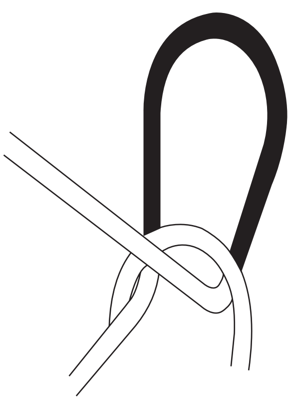
Underlap: this is the other section of stitch in a warp knitted fabric. The yarn is horizontal and appears at the back of the fabric (see Fig. 9.19). It can cover 14 needle spaces or more depending on the design of machine and fabric.

Open lap: if the overlap and the next underlap are made in the same direction, an open lap is produced (see Fig. 9.20).

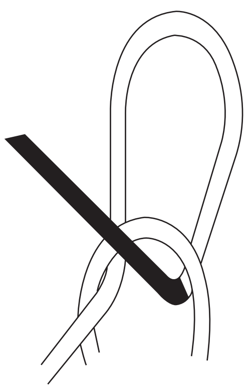
Closed lap: if an overlap and the next underlap are made in opposite directions to each other, a closed lap is then produced (see Fig. 9.21). A



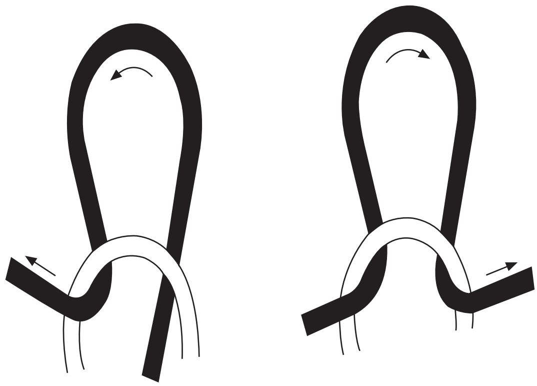
9.17 Warp knitted fabric.



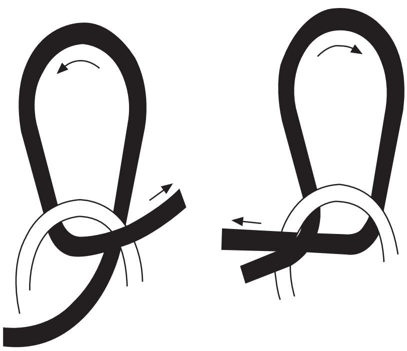
9.18 Overlap.



9.19 Underlap.



9.20 Open lap.



9.21 Closed lap.

closed lap is heavier, less extensible and more compact than an open lap.

Rack: this is the working cycle of 480 knitted courses of warp knitting.

Run-in: this is the yarn consumpition of each guide bar at warp knitting and it is the length of each yarn knitted into fabric during 480 knitting cycles (one rack).

Run-in ratio: this is the ratio of run-in value of different guide bars at warp knitting.[4–6]

9.3 Classification of knitting technology

Knitting technology is classified into two main groups according to yarn presentation and yarn processing, i.e., weft knitting technology and warp knitting technology. In weft knitting technology, one yarn end is horizontally fed into all needles in the needle bed. Needles mostly are moved successively (individual needle motion as in circular knitting or V bed flat knitting) or simultaneously (collective needle motion as in straight bar knitting and loop wheel knitting). Yarn ends are mostly fed from a bobbin. Yarn ends in the fabric can easily be unravelled in a horizontal direction from the end knitted last. Products obtained from weft knitting technology are widely used in the apparel industry for pull-overs, t-shirts, sweatshirts, etc. Materials used are mostly natural fibres or blends with synthetic fibres. Weft knitting machines have relatively low investment cost, small floor space requirements, low stock holding requirements and quicker pattern change capabilities than warp knitting machines.

In warp knitting technology, one yarn end is longitudinally fed into one needle in the needle bed. Needles are moved simultaneously and collectively. Yarn ends are mostly fed from a warp beam. A yarn end in a fabric can hardly be unravelled in the vertical direction. Products obtained from warp knitting technology are widely used for household and technical textiles such as geotextiles, laces, curtains, automotive, swimwear, towelling, nets, sportswear, bed linen, etc. Materials used are mostly synthetic fibres in filament form. Higher machine speeds (up to 3500 cpm), finer gauges (up to 40 needles per inch), wider machines (up to 260 inches) and a multiaxial structure for technical application are available with warp knitting technology, compared to weft knitting technology. Generally, warp knit fabrics are less elastic than most weft knitted fabrics. They have a certain amount of elasticity in the width and a tendency to increase in a lengthwise direction after repeated wearing and washing.[3,4,6]

9.4 Weft knitting technology

There are several different types of weft knitting machines, such as circular knitting machines (large diameter), hosiery machines, straight bar frames, V bed flat knitting machines, flat bed purl machines, etc. However, especially for outerwear and underwear, there are two main widely used weft knitting machines, i.e., circular knitting machines (large diameter) and V bed flat knitting machine. Since these two types are widely used, these two technologies are described here. The main differences between the two technologies are described below:

- Machine frame of the circular knitting machine is of a cylindrical shape, while machine frame of the V bed flat knitting machine is flat with the needle beds located approximately 90 degrees to each other.
- Products of the circular knitting machines have a tubular form, while flat form fabrics are produced by the V bed flat knitting machines.
- On V bed flat knitting machines, the needle bed is stationary and the carriage, which contains a cam system, traverses the machine width and activates the needles. In circular knitting, the needle bed generally rotates and stationary cam blocks around the needle bed activate the needles.

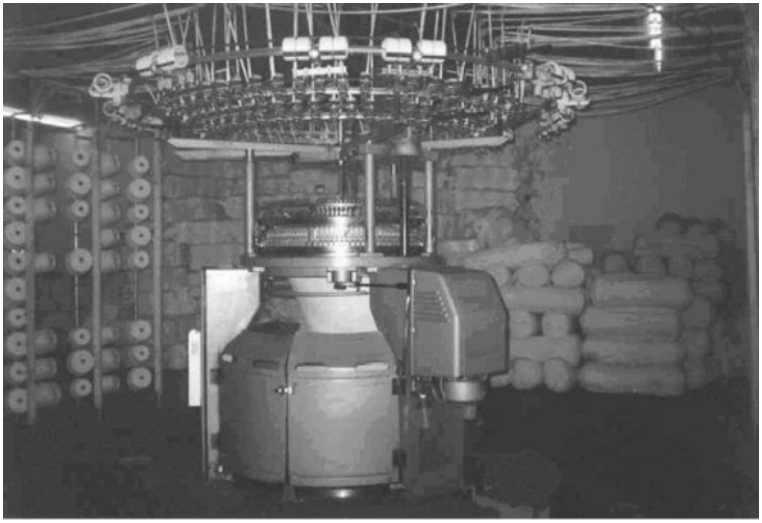
- Production rates in circular knitting are generally higher than flat knitting, due to higher velocity and higher number of knitting (cam) systems.
- Flat knitting machines have more versatility than circular knitting machines. More complex fabric designs can be produced by flat knitting machines.
- Flat knitting machines have generally a coarser machine gauge than circular knitting machines, thus coarser fabric structures used mainly for outerwear in cold weather conditions such as pullovers, sweaters, etc., are produced.

9.4.1 Circular knitting machines

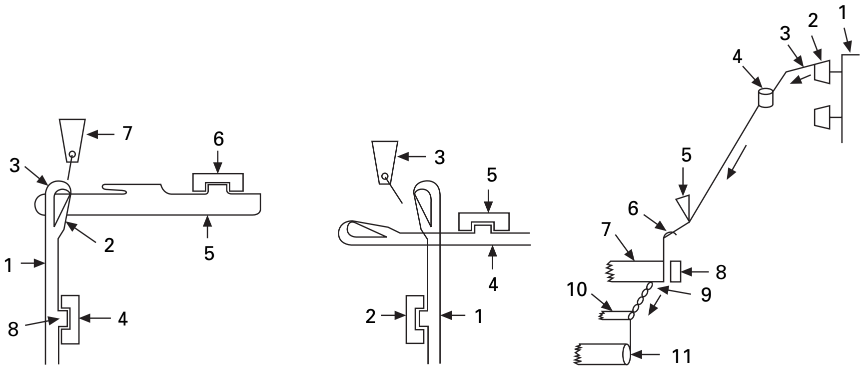
In circular knitting (Fig. 9.22), the machine gauges and the machine diameters range from 4 to 32 needles per inch and 8 to 48 inches in diameter, respectively. They can run at the speeds of 76 rpm and may have up to 132 yarn feeders.[1,2]

Arrangement of machine parts

The machine frame of a circular knitting machine is of cylindrical form and fabric is produced in tubular form. Figure 9.23(a) and Fig. 9.23(c) show the arrangement of main machine parts of a plain circular knitting machine used for the production of single jersey fabrics. In most circular knitting machines the needle beds rotate while the cam blocks are stationary. During rotation, the needle butt contacts with the cam and produces a knit or a tuck stitch. At every knitting system (cam together with yarn feeder) on a circular machine frame, the needle can produce a knit, tuck or float stitch. Thus, for example, if a plain knitting machine has a 90 knitting system, at the end of one



9.22 Circular knitting machine.



(a)

1 Needle
2 Needle latch
3 Needle head
4 Needle camblock
5 Holding down knocking over sinker
6 Sinker cam block
7 Feeder
8 Needle butt

(b)

1 Needle
2 Needle camblock
3 Feeder
4 Dial needle
5 Dial needle cam block

(c)

1 Yarn creel
2 Bobbin
3 Yarn
4 Yarn delivery system
5 Feeder
6 Cylinder needle
7 Cylinder
8 Cylinder needle cam
9 Fabric
10 Fabric take-down roller
11 Fabric winding system

9.23 Illustration of circular knitting machine (a) plain circular knitting machine, (b) rib circular knitting machine, (c) schematic view of plain circular knitting machine.

revolution, one needle can produce 90 stitches (90 course). If the knitting machine is interlock type (1 × 1 interlock), two knitting systems produce one course, thus, at the end of one revolution, 45 courses are produced.

The other type of knitting machine used for the production of double jersey fabrics is the rib knitting machine (see Fig. 9.23(b)). It also has a similar arrangement to a plain circular knitting machine except for the dial which is set perpendicular to the cylinder and contains dial needles too. In this type of machine, there is no 'holding down-knocking over sinker' (see page 291) since the dial needles (not available on a plain knitting machine) hold and support the fabric.

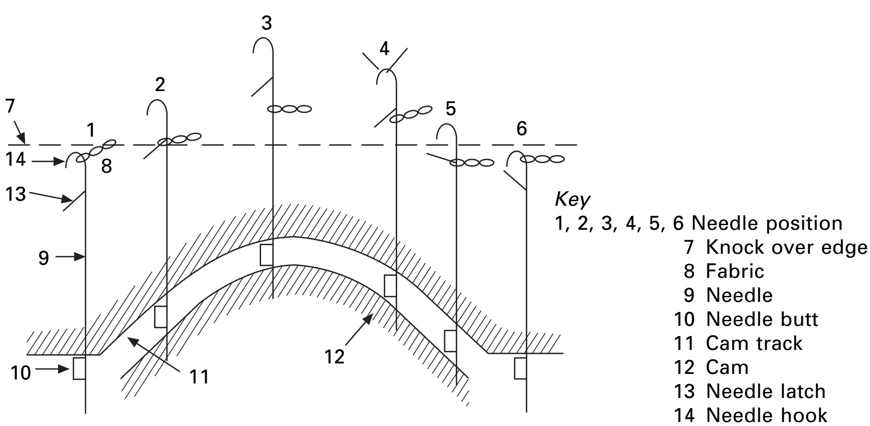
Stitch formation

The stitch formation with latch needle for a plain knitted fabric is illustrated in Figs 9.24 and 9.25. There are six main positions:

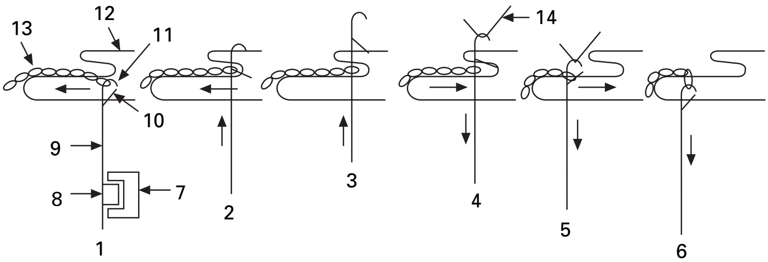
1. Rest position. The needle is in rest position with the needle positioned outside the cam. The sinker moves towards the machine centre (1st position in Figs 9.24 and 9.25).

2. Tucking position. The needle butt follows the cam track and is pushed upwards by the cam. The old loop moves downwards and opens the latch of the needle. Sinker still moves towards machine centre, thus fabric is held down in the sinker throat. However, the old loop is still on the latch. This position is also used to produce tuck stitch (2nd position in Figs 9.24 and 9.25).
3. Clearing position (knitting position). The needle butt is still pushed upwards by the cam and the old loop is on the needle stem and behind below the needle latch (3rd position in Figs 9.24 and 9.25).
4. Yarn feeding position. A new yarn is fed into the needle hook by a yarn feeder while the needle is moved downwards by following the cam track. Holding down-knocking over sinker begins moving away from the machine centre. The old loop starts to close the latch of needle (cast-off) by moving upwards (4th position in Figs 9.24 and 9.25).
5. Cast off position. The needle is moved further downwards, the needle latch is closed by the old loop (5th position in Figs 9.24 and 9.25).
6. Knock-over position. The new yarn is drawn through the old loop, thus new yarn produces a new loop. If knock over position is shifted vertically, stitch length can be changed (6th position in Figs 9.24 and 9.25).

If a double jersey fabric is produced, a similar stitch formation process is carried out by the dial needle at the dial (see Fig. 9.26(a) and Fig. 9.26(b)). The coordination between cylinder and dial needle can be classified into two groups for double jersey fabrics, the rib setting and the interlock setting. At the rib setting (rib machines), cylinder and dial needle cross one another, i.e., they are not directly face to face. All the cylinder and dial needles at the given working point (cam system) move to produce a stitch (see Fig. 9.27). At the interlock setting, cylinder and dial needles are directly opposite each

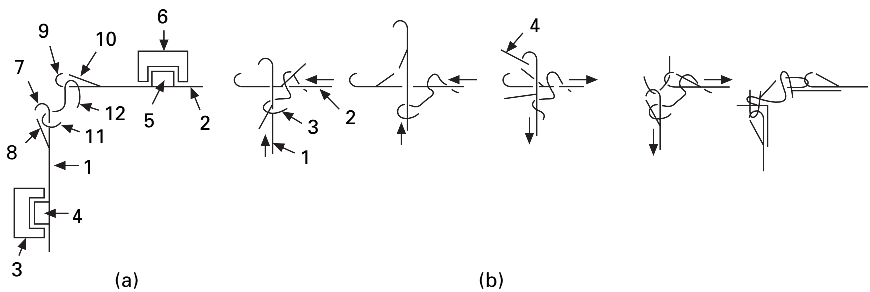


9.24 The needle position in cam track.



Key
1, 2, 3, 4, 5, 6 Needle position
7 Needle cam
8 Needle butt
9 Needle
10 Needle latch
11 Needle hook
12 Holding down-knocking over sinker
13 Fabric

9.25 Stitch formation.

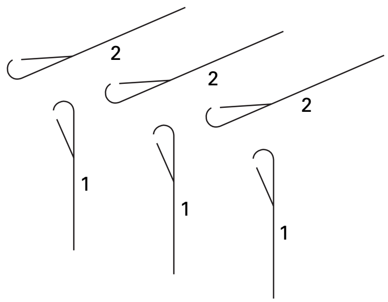


Key
1 Cylinder needle
2 Dial needle
3 Cylinder cam
4 Cylinder needle butt
5 Dial needle butt
6 Dial cam
7 Cylinder needle hook
8 Cylinder needle latch
9 Dial needle hook
10 Dial needle latch
11 Cylinder stitch
12 Dial stitch

Key
1 Cylinder needle
2 Dial needle
3 Fabric
4 Yarn

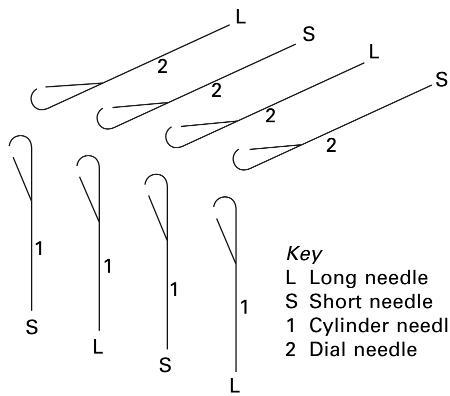
9.26 Rib knitting machine and stitch formation (a) rib knitting machine and (b) stitch formation on rib knitting machine.

other, i.e., they are face to face (see Fig. 9.28). At the interlock setting, two kinds of needles in the cylinder and in the dial are available, the long needle and the short needle. Thus, at any given working point, both cylinder and dial needle do not work at the same time. In one knitting system, only long



Key
1 Cylinder needle
2 Dial needle

9.27 Rib setting (gating).



Key
L Long needle
S Short needle
1 Cylinder needle
2 Dial needle

9.28 Interlock setting (gating).

needles on both cylinder and dial work; with the other knitting system, only short needles on both the cylinder and dial work.

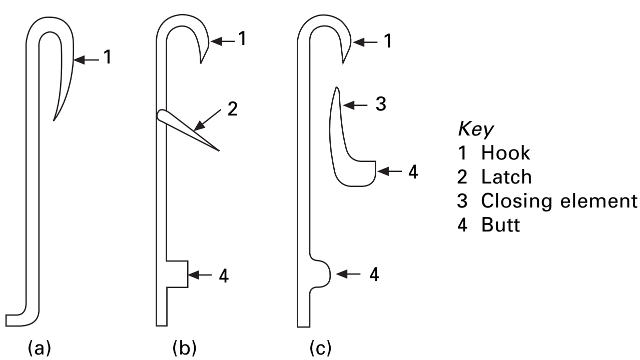
The coordination between the cylinder and the dial cams can be classified into three groups, the synchronised timing, the delayed timing and the advanced timing. At the synchronised timing, the cylinder and the dial needle are pulled down at the same point of the cylinder cam and the dial cam. This timing can be used on all machines and for all types of fabrics. There is a high tension at the cylinder and dial loop. At the delayed timing, the dial cam knocks over its needles later than those on the cylinder needles (about five or six cylinder needles move further than the dial needles), thus the dial loops are larger than the cylinder loops due to yarn taken from the cylinder loops. Only fabric types where all the cylinder needles work in each cam system can be produced. Thus, at the delayed timing, broad ribs and rib jacquard fabrics cannot be produced. Fabrics produced by the delayed timing have a more even loop appearance compared to the synchronised timing. The advanced timing is the reverse of delayed timing where the cylinder cam knocks over the needles later than the dial needles.[1,2]

Main machine parts

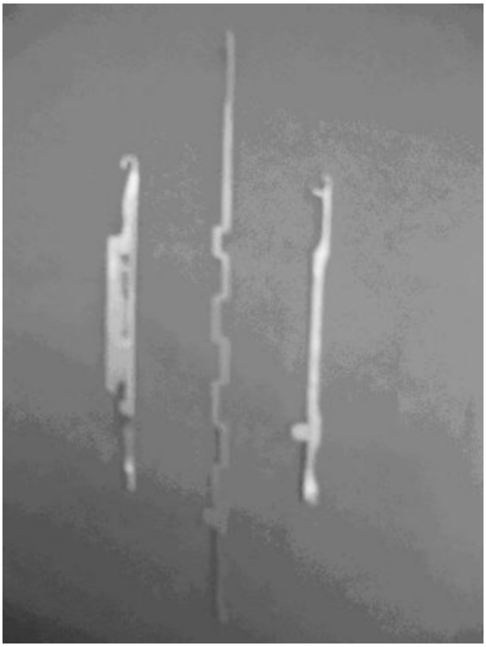
Needle: on circular knitting machines, latch and compound needles are generally used, while bearded needles are seldom used (see Fig. 9.29). They have different shapes and dimensions depending on the machine type and the fabric design. They are generally controlled by the needle cam. The hook of a bearded needle is closed by a presser, while latch and closing elements are used to close the hook of the needle for latch needle and compound needle, respectively. A bearded needle is less expensive and produces more uniform stitches compared to other needle types. It can also be thinner than the other types of needles. However, it has a limitation with regard to the types of material and structure that can be knitted. The latch needle (Fig. 9.30) has an individual movement and the compound needle has a short, smooth and simple action, thus it has a higher producton rate compared to the other two types of needles.

Sinker (holding down-knocking over): in textile terminology the sinker commonly used on plain circular knitting machines is called a 'holding down-knocking over' sinker (see Fig. 9.31). Its main function is to hold the sinker loop when the needle is moved from the rest position into the clearing position. It is controlled from the sinker butt by a sinker cam. It also takes over the formation of a new loop across the knock over edge (the area of the machine that the sinker loop is formed) at the end of loop formation. They have different shapes and dimensions depending on the machine type and the fabric design.

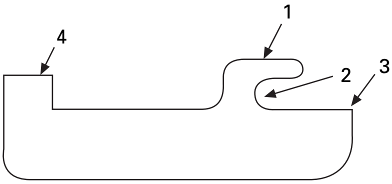
Cam: the cam controls the movement of the needle or sinker (holding down-knocking over). Basic and simple fabric designs can be produced by using just the cam block, however, complex fabric designs need different needle control systems such as pattern wheel, pattern drum or electronic selection devices, etc. There are different types and designs of cam structure



9.29 Needle types: (a) bearded needle, (b) latch needle, (c) compound needle.



9.30 Latch needle.

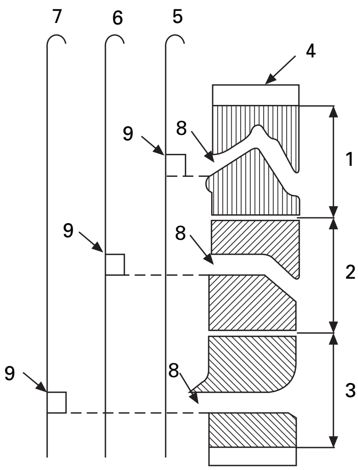


Key
1 Nib
2 Throat
3 Knock-over edge
4 Butt

9.31 Holding down-knocking over sinker.

in order to control the needle motion. One of them is the changeable cam. In this cam type, cam parts can be replaced for pattern changes, such as a knit cam for knit stitch, tuck cam for tuck stitch, miss cam for float stitch (see Figs 9.32 and 9.33).

Yarn delivery: yarn tension presented to a needle hook has to be uniform, constant and as low as possible, in order to get uniform, good fabric appearance and also to prevent yarn breaks. Therefore, several different types of yarn delivery devices are used. These devices are divided into two main groups, those for constant yarn consumption per unit time on given feeders (positive feeding, yarn metering) and those for variable yarn consumption per unit time on a feeder (negative feeding, yarn storage). The first one is used for simple fabric designs with no large pattern repeat area (see Fig. 9.34). The second one is used for jacquard designs that have



Key

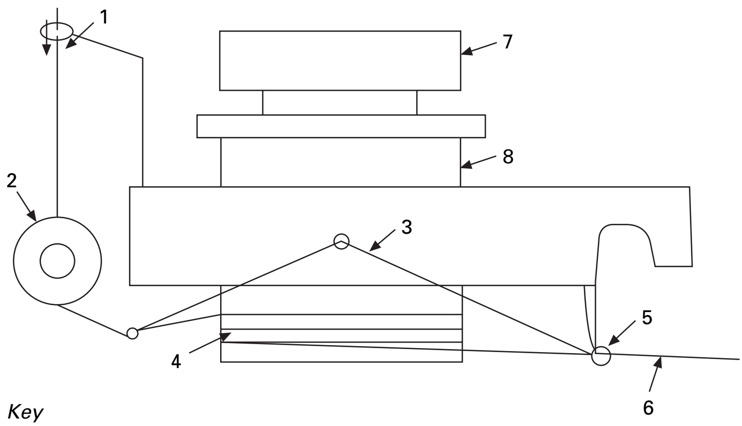
1 Knit cam for stitch
2 Tuck cam for tuck stitch
3 Miss cam for float stitch
4 Cam block
5, 6, 7 Needle with different butt position
8 Cam track
9 Needle butt (needle 5 moves through cam 1 to produce a stitch, needle 6 moves through cam 2 to produce tuck stitch and needle 7 moves through cam 3 to produce miss stitch)

9.32 Illustration of changeable cam.

9.33 Changeable cam.

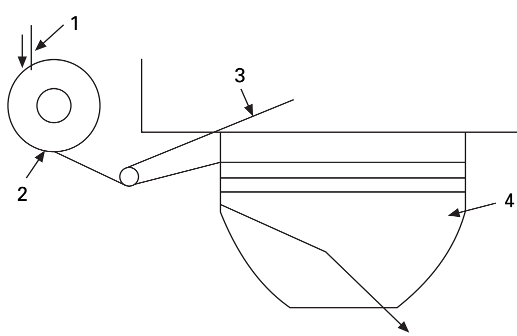
a large pattern area and most of the feeders have varying yarn consumptions per unit time (see Fig. 9.35).

Fabric take down: fabric take down equipment has three main functions, fabric spreading, fabric tensioning and fabric winding. On circular knitting machines, fabric is knitted into a tube form on needles. The fabric is then stretched into a flat form by the spreader located above the take down system. The fabric is then pulled down by the fabric tensioning system (fabric take down roller) and wound into fabric roll by the fabric winding system (see Fig. 9.36).



Key
1 Yarn
2 Yarn brake system
3 Yarn feeler (yarn knock-off device)
4 Yarn winding roller
5 Eyelet
6 Yarn
7, 8 Drive roll

9.34 Positive yarn delivery system.

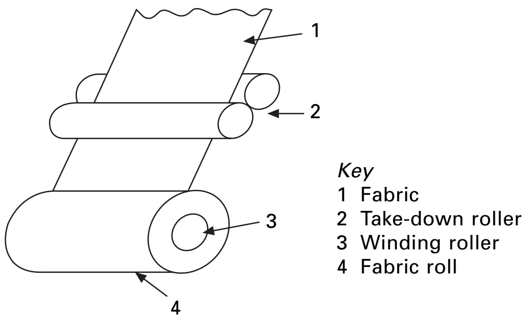


Key
1 Yarn
2 Yarn brake system
3 Yarn feeler (yarn knock-off device)
4 Yarn coiler

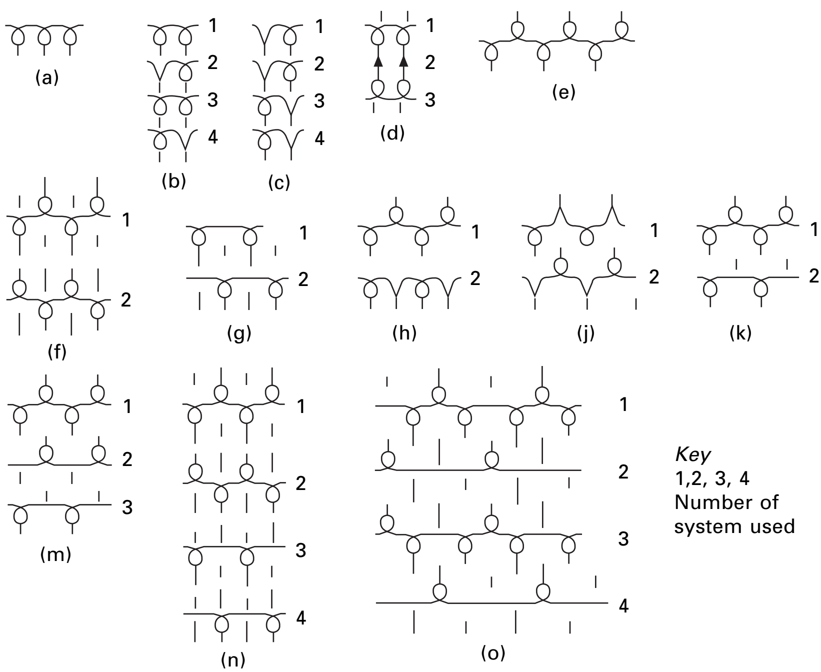
9.35 Negative yarn delivery system.

Basic fabric types

There are many different types of fabric designs produced on circular knitting machines, such as single jersey fabric or double jersey fabric. These are produced by either the rib technique or interlock technique. In Fig. 9.37, stitch diagrams of several fabric designs have been illustrated; plain knit fabric, lacoste, double lacoste, 1 × 1 purl fabric, 1 × 1 interlock fabric,



9.36 Fabric take-down system.



9.37 Basic fabric types. (a) plain, (b) lacoste, (c) double lacoste, (d) purl, (e) rib (1 × 1), (f) interlock (1 × 1), (g) cross miss, (h) half cardigan, (j) cardigan, (k) half Milano, (m) Milano rib, (n) interlock half Milano and (o) Swiss double pique.

1 × 1 rib, half cardigan, cardigan, half Milano, Milano rib, swiss double pique, interlock half Milano and cross miss.

9.4.2 V bed flat knitting

Machine gauge in the flat knitting (see Fig. 9.38) is in the range of 3 npi and 18 npi (needles per inch). Needle bed widths are in the range of 30 and 244 cm or more. Number of cam systems (cam together with feeder) at one side of one cam carrier is not more than four. Average knitting speed is around 1.2 metres per second.[2–4]

Arrangement of machine parts

In contrast to the circular knitting machines, the machine frame of flat knitting machines is in flat form, and knitted fabrics are also in flat form. Nowadays, most flat knitting machines are electronically controlled. Figure 9.39 illustrates the arrangement of main machine parts of a hand-operated V bed flat knitting machine. The needle bed is in V form and the angle between rear and front needle bed is about 90 and 104 degrees to each other. Needles at the front and rear needle beds are arranged in a rib setting. The needle bed is stationary while the carriage that contains the cam systems (cam and feeder) travels along the needle bed. The yarn feeder is set on the rails that extend across the width of the machine. During traversing, the carriage takes

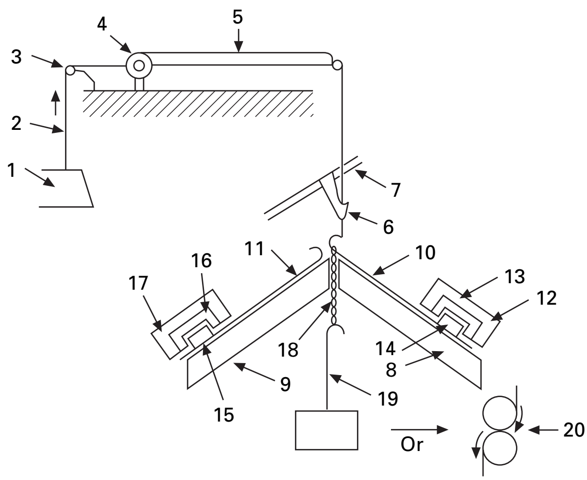
9.38 V bed flat knitting machine.

a yarn feeder on the rails and moves along the needle bed with it. While the carriage moves along the needle bed, the needle butt contacts with the cam on the carriage and produces stitch, tuck stitch or float. The yarn that is taken over the cone continues through the knot catcher assembly and spring loaded brake disc. It then passes through the tension arm. A brake disc is used to tension the yarn between cones and yarn feeder. The tension arm is used to pull out excess yarn when the carriage traverses. Flat fabric that is not produced in tubular form, as in a circular knitting machine, is pulled down by take-down rollers.

Modern electronic V bed flat knitting machines possess a holding down sinker placed at the front edge of the needle bed between needles. It is used to hold the fabric when the needle is raised into the clearing position. The selection of the needle for knit, tuck or float stitch or transferring/receiving position is carried out by an electronic system.

Stitch formation

The following section explains the stitch formation at the rear and front needles. There are six main positions. These six positions are similar to



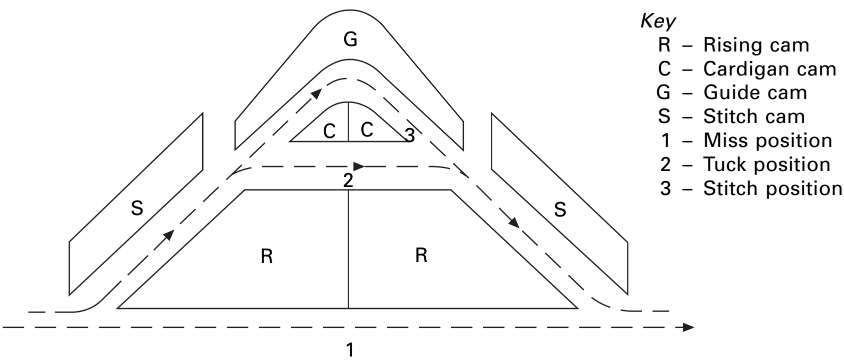
Key

1 Bobbin
2 Yarn
3 Knot catcher
4 Brake disc
5 Tension arm
6 Yarn feeder
7 Rail
8 Rear needle bed
9 Front needle bed
10 Needle on the rear needle bed
11 Needle on the front needle bed
12 Cam block on rear needle bed
13 Rear cam carriage
14, 15 Needle butt
16 Cam block on front needle bed
17 Front cam carriage
18 Fabric
19 Load
20 Fabric take-down roller

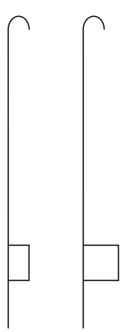
9.39 Illustration of hand-operated V bed flat knitting machine.

needle positions mentioned in the circular knitting section, except for sinker movement in the circular knitting machine, i.e., rest position, tucking position, clearing position, yarn feeding position, cast off position, knocking over position (see Figs 9.40 and 9.41). Needles with two different butt lengths are mostly used in hand-operated V bed flat knitting machines, i.e., long butt and short butt (see Fig. 9.41). The butt of the needle is in a straight line until it contacts with the raising cam (see Fig. 9.40). The rising cam can be in an active, semi-active or inactive position. If it is in the active position, both needle types (short and long butt) are raised by the raising cam (position 2 in Fig. 9.40), if it is in an inactive position, both needle types stay a straight line (position 1 in Fig. 9.40). If it is in the semi-active position, the needles with long butt will be raised by the raising cam, while the needles with short butt will be in a straight line. At the end of the raising cam, if the needle has been activated, it is in tucking position (position 2 in Fig. 9.40). If the needle moves under the cardigan cams, a tuck stitch is produced. If it moves over the top of the cardigan cams, the needle reaches full clearing height and produces a knit stitch (position 3 in Fig. 9.40).

The cardigan cams can also have three different positions; active, semi-



9.40 Needle position on cam block.



9.41 Needles with long and short butt.

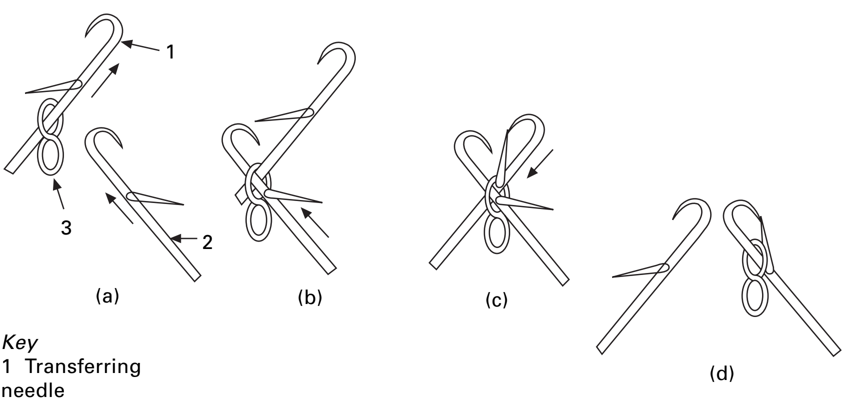
active or inactive position. If it is in the active position, both needle types (short and long butt) are raised by the cardigan cam (position 3 in Fig. 9.40), if it is in the inactive position, both needle types stay in the tucking position. If it is in the semi-active position, the needle with a long butt will be raised by the cardigan cam to produce a stitch (position 3 in Fig. 9.40), while the needle with short butt will be in the tucking position (position 2 in Fig. 9.40). Thus, it is possible to produce both knit, tuck or float stitches to get different fabric designs. The stitch cam can be moved in the vertical direction (raised or lowered) to change the stitch length.

The transferred loop

To produce a different fabric design it is necessary sometimes to transfer the loop from one needle to another. The latch needle used in flat knitting machines has a transfer spring which is used for transferring a loop to another needle. Loops can be transferred from a needle on the front needle bed to a needle on the rear needle bed or vice versa. As seen from Fig. 9.42 the transferring needle is raised more than the receiving needle (see Fig. 9.42a). The receiving needle enters inside the loop which is on the other needle (see Fig. 9.42(b)). The transferring needle retreats (see Fig. 9.42(c)) and leaves its loop in the hook of the receiving needle (see Fig. 9.42(d)).

Racked needle bed

One needle bed can be racked sideways by several needle spaces (up to four inches of machine length, i.e., 48 needles for a 12 gauge machine) to produce



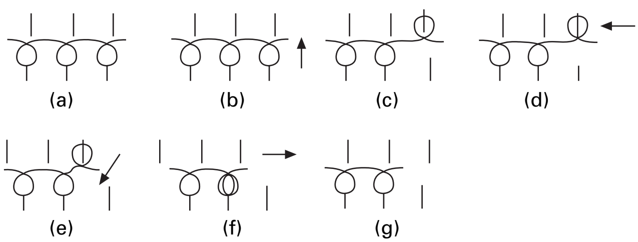
Key
1 Transferring needle
2 Receiving needle
3 Fabric

9.42 Transferred loop (a) beginning of transfer process, (b) receiving needle inserted into loop, (c) transferring needle begins decent and (d) transfer process completed.

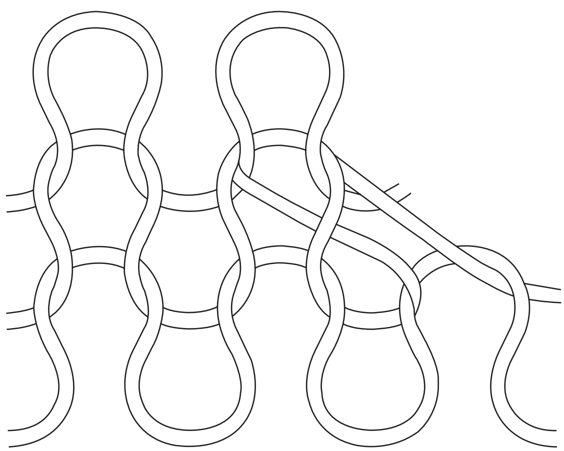
different fabric designs. As seen from Figs 9.43 and 9.44, a loop has been transferred from the front needle bed into a needle on the rear needle bed (see Figs 9.43(b) and 9.43(c)). Then, the rear needle bed is racked sideways by one needle space (see Fig. 9.43(d)). A loop on the needle at the rear needle bed is transferred into a needle on the front needle bed (see Fig. 9.43(e)). Thus, there will be two loops on the needle at the front needle bed (see Fig. 9.43(f)). The final fabric appearance will be similar to Fig. 9.44.

Basic fabric types

Most of the basic fabric designs mentioned in circular knitting technology are also widely used in V bed flat knitting machines. In addition to these designs, many of the complex fabric designs which are impossible or hard to produce on circular knitting machines, such as intarsia design, cable design,



9.43 Racked needle bed (a) normal position of needle beds, (b) loop on last needle on front needle bed transferred into rear needle bed, (c) transfer complete, (d) rear needle bed (racked) sideways by one needle space, (e) loop on rear needle bed transferred into needle on front needle bed, (f) two loops on needle at front of needle bed and (g) final appearance of fabric.



9.44 Racked and transferred stitch.

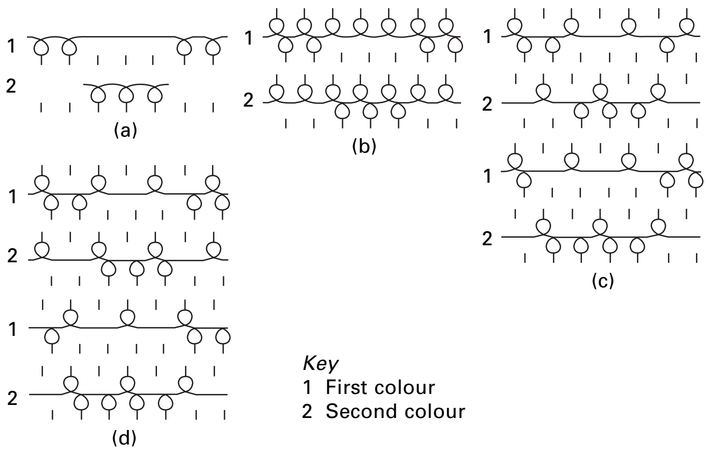
whole garment design, etc., can be produced on flat knitting machines. Figure 9.45 gives the stitch diagrams of two-colour jacquard fabric with a different fabric design on the back (horizontally striped backing, vertically striped backing, birds eye backing, miss backing).

9.4.3 Properties of basic weft knitted fabrics

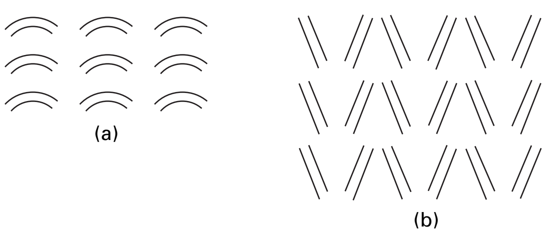
There are four primary structures; plain, rib, purl and interlock, from which all weft knitted fabrics are derived. The main properties of these fabrics are described below.

Plain knitted fabric

The appearance of the technical face of fabric is in V form through the wales (see Fig. 9.46(b)). On the technical back of the fabric, the appearance of the fabric is in semi-circles (see Fig. 9.46(a)). The yarn can be unravelled from



9.45 Two-colour jacquard fabric (a) miss backing, (b) horizontally striped backing and (c) vertically striped backing; (d) birds eye backing.



9.46 Dominant appearance of fabric. (a) semicircle appearance; (b) the V form appearance.

the last course or the first course of the fabric (see Figs 9.1 and 9.37(a)). Fabric curls from the sides and the top/bottom and has an approximate recovery of 40% in width after stretching.[2]

Rib knitted fabric

Rib fabrics are described as 1 × 1, 2 × 2, 6 × 3 rib, etc., and the most simple one is the 1 × 1 rib (see Figs 9.11 and 9.37(e)) (a × b; a represents the number of front stitches, b represents the number of back stitches). The 1 × 1 rib fabric is thicker, narrower, heavier, warmer and more elastic and expensive than plain knit fabric. It has higher width-wise recoverable stretch than plain knit fabric. It is also typically knitted using a finer yarn than a plain knit fabric. The yarn can be unravelled easily from the last course of the fabric. Balanced rib fabric such as 1 × 1, 2 × 2, 3 × 3 rib does not curl from the sides and the top/bottom.

Interlock knitted fabric

Like rib fabrics, there are several types of interlock fabrics such as 1 × 1 interlock, 2 × 2 interlock. 1 × 1 interlock fabrics are thicker, heavier, narrower and more stable and expensive than plain and rib knit fabrics (see Figs 9.12 and 9.37(f)). It has less width-wise recoverable stretch than plain and rib knit fabric. The V letter appearance is dominant on both sides of the fabric. The yarn can be unroved easily from the last course of the fabric. 1 × 1 interlock fabric does not curl from the sides and the top/bottom. However, it is less productive than rib and plain knitted fabrics.

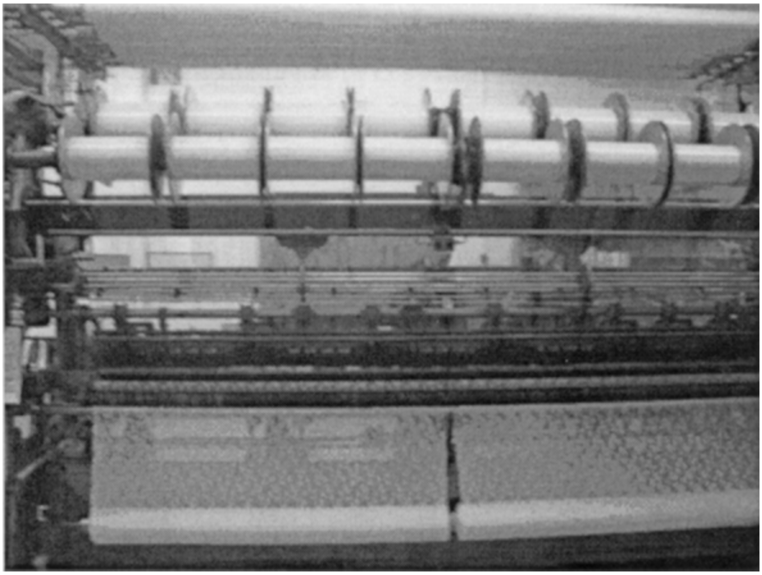
Purl knit fabric

The semi-circular appearance is dominant on both sides of a fabric. There are several types of purl fabrics such as 1 × 1, 5 × 3, 4 × 4 purl fabrics and the most simple one is the 1 × 1 purl fabric (see Figs 9.13 and 9.37(d)). It is thicker, softer and warmer than a plain knit fabric and it has more elasticity lengthwise than a plain knit fabric. It can be unroved from both ends of the fabric.

9.5 Warp knitting technology

There are two main warp knitting machine classifications (see Fig. 9.47), Tricot and Raschel. The main differences between them are described below.

- Raschel machines are generally coarser and slower than Tricot machines



9.47 Warp knitting machine.

due to a higher number of guide bars (up to 80 guide bars for Raschel compared with up to four guide bars for Tricot) and have a longer and slower needle movement.

- Raschel machines are much more versatile, i.e., most type of yarns and slit films can be used. Complex fabric designs can be produced on Raschel machines, while Tricot machines are limited to only basic fabric designs.
- The sinker used on a Tricot machine controls the fabric and holds the fabric while the needles rise to the clear position. However, in Raschel knitting, the fabric is controlled by a high take-down tension and the sinker is not so important for fabric control. The fabric produced on a Raschel machine is pulled tightly downwards (about 160 degrees), while fabric produced on a Tricot machine is pulled gently from the knitting zone (about 90 degrees).
- The fabric take-up mechanism in Tricot machines is positioned further away from the knitting zone, however, in Raschel machines, it is positioned close to the knitting zone.
- In the past, bearded needles and latch needles were used for Tricot and Raschel machines, respectively. However, nowadays, compound needles have replaced the bearded and latch needle in warp knitting technology.
- While the machine gauge in Tricot is described as the number of needles per inch, it is generally described in Raschel machine as the number of needles per two inches.

- The chain links in Tricot machines are numbered as 0, 1, 2, 3, 4, etc., while the chain links in Raschel machines are numbered in even numbers, such as 0, 2, 4, 6, etc.[2,3,5,6]

9.5.1 Tricot knitting machine

Tricot machine gauge is in the range of 6–44 and knitting width can reach up to 260 inches. A schematic illustration of a Tricot machine is given in Fig. 9.48. The main machine elements are briefly described below.[3,6]

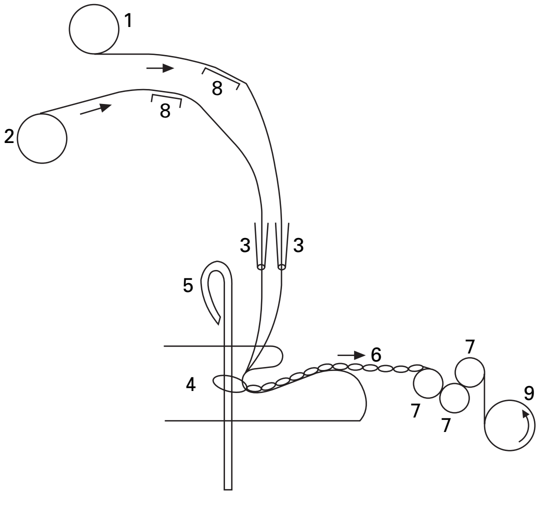
Main machine parts

Needle

Nowadays, compound needles are widely used on Tricot machines. The main part of the needle is set in tricks cut in the needle bed of the machine, while the closing part of the needle is set in a separate bar. The closing part of the needle along the machine bed consists of segments half an inch long (see Fig. 9.49).

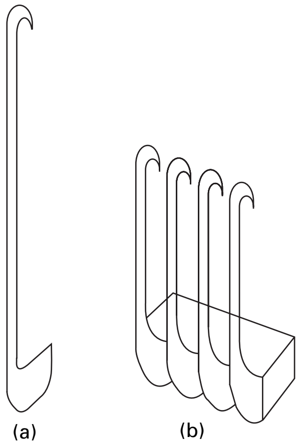
Sinker

Sinkers, placed between each needle, are set into a sinker bar (see Fig. 9.50). Sinker segments one inch long are placed along the sinker bar.

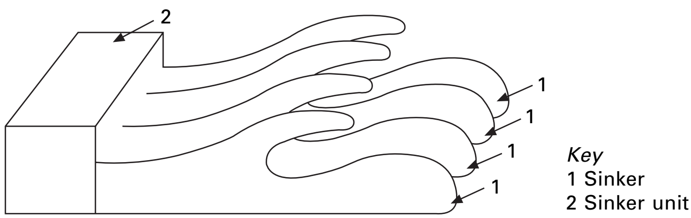


Key
1 Front warp beam
2 Back warp beam
3 Guide
4 Sinker
5 Needle
6 Fabric
7 Take-up roller
8 Warp yarn tension element
9 Fabric winding system

9.48 Illustration of Tricot machine.



9.49 Compound needle. (a) main part of needle and (b) closing element of needle.



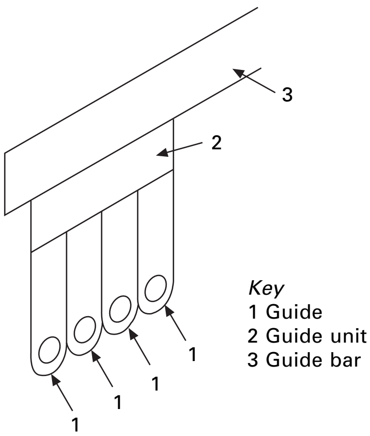
9.50 Sinker unit.

Guide bar and guides

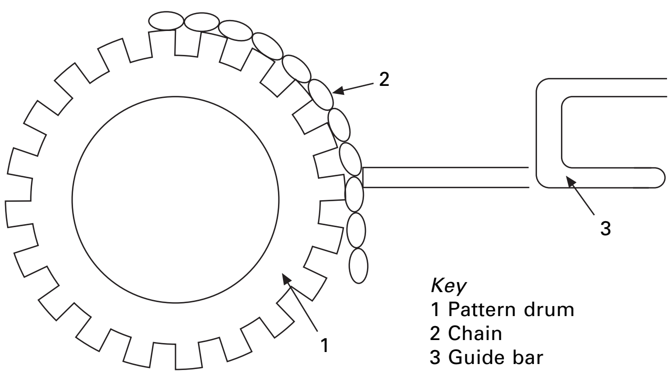
Each yarn end fed from a warp beam is passed through the eye of a guide. The guide segments are one inch long and placed into the guide bar (see Fig. 9.51). The guide bars have two motions, swing and shogging. The guide bars swing between needles and they also shog sideways to produce overlap and underlap. Tricot machines are generally equipped with two to four guide bars. The loops of the front bar will appear on the face of the fabric. Thus, any coloured thread in the front guide bar will appear on both fabric surfaces.

Pattern drum and pattern disc

The shogging movement of the guide bar is generally produced by pattern drum or pattern disc. A chain with different height links is placed on the pattern drum. This pattern drum rotates and the rod of the guide bar contacts with the link, thus the guide bar shogs sideway. Different shogging



9.51 Guide bar.

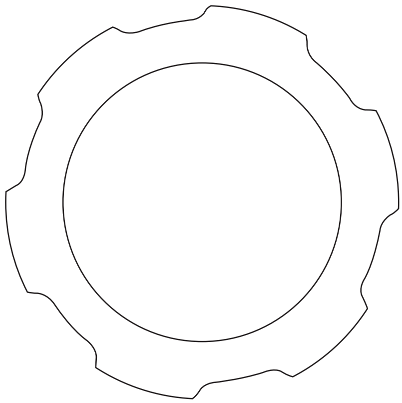


9.52 Pattern mechanism.

movement distances are obtained by different height of links (see Fig. 9.52). Pattern disc (see Fig. 9.53) has a pre-cut for a certain design and it is used instead of a pattern drum, due to the very accurate, smooth and high-speed performance.

Yarn feeding system

Each guide bar is supplied with yarns taken from each warp beam, however, it is possible to use two or three warp beams for one guide bar. The opposite situation is also possible if equal yarn amounts are used. There are two main yarn let-off mechanisms, negative and positive. With the negative yarn let-off mechanism, a restricting force is applied to the warp beam, thus its free turning movement is restricted, i.e., the beam will not turn without being



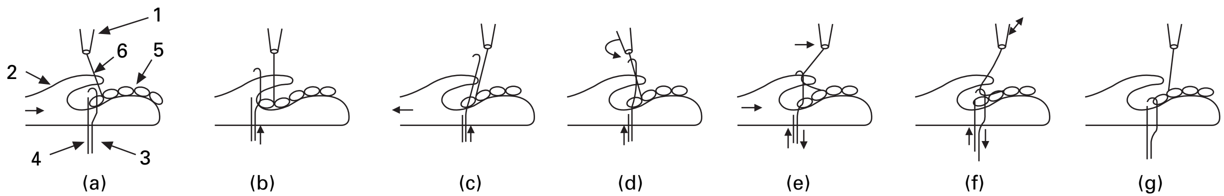
9.53 Pattern disc.

pulled by yarns. There are two types negative yarn let-off mechanisms, one is termed the cord let-off mechanism and the other is brake let-off mechanism. The cord let-off mechanism is inexpensive and simple, however, it has several disadvantages such as sensitivity to enviromental conditions and maintenance of the yarn tension by the operator. With the positive yarn feeding system, the warp beam is positively driven and constant yarn feeding together with constant yarn tensions are obtained. In this mechanism, the yarn is fed to the needle, instead of the yarn being pulled against the brake as in the case of the negative feeding system.

Stitch formation

The stitch formation in Tricot machines is schematically illustrated in Fig. 9.54. A description of the stages is as follows:

(a) This is the starting position; the previous course has just been completed and the sinker moves forward to hold the fabric. A guide bar shogs sideways to come to the position close to the needles.
(b) Needle starts to rise and shogging movement of the guide bar is now completed.
(c) Needle is in the clearing position, sinker moves backwards. The guide bar starts to swing in between the needles
(d) The guide bar is shogged sideways for one needle space to warp the yarn onto the needle hook, thus an overlap is created.
(e) Guide bar swings back.
(f) Needles continue to descend, sinker moves backward. The guide bar starts to new shogging movement in order to produce a new underlap. An underlap movement is generally more than one needle space, depending on the fabric design.



Key
1 Guide
2 Sinker
3 Main body of needle
4 Closing element of needle
5 Fabric
6 Yarn

9.54 Stitch formation.

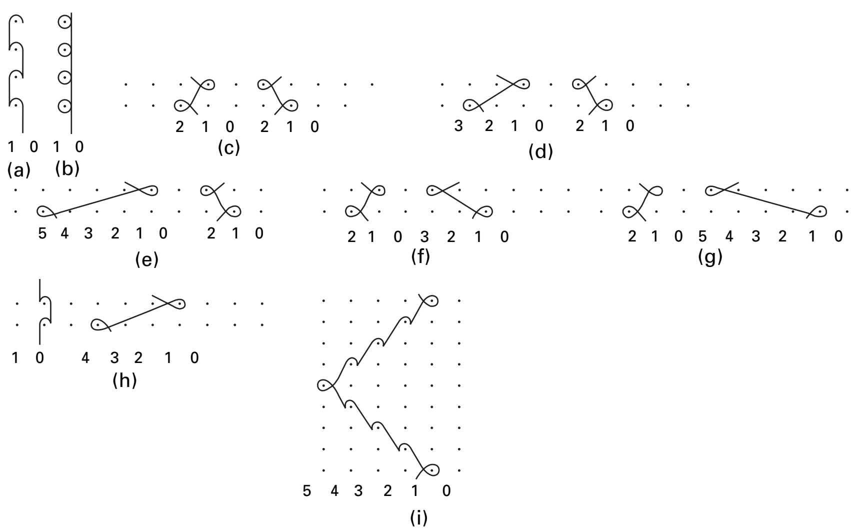
(g) The needle descends to the knockover position, the guide bar is in the centre of the underlap shogging movement and the knitting cycle is complete.

Basic fabric types

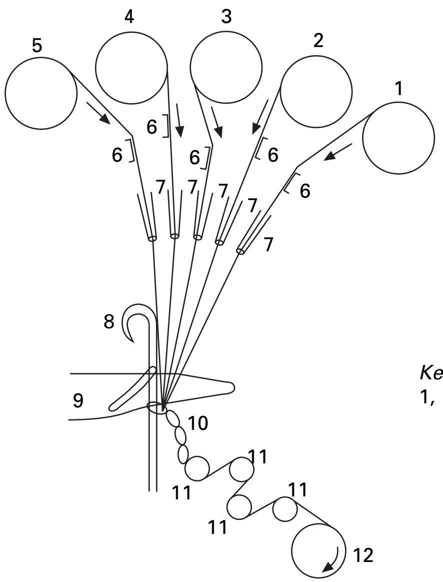
There are several basic fabric designs used in Tricot machines such as 'atlas lapping', 'tricot', 'locknit', 'satin', 'reverse locknit', 'sharkskin', 'queen's cord' (see Fig. 9.55). All of these fabrics are produced by one or two fully threaded guide bars. Although it is difficult to produce a pillar stitch on a Tricot machine, if the second guide bar has an underlaying movement more than one needle space, a pillar stitch can also be produced. It is also possible to produce open-work fabrics (net fabric) by using a partially threaded guide bar.

9.5.2 Raschel knitting machine

Raschel machine gauges are in the range of 5–32 needles per inch and it can be equipped with guide bars up to 80 to allow greater patterning capability. A schematic illustration of a Raschel machine is shown in Fig. 9.56. The properties of the main machine elements are briefly described below.[2,3,5,6]



9.55 Basic fabric types. (a) open pillar stitch (0-1/1-0); (b) closed pillar stitch (0-1); (c) tricot (front 1-2/1-0, back 1-0/1-2); (d) locknit (front 2-3/1-0, back 1-0/1-2); (e) satin (front 4-5/1-0, back 1-0/1-2); (f) reverse locknit (front 1-2/1-0, back 1-0/2-3); (g) sharkskin (front 1-2/1-0, back 1-0/4-5); (h) queen's cord (front 1-0/0-1, back 3-4/1-0) and (i) atlas (1-0/1-2/2-3/3-4/4-5/4-3/3-2/2-1/1-0).



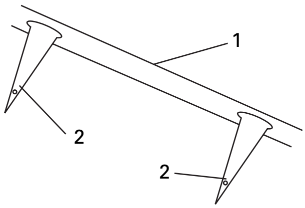
Key
1, 2, 3, 4, 5 Warp beam
6 Warp yarn tension element
7 Guide
8 Needle
9 Sinker
10 Fabric
11 Take-up roller
12 Winding system

9.56 Illustration of Raschel machine.

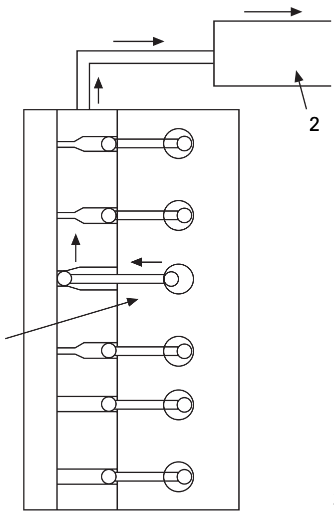
Properties of machine elements

The original needle on a Raschel machine is a latch needle, however, most modern Raschel machines are built today with compound needles. Compound needles are set into Raschel machines as in a Tricot machine while the latch needles in segment form one inch long are placed along the needle bar. Two types of guide bars are used in Raschel machines. One is similar to the one used in Tricot, i.e., it consists of a guide unit one inch long and usually fully threaded to produce the ground structure of fabric. Generally, one to three such guide bars are used to produce ground fabrics. Other types of guide bars are used for patterning onto ground fabrics. These bars usually require one thread for each patterning repeat, thus only a few yarns are threaded across the whole width of a bar (see Fig. 9.57).

The knitting action of Raschel machines with compound needles is somehow different from that of a Tricot machine with compound needles, i.e., the sinker bar is stationary, the guide bar does not swing and the swing movement is made by the needle bar. For pattern mechanism, the SU ‘summary drive’ is replaced with traditional chain link patterning mechanism (pattern drum or pattern disc) due to its high pattern repeat length, greater accuracy, speed and less patterning cost (see Fig. 9.58). Every pattern bar is equipped with an SU unit and each unit consists of six eccentric cams with two electro-magnets placed an each side of the cam. Thus, each cam system can be active or inactive according to the transmitted electrical signal via a microprocessor.



9.57 Pattern guide bar.

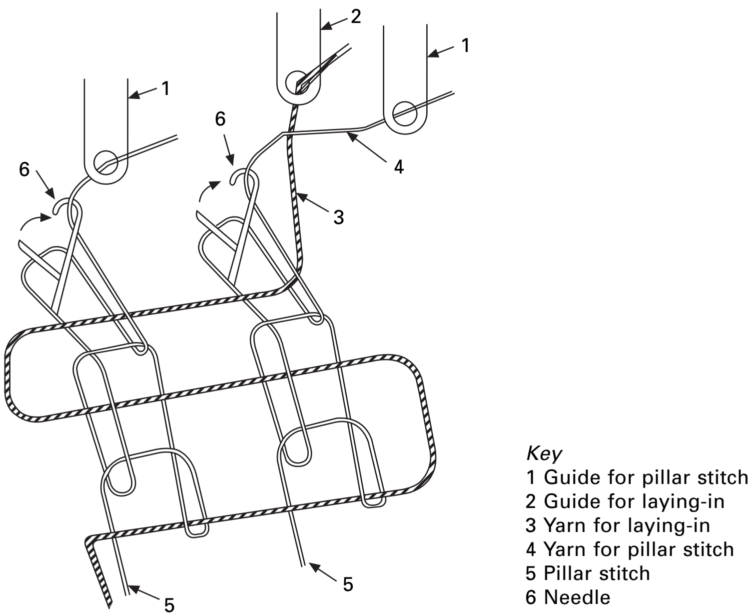


9.58 SU unit.

Each eccentric cam produces a different shogging movement when it is activated. For example, the bottom cam produces a shogging movement with one needle space, while the top cam produces a shogging movement with 16 needle spaces. Thus, shogging movements with needle spaces up to 47 can be produced by activating a different cam on this unit. In addition to basic warp beam, warp bobbins are also used to give a design to the fabric surface.

Commonly used design techniques

Raschel warp knitting machines are commonly used to produce lace and net curtains which usually need more guide bars than Tricot machines. These types of fabrics commonly use a laying-in movement and pillar stitch. Laying-in movement is obtained by special movement of the guide bar. In this movement, the guide bar does not knit the yarn into fabric, it lays a yarn into fabric (see Fig. 9.59). One guide bar (front bar) which is usually fully threaded, generally produces a pillar stitch (ground fabric), while the laying-in guide

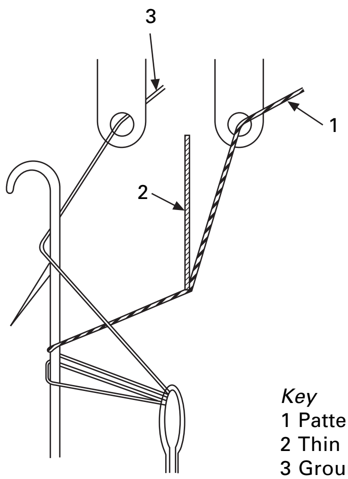


9.59 Laying-in movement.

bar which is partly or fully threaded does not produce overlap and lays the yarn into the fabric (only underlap). Partly threaded laying-in guide bars are usually used to produce a pattern on the ground fabric. Laying-in technique is used to get a flat pattern on the fabric back surface for dress laces, underwear materials, etc.

In addition to these fabrics, certain fabric designs requiring the use of a special mechanism such as a fall plate can be produced. When three-dimensional pattern effects are required, as in the case of curtains, the fall-plate technique is usually used. In the fall-plate technique, fall plate devices which consist of a thin metal plate, extending across the width of the machine push the yarn under the needle latch (see Fig. 9.60). Thus, yarn pushed with the fall-plate and the loop at the previous course are knocked over together. The yarn pushed by the fall plate (on front guide bar) gives a three-dimensional effect on the fabric surface. Opposite to laying-in, the yarn which is pushed by fall plate makes both motions, i.e., overlap and underlap.

Elasticated fabrics can be produced on Raschel machines in a similar way to Tricot machines. The main differences between these two are the adding technique of elastomeric yarn into fabric. On Raschel machines, elastomeric yarn can be inlaid into the structure rather than knitted into the loop structure. On Tricot machines, the inlaying of elastomeric yarn is not possible because the elastomeric yarn will pull the fabric out of the sinker throats. However, on Tricot machines, the elastomeric yarn can be knitted into the structure.



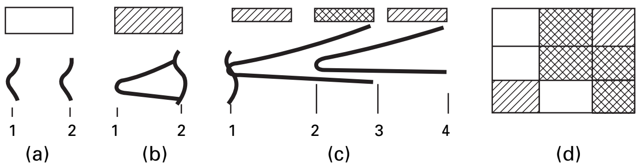
Key
1 Pattern yarn
2 Thin metal of fall plate
3 Ground yarn

9.60 Fall plate technique.

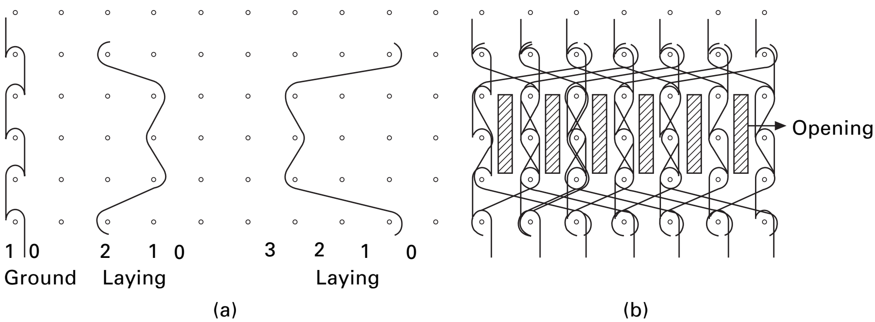
Jacquard mechanisms, weft insertion magazines and double needle beds are also available on Raschel machines. In jacquard knitting, jacquard guide bars that take a yarn from a bobbin are used, in addition to other conventional guide bars, which usually take yarn from a warp beam to produce a pillar stitch. The guides in the jacquard guide bar that are selected for deflecting sideways are long and flexible. The selection of each guide is carried out independently. Selected guides on jacquard guide bars are deflected in order to lay the yarn to a greater or lesser extent than undeflected guides at that course. Thus, open, semi-solid or solid structures at that course can be obtained (see Fig. 9.61).[6]

Basic fabric types

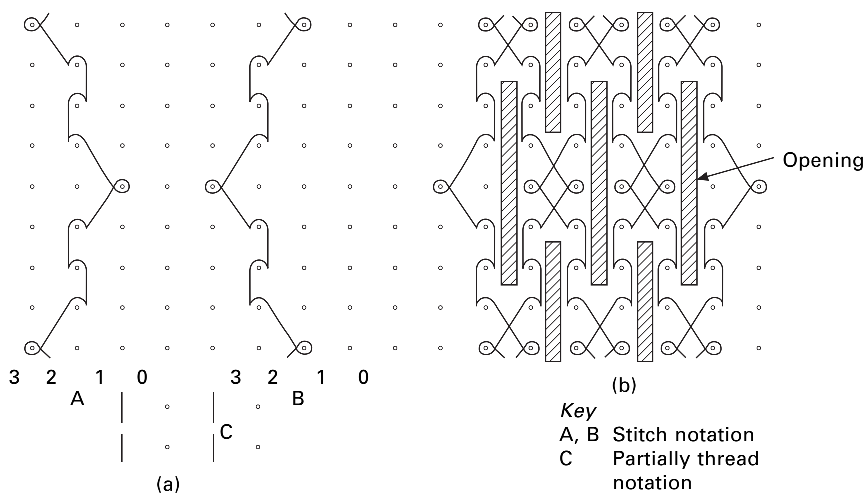
There are many different types of fabric designs that can be produced on Raschel machines. One of them is net fabric. Net fabrics can be produced by vertical pillars or interlacing pillars. On net fabrics with vertical pillars, the guide bars are usually fully threaded and net appearance is obtained by using too fine yarn compared to the machine gauge (see Fig. 9.62). At net fabrics with interlacing pillars, guide bars are partially threaded generally in a sequence of 1 in and 1 out and net appearance is obtained by a partially threaded structure, since certain wales are not connected at each courses. The opening in the fabric is obtained at these points as there are no side connections between adjacent wales (see Fig. 9.63).



9.61 Deflection of guides (jacquard structure). (a) open structure, net opening is not covered by any underlap ▭ (b) semisolid structure, net opening is covered by two underlaps ▨ ; (c) solid structure, net opening is covered by four underlaps ▩ and (d) open, semisolid and solid structure.



9.62 (a) Net fabric with vertical pillar and (b) fabric structure.



9.63 (a) Net fabric with interlacing pillar and (b) fabric structure.

9.5.3 Properties of basic warp knitted fabrics

There are several basic warp knitted fabrics, such as m × n lapping (m indicates the underlaying distance, n indicates overlap), atlas lapping, tricot, locknit, satin, sharkskin, queen's cord. The main properties of these fabrics are briefly described below.

m × n lapping fabrics

The most popular m × n lapping fabrics are 1 × 1, 2 × 1 and 3 × 1 lapping fabrics. An increase in the underlaying distance (m) leads to an increase in fabric weight, fabric cover factor, smooth appearance at the technical back of the fabric, extensibility in the wale direction and stability in course direction and leads to a decrease in extensibility in the course direction. The most popular fabric designs (one or two fully threaded) which are also described below are produced by this type of lapping.

Atlas lapping fabrics

The loops at the atlas lapping fabric incline towards the same direction for a few courses and then incline towards the opposite direction for another few courses. Thus, horizontal stripes or coloured zig-zag pattern effects will occur on the technical face of the fabric.

Tricot fabric

It is produced by two fully threaded guide bars which have 1 × 1 lapping movement. The fabric has a light weight and it can be split very easily due to short underlaying movement. The loop will not incline towards one direction, the wale therefore will remain vertical. The appearance of tricot fabrics may generally be improved by using a coloured yarn which gives vertical stripes in the fabric.

Locknit fabric

It is produced by two fully threaded guide bars. Splitting problem is less than that of Tricot fabrics. Locknit fabrics contract widthwise when leaving the knitting zone. It has a curling tendency. Coloured stripes can be obtained by using coloured yarns. The front guide bar generally requires approximately 30% more yarn than the back yarn.

Satin fabric

The technical face of a satin fabric is similar to the face of a locknit fabric. The technical back of the fabric is smoother and shinier due to longer underlap movement of the front guide bar. It contracts in a widthwise direction when leaving the knitting zone due to longer underlap movement of the front guide bar. It has a curling tendency and greater risk of snagging.

Sharkskin

It is more rigid and more stable in a lengthwise direction than satin fabric due to shorter underlap movement of the front guide bar. The technical back of the fabric is rough due to short underlap movement of the front guide bar.

Queen's cord

The fabric width changes very slightly when leaving the knitting zone. It is a very stable and rigid fabric.[2,3,5,6]

9.6 Faults in knitted fabrics

Weft knitted fabrics can generally possess two types of faults, which may emanate from the knitting machine, i.e., faulty stripe placed on fabric in horizontal direction and faulty stripe placed on fabric in vertical direction.

9.6.1 Faults in the horizontal direction

Faults in the horizontal direction generally come from settings of the machine or quality of yarn. If there are differences between each yarn tension, which is fed into the needles, faults in the horizontal direction on the fabric will appear. These will be continuous and periodical in the course direction, since the loop length (stitch dimension) varies according to changes of yarn tension, i.e., an increase in yarn tension leads to a decrease in loop length. If the quality of the yarn on the feeding system is different from the others (such as different yarn count, twist, raw material, etc.), again, a fault in the horizontal direction of the fabric will appear. A simple way to determine the source of faults is to measure the course length in the faultless and faulty regions of the fabric. If there is course length differences between each region, the fault is caused by the settings of the machine (differences between each yarn tension). If Uster values of the yarn (yarn evenness) from the creel are not suitable, again faults in the horizontal direction will appear, but will be in a discontinuous form in courseway and it will appear on the whole surface of the fabric (cloudiness). If the CV value of the yarn twist or yarn count is high, again, faults in the horizontal direction in discontinuous form will appear.[1–3,7]

9.6.2 Faulty stripes placed on fabric in vertical direction

Faults in the vertical direction generally come from defective needles and sinkers or faulty oiling system or quality of oil. Several factors also have to be taken into consideration for quality of the weft knitted fabrics. These factors are now briefly described. If the yarn used does not have enough strength or has a big knot/splice or the knitting element (needle, sinker, etc.) is heavily worn, the yarn will be easily broken and a hole on the fabric will appear. The twist value of the yarn should not be too high (not more than 3.5 α_e for cotton yarn), otherwise the fabric will not have a soft handle and serious spirality problems, where the angle between course and wale is not 90 degrees will occur. If the twist value of the yarn is very low and the yarn consists of short staple fibres, pilling problems on the fabric surface will occur.

The yarns used for knitting should be more elastic and have less twist value than those used in weaving. This is very important, especially for the special designs, which contains tuck stitches. The humidity and the temperature of the environment should be suitable for the process (around 65% humidity at 22 °C temperature), otherwise yarn breaks during production increase and increase of temperature also leads to permanent paraffin migration. Insufficiently lubricated yarn causes drop stitches and holes in the fabric. However, excessive lubricant can increase frictional forces on the yarn and also migrate into the yarn structure ruining its frictional and elastic properties.

The settings (distance, dimensions) of the machine elements such as distance between feeder and needle, distance between cylinder and dial and cam setting have to be suitable for knitting conditions, otherwise several problems such as double stitch, etc. can take place. An increase in the number of fibres in the yarn or the percentage of synthetic fibres in the yarn or decrease in fabric weight leads to an increase in pilling problems. Take-down tension of fabric has to be suitable, otherwise it causes several problems such as high take down tension leading to dimensional stability problems, however, low take down tension leads to a double stitch on the needle. Yarn tension around the yarn feeder should not be more than 5 cN, otherwise broken yarn and dimensional stability problems increase. Fibre fly (fibre particles in the air) has to be avoided, otherwise it will settle into the fabric structure and, when dyed, will appear as a different colour from the fabric surface. The conicity of the feeding yarn bobbin should be around 3.5°, 5°, 9° for synthetic, cotton and wool, respectively, otherwise yarn take-off from the feeding bobbin will be difficult.[1–3,7]

9.6.3 Comparison between ring and open-end yarn

Ring yarns typically have more strength and less extension than open-end yarns. Open-end yarns are typically better in terms of Uster evenness values and uniformity, and are cleaner than ring yarns. Open-end yarns also have a harsher handle because of their yarn structure (see Chapter 8), and are typically bulkier than ring yarns. Open-end yarns result generally in more abrasion, dimensional change and greater recovery after compression and also cause less pilling, less spirality, less compression and less wickability than ring yarns.[1–3, 7–15]

There are several fault types often observed in warp knitted fabrics

Faults arise from differences in yarn quality such as different yarn count, different fibre material or different number of fibres in yarn, etc., and from differences in yarn tension. Each of these will cause a vertical stripe fault on the fabric surface. Any defect on the needle or oiling system will also cause vertical stripe faults on the fabric surface. Any defect in the patterning system such as pattern disc or pattern chain causes faults in the horizontal direction. If the position of the guide bar or timing between the needle bar and the guide bar are not set correctly, this may cause a stitch-off.

The temperature and humidity of the environment and static have to be taken into consideration for warp knitting production because of the properties of the thermoplastic yarns and the expansion of the guides. When a knitting machine is stopped, a defect in the horizontal direction can occur due to low tension on the yarn arising from the stoppage. The amount of yarn fed into the machine has to be suitable to fabric take-down, otherwise the fabric can be tensioned or can be slack.

9.7 Physical and mechanical properties of knitted fabrics

In this section, several important factors that affect the dimensional, aesthetical and mechanical properties of the knitted fabrics will be described.

Fabric relaxation reduces the internal forces and friction within the fabric. Generally, five cycles of washing and drying treatment are enough to obtain stable (relaxed) fabric. There is a linear relationship between loop length and fabric parameters such as course density, wale density and stitch density. Loop shape factor (course density/wale density) for fully relaxed cotton plain and 1×1 rib fabric, which points out the dimension of fabric at the relaxed state is 1.3 and 1.1, respectively. Although all machine settings (thus, loop length) are kept constant, a change of fibre type (cotton, wool, etc.), yarn diameter, yarn twist level, yarn type or machine gauge results in a slight change in dimensional parameters at the fully relaxed fabric such as course and wale density (especially course density).

The constant values (k_c and k_w, dimensional parameters), which point out the linear relationship between course density and stitch length and between wale density and stitch length, respectively, will change according to pattern of the fabric such as plain, rib, cardigan, etc. For complex pattern design such as Punto-di-roma and Swiss double pique, dimensional parameters also depend on the run-in ratio (course length ratio for each course), in addition to stitch length and other constant values, i.e., as the run-in ratio changes, the dimensional parameters also change.

The dimensional behaviour of fabrics depends on the pattern of the fabric, for example, while plain knit fabrics exhibit both width and length shrinkage after relaxation treatment, rib and interlock fabrics generally exhibit width expansion and length shrinkage after relaxation treatment since the link portion connecting the back and front loop, which is almost perpendicular to the fabric plane, tries to come into the fabric plane resulting in widthwise extension. As the tuck stitch at the successive courses increases, lengthwise shrinkage after relaxation increases because of more distorted loop shape and machine-imposed forces, thus, double half cardigan fabric generally shrinks more than half or full cardigan fabric. Plain knit fabrics have more dimensional changes in the coursewise direction than the walewise direction, while lacoste knit fabrics present the opposite to plain knit fabrics during relaxation. Dimensional behaviour of the fabrics also depends on the fibre type used, for example, presence of lyocell fibre in yarn causes lengthwise dimensional shrinkage and widthwise dimensional extension after relaxation. An increase in the elasticity properties of the fabric leads generally to an increase in dimensional change.[7,9–25]

Fabric thickness depends mostly on yarn diameter and little on stitch length and yarn twist due to loop curvature. Presence of elastomeric yarn leads to an increase of fabric thickness due to an increase of loop curvature.[7,23,25,26]

Tightness factor is proportional to the ratio of the yarn diameter to the loop length. Thus, an increase in yarn diameter or a decrease in loop length results in an increase of the tightness factor. Change in stitch length generally affects course density more than wale density. An increase in tightness factor generally causes a reduction in effective yarn diameter at the loop interlocking region and an increase in loop curvature.

Tighter fabrics generally exhibit less dimensional change due to less free movement of the loops within the fabric structure. The tightness factor varies in the range 9–19 but the tightness factor between 11–17 is more practical for production. Tightness factor has to be around 14–15 for single jersey fabrics and double jersey fabrics in order to decrease forces on yarn during knitting (for optimum knitting).[7,10,18–22,25,27–29]

Technically, the wale in a knitted fabric is perpendicular to the course, however, the wale is not usually perpendicular to the course due to several factors such as twist liveliness of the yarn (yarn twist), number of knitting systems (or yarn feeder) on machine, etc. These factors create a problem known as spirality, i.e., an increase of yarn twist or number of knitting systems lead to an increase of spirality. Spirality occurs when the twist value of one loop leg is different from the other loop leg, leading to differences of yarn diameter at each loop leg. These differences of twist cause a loop rotation towards the third dimension, leading to spirality and skewness in the fabric. Spirality can be measured by the angle. The angle between the wale and line which is perpendicular to the course direction should not be more than five degrees.

As the fabric tightness increases, the spirality decreases due to less space rotation and higher inter-yarn friction. A decrease in machine gauge and an increase in the number of knitting systems on a machine lead to an increase in spirality. After relaxation of the fabric, the spirality can increase or decrease depending on the tightness value of the fabric. If the tightness value of the fabric is low, it is expected to have an increase in spirality. Spirality depends on the fibre type, for example, an increase of the amount of lyocell fibre in the blend yarn results in an increase of spirality on the fabric.[7–10,12,23,31]

The behaviour of knitted fabrics under tensional loads depends on several factors such as fabric design, fabric tightness, yarn type, fibre type, applied load, etc. When tensile loading is applied to the fabric, the yarn within the structure moves until it jams and then the yarn elongates until it breaks. Under an applied load, plain knitted fabric has less elongation in the walewise direction than that in coursewise direction due to widthwise jamming occurring sooner than coursewise jamming.

Slack fabrics generally exhibit more extension and growth than tight fabrics due to easier yarn movement and decreased loop curvature (less spring-like behaviour). However, this behaviour also depends on the pattern of the fabric, for example, simple fabric designs such as slack plain knit fabrics exhibit more residual bagging deformation than tighter ones, while tight complex design fabrics such as a cardigan fabric exhibit more residual bagging deformation than slacker ones because of greater frictional resistance during recovery from deformation.[27,45]

Bending resistance and shear resistance of the fabric are generally higher in the course direction than in the wale direction due to the two loop legs. They generally decrease with a decrease in fabric tightness and with an increase in fabric relaxation due to the reduction of inter-fibre and inter-yarn frictions.

Bending rigidity for the negative curvature (the face of the fabric is on the concave side) when the bending moment is applied around the axis parallel to the courses is lower than that of the positive curvature (the face of the fabric is on the convex side). However, the bending rigidity for positive curvature when the bending momement is applied around the axis parallel to the wales is lower than that of the negative curvature. Therefore, curling problems on unbalanced knit fabrics such as plain knit fabric occur, i.e., at the top and bottom edges, curling occurs from the back to the front, at the sides of the fabric, curling occurs from the front to the back. Curling distance at the top/bottom side is generally lower than that at the sides of the fabric, due to the higher bending rigidity of the fabric in the course direction although there is a higher bending moment in the course direction. As the tightness of the fabric and bending rigidity of yarn increase, the curling tendency of fabric increases.[27–30,32,33]

Air permeability of knitted fabrics depends on several factors such as thickness, fabric density, yarn properties, volume and arrangement of fibres, etc. Generally, the fabrics produced by the yarns with lower density fibres result in lower air permeability due to greater tightness.[12,14,15,17,34]

Water absorption and wickability of the knitted fabrics generally depends on the gaps within the fabric structure, capillarity and absorption properties of the fibres. Increasing these factors results in an increase in water absorption and wickability properties of the fabrics. As the ratio of the fibre with low density in the blend increases, moisture absorption of the fabric decreases. A fabric knitted with fibres with less crimp and less fibre thickness has more water absorption capacity than fabrics knitted with crimpy and thicker fibres, due to the number and dimension of pores within the fabric structure. Capillary forces increase as the diameter of the fabric pores decreases, thus resulting in an increase in spreading of water or moisture. An increase in water absorption capacity leads to an increase in drying time. Thus, cotton fabrics spread water slower than polyamide or polyester fabrics and give less wet feeling on the skin than polyamide or polyester due to the higher water absoption properties of cotton. It needs more drying time than polyamide or polyester fabric due to the higher water absoption properties of cotton.

The presence of elastomeric yarn in cotton knitted fabrics leads to a decrease in wickability due to an increase in stitch density. It also causes an increase in water absorption due to an increase in the amount of cotton per unit area of fabric resulting from an increase in stitch density. An increase in hairiness of yarn on the fabric generally leads to an increase in drying time due to an increase in dead-air volume (no air circulation). However, certain values of hairiness can also lead to a decrease in drying time due to the increase in surface area through which evaporation occurs. Spreading water (wickability) in the wale direction is generally faster than the course direction due to lower wale density.[17,34–38]

An increase in fabric thickness or decrease in packing factor and fibre thermal conductivity causes an increase in the thermal resistance of fabric. In knitted fabrics, conductive and convective heat transfer mechanisms are more important than radiative type heat transfer, which is important especially for structures with very low density. Thus, the fabric knitted with bulky yarn or finer and crimpier fibre provides better insulation due to more dead air within the fabric structure (conductivity of air is low). For example, an increase in the number of the ribs on the rib fabric in extended form such as 1×1, 2×2, 3×3, etc., leads to an increase in heat loss, due to less air entrapped within the fabric.

Convective heat loss is very important for knitted fabrics due to their low or medium tight structures, thus, as the fabric gets tighter, heat loss usually decreases because of decreased convective heat loss. However, there is a critical density for fabric, i.e., if density is lower than this critical density, conductive heat transfer decreases, while convective heat transfer increases.[39,40] Heat transfer from body to the enviroment increases with an increase in moisture rate on the fabric due to the higher conductivity properties of moisture. Fibre also releases heat during moisture absorption into the structure, resulting in a decrease in temperature within the fabric.

The distance between the fabric and the skin is important for heat transfer from the body to the environment, if it is higher than 0.3 or 0.4 inch, convective heat loss increases, although conductivity of air is low. A cold feeling when touching the fabric surface mostly depends on the heat transfer from the skin to the fabric surface and moisture desorption from the fibre to the skin. Thus, decrease of roughness causes an increase of cold feeling due to increase of contact area and also an increase of water absorpion properties of fibre or decrease in fibre diameter lead to an increase in cold feeling due to the increase in desorption from fibre.[17,34,39,40]

An increase in relaxation of the fabric, percentage of synthetic fibres and relative humidity or decrease in fabric density and yarn twist cause an increase in fabric pilling due to easier fibre migration. As the fabric weight (or density) decreases, abrasion on the fabric surface and pilling tendency increases due to less compactness of the fabric. The design of the fabric is also an important factor for pilling on the fabric surface, for example, generally a rib fabric has a greater pilling tendency than a plain knit fabric, due to the low density of the fabric and lacoste fabrics have higher resistance against pilling than plain knit fabrics, due to the easy abrasion of the surface resulting from less compactness and strained yarn (easy wear-off pilling). Strength, elasticity and frictional properties of fibres (or yarns) are very important for abrasional properties of the fabrics. An increase in strength and elasticity and decrease in frictional coefficent lead to a decrease in the surface abrasion.[7,12,14,15,23,25,41]

Handle of the fabric depends on tensile, bending, shearing, compression, surface, thermal properties of fabric and also on fabric weight and thickness. Surface friction, weight and bending properties can be taken as predictors for fabric handle. Lower bending rigidity, less roughness and less weight generally give better handle. Fabrics produced without tuck stitch are most preferred for handle due to silkier, smoother and thinner structures. Fabric itchiness depends on the fabric surface properties. Increase of fibre diameter and roughness lead to an increase of fabric itchiness.[27,42]

For fabric drape, less bending, shear resistance and less weight generally presents better drapability. Drapability in the wale direction is usually better than that in the course direction.[33,43,44]

9.8 Production calculation

In this section, several important production parameters for weft knitting are described and examples are given.[1,2,6,7] Many of the terms used have been described as 'Terms Used in Knitting Technology Section' of this chapter.

Production and fabric parameters for weft knitting

Machine gauge

$$E = N/L \tag{9.1}$$

Machine pitch

$$T = 25.4/E \tag{9.2}$$

Machine speed

$$MS = (3.14 \times 2.54 \times D \times rpm)/6000 \tag{9.3}$$

Production length

$$PL1 = (F \times rpm \times 60 \times \eta) / (FC \times CD \times 100) \tag{9.4}$$

$$PL2 = (F \times \eta)/(FC \times CD \times t \times 100) \tag{9.5}$$

Fabric width

$$FW1 = (D \times 3.14 \times E)/(WD \times 100) \tag{9.6}$$

$$FW2 = (FWM \times E)/(WD \times 100) \tag{9.7}$$

Production weight

$$PW = (PL \times FW \times FG)/1000 \tag{9.8}$$

Relationship between yarn count and machine gauge

$$YC = constant/ (E/2.54)^2 \tag{9.9}$$

(constant is 1650 for single jersey, 1400 for double jersey)

Course and wale density[18,21,22]

$$CD = kc/l \text{ and } WD = kw/l \tag{9.10}$$

(kc and kw are constants. They depend on several factors such as relaxation, fabric design, fibre type, yarn count, yarn twist, etc. For washed cotton plain knit fabrics, kc and kw can be taken as 5.6 and 4.3, respectively.)
Tightness factor[18,21,22]

$$TF = (YC)^{1/2}/l \tag{9.11}$$

Yarn diameter

$$d \approx [(4 \times YC)/(100000 \times 3.14 \times \rho)]^{1/2}$$

$$d \approx 0.0036 \times (YC)^{1/2} \quad \text{(by assuming } \rho = 1) \qquad 9.12$$

Machine diameter and machine gauge[24]

The following equations are suitable for plain circular knitting machine ranges 14–36 inch diameter and 20–30 machine gauge (knitted fabric parameters have to be taken from fully relaxed cotton plain knitted fabric).

$$D = [17.5 + (32 \times FW1)]/2.54 \qquad 9.13$$

$$E = [2.6 + (0.11 \times YCNe) + (0.336 \times WD)] \times 2.54 \qquad 9.14$$

where,

E: machine gauge (number of needles per inch placed on cylinder)
N: number of needles on cylinder
L: circumference of needle carrier (inches)
T: needle pitch (mm)
MS: machine speed of circular knitting machine (metre/hour)
D: machine diameter of circular knitting machine (inches)
rpm: number of machine revolutions per minute for circular knitting machine
PL1 (or PL): production length for circular knitting (fabric length produced in one hour, metre/hour)
PL2 (or PL): production length for flat knitting (fabric length produced in one hour, metre/hour)
t: time for the cam carrier on a flat bed knitting machine to travel across the needle bed, from one end to the other (hour), (length of needle bed (metres)/MS1, MS1 is the machine speed as metre/hour)
F: number of feeders
η: efficiency
FC: number of feeders for one course production
CD: course density (course/cm)
FW1 (or FW): fabric width for circular knitting (metres)
FW2 (or FW): fabric width for flat knitting (metres)
WD: wale density (wale/cm)
FWM: fabric width on flat knitting machine (inches)
PW: production weight (fabric weight produced in one hour, kg/hour)
FG: fabric weight, gram/m^2
YC: yarn count in Tex, g/km
YCNe: yarn count in Ne (number of 840 yd hanks per pound of yarn)
TF: tightness factor
l: stitch length (cm)
d: yarn diameter (cm)
ρ: fibre density (g/cm^3)

9.9 Conclusions

Knitting technology developed from a very primitive method to high-tech methods, such as computer controlled production and design. During the last two decades, electronic control of knitting machines developed rapidly.

Different fibre types such as cotton, wool, polyester, acrylic, viscon, etc., can be used on knitting machines. However, cotton and cotton blend yarn are widely used on circular knitting machines for the apparel industry producing t-shirts, sweatshirts and underwear, due to their comfort and healthy properties. Although different man-made fibres have been developed, not one could still attain the properties of cotton. It seems therefore that cotton and cotton blend yarn will be preferred for use in sports wear and underwear, for a long time.

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10
Cotton weaving technology

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10.1 Introduction

Fabric is generally defined as an assembly of fibres, yarns or combinations of these. Fabrics are most commonly woven or knitted, but the term includes assemblies produced by lace making, tufting, felting, and knot making as well as by the so-called non-woven processes. The raw materials used and the machinery employed mainly govern the type of fabrics produced.

Of all the fabric formation procedures, weaving is the oldest method and it is probably as old as human civilization itself. Historical evidences show that Egyptians made woven fabrics some 6000 years ago and Chinese made fine fabrics from silk over 4000 years ago. Woven fabric is produced by interlacing of threads placed perpendicular to each other. The yarns that are placed length-wise or parallel to the selvedges (edges) of the cloth are called warp yarns. The yarns that run cross-wise are called weft or filling yarns. There are numerous ways of interlacing yarns to produce a variety of fabric structures.

In different civilizations, it is believed, various types of handlooms were invented for weaving cloth. Weaving was a cottage industry until John Kay invented the hand-operated fly shuttle in the year 1733. Edmund Cartwright invented the power loom in 1785. Introduction of the electric power driven loom opened up a new vista and particular emphasis was placed on increasing the loom speeds and thereby achieving higher productivity. Besides, developments in science have significantly changed the technologies of *inserting weft yarns* whereby not only productivity increased but also newer weaving processes and product developments took place. As a result of these advances, shuttleless and multiphase looms emerged *in the 20th century*. In this chapter a brief description of the weaving processes is presented to help readers understand how wonderfully fibres, individually small are made into cloth running into several metres in length.

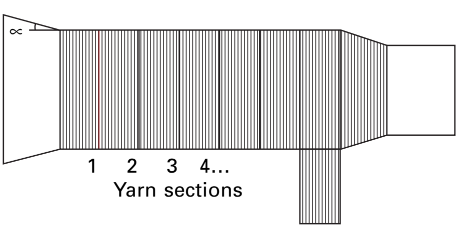
The various weaving processes are dealt with in the same sequence as they occur in the weaving of a fabric. Also, for better appreciation of the basic principles of weaving, for most of the explanations, features of the earlier generations of machinery are also mentioned along with those of contemporary machines since the new generations of machines are, by and large, the technological upgrades of the preceding generations of machines.

The chapter is divided into seven sections, including this introduction which forms the first section. The Section 10.2 describes the various preparatory processes for weaving whilst the Section 10.3 covers the weaving operations and mechanisms. The Section 10.4 explains the significance of the important fabric properties in relation to specific end uses. Modern weaving machines are dealt with in Section 10.5. The concluding section gives some useful statistics on the installed capacities of looms in selected countries as well as production costs. An indication is also given of the likely growth scenario of weaving in the developing and developed countries.

10.2 Preparatory processes for weaving

10.2.1 Warping

The objective of preparing a warp is to supply a sheet of yarns, of desired length to the succeeding processes, laid parallel to each other. Warping is done by winding a number of yarns from a creel of single-end packages such as cones or cheeses onto a beam or a section beam. The warp beam that is installed on a weaving machine is called a weaver's beam. The two basic systems of preparing warp are known as the direct system and the indirect system. Direct warping is used in two ways. First, it can be used to produce directly the weaver's beam in case of strong yarns and when the number of warp ends on the warp beam is relatively small. Second, it can be used to produce smaller intermediate beams, and the warper's beams are combined later at sizing stage to produce the weaver's beam. Indirect warping is used to produce a section beam which facilitates a wide range of fabric constructions that would require the use of multi-coloured yarns, fancy weaves and assortment of yarn counts. Warp yarn is wound onto the beam in sections, beginning with the tapered end of the beam. Because of the geometry of the concentrically wound yarn sections, the end of the beam is tapered to ensure the yarn on the beam is stable (Fig.10.1). After all the sections on the beam



10.1 Tapered section beam.

are wound, the yarn on the beams is rewound simultaneously under tension onto a weaver's beam.

Today's warping machines can process all kinds of materials including coarse and fine filament and staple yarns, mono-filaments, textured and smooth yarns as well as silk and synthetic yarns such as glass.

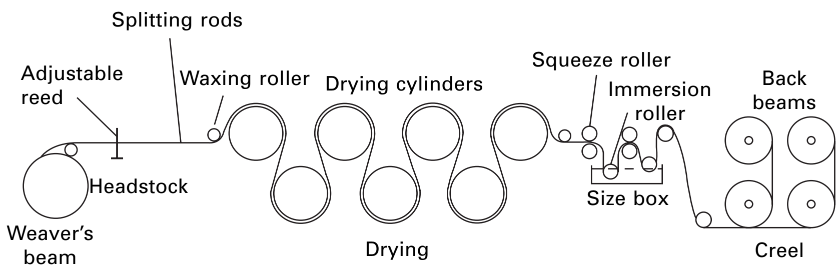
10.2.2 Warp sizing

Sizing gives a protective coating to warp yarns for them to withstand the tension and abrasion that yarns undergo during the weaving process. In other words, sizing increases the strength and reduces hairiness of yarn and at the same time helps maintain the required flexibility and elasticity. Thus, sizing is done to attain a high weaving efficiency by reducing warp breaks during weaving. Sizing is the operation of coating of a polymeric film forming agent (called size) on the warp yarns. Generally, the size mix contains film forming agents (e.g. starch, PVA), lubricants like mineral oils, paraffin wax, humectants such as ethylene glycol, glycerol, etc., preservatives, water and defoamer.

The major parts of sizing machines are the creel, size box, drying units, beaming and various control devices (Fig. 10.2). After leaving the warper, the beams are placed on the creel and the sheet of yarn from the creel is passed through the size box which contains the sizing solution. The yarns pick up the required quantity of size solution and pass through the squeezing rolls where any excess size is squeezed off. In the next process when the yarns pass through drying section, most of the water from the warp evaporates and the yarns are wound on the weaver's beam. Then, the weaver's beam goes through drawing-in and denting. Once the fabric is woven, the size is removed by desizing process, except in a few cases where it is loom finished material.

10.2.3 Drawing-in and denting

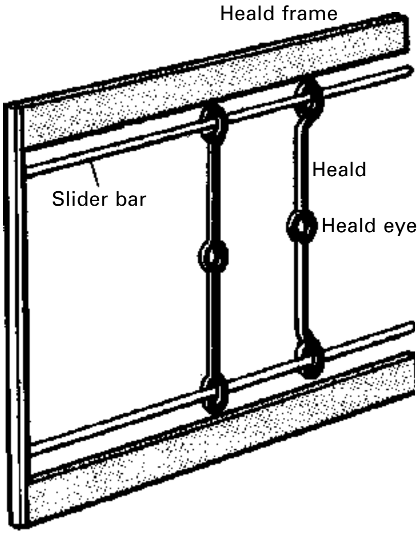
Drawing-in and denting form an essential link between the designing of a fabric and the working parts of the loom. Drawing-in is the threading of



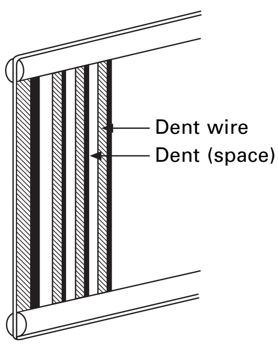
10.2 Multi-cylinder sizing machine.

warp yarns from the sized weaver's beam into the eyes of the healds which are mounted in the heald frames in the loom (Fig. 10.3). The threading of yarns follows the desired pattern of the fabric. Each warp yarn end will be drawn through the eye of one heald. Healds which are required to be raised at the same time will be placed on the same heald frame, while healds that lift differently will be placed on different heald frames. Healds control the movement of warp threads to separate themselves into two layers so as to make a tunnel for filling or weft yarns to be inserted in the gap. This opening is called the shed. After the warp yarns in the beam are exhausted and if there is no change in the design, then the corresponding ends of yarns of old and new warp beams are tied together and this is called tying-in process.

Denting is the arrangement of warp ends in the reed space (Fig. 10.4). The reed is made of flat metal strips fixed at uniform intervals on a frame to form



10.3 Heald frame and healds.



10.4 Reed.

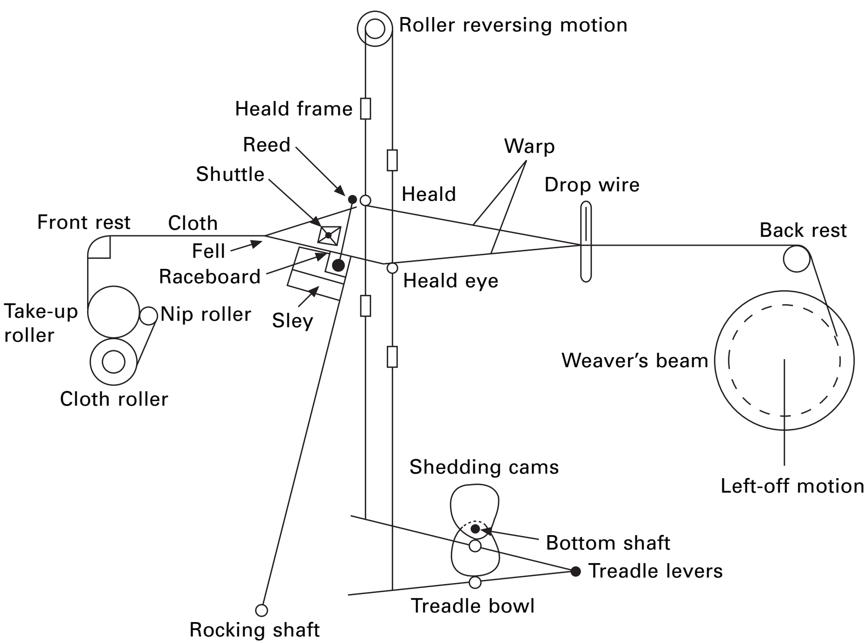
a closed comb-like structure. The spaces between the metal strips are known as dents. Reeds are identified by a reed number which is the number of dents per unit width. The reed holds one or more warp yarns in each dent. Denting plans describe the arrangement of the warp ends in the reed which controls the warp yarn density in the fabric. Warp density is expressed as either ends per inch or ends per centimetre. The main functions of the reed are to hold the warp yarns at uniform intervals, beat up the newly inserted weft and simultaneously support the shuttle during its traverse motion.

10.3 Weaving process

10.3.1 Weaving operation

The weaver's or loom beam stores warp yarns. It is placed at the back of the loom. The yarns from the beam pass round the back rest roller which ensures that the yarns are maintained at the same weaving angle as the weaver's beam decreases in size during weaving. The warp let-off mechanism unwinds the warp yarns from the beam, as the yarns are woven into fabric, at the desired rate and at constant tension as required. The schematic diagram (Fig. 10.5) illustrates how the warp yarns pass through a loom.

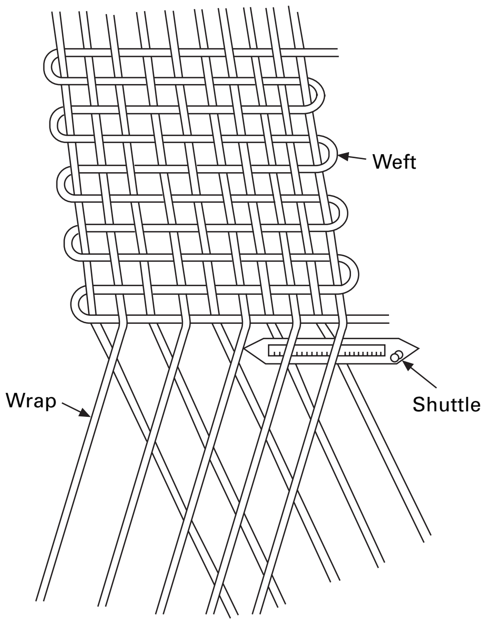
The yarns from the back rest roller are brought forward. Each end of the yarns from the beam is threaded through the eye of a drop wire. The drop



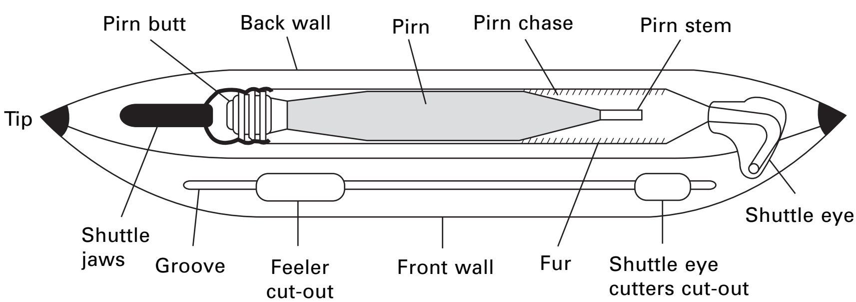
10.5 A cross-section through the loom.

wire stops the loom when a break occurs in any of the warp yarns. From here, yarns pass first through the eye of the heald and then through the dents of the reed. The operation that raises and lowers the heald frames according to the fabric pattern is known as shedding. In front of the reed, a triangular warp shed is formed by the two warp sheets and the reed. After the shed has been formed, the shuttle carrying the weft yarn traverses across the fabric (Fig. 10.6). This is known as picking (weft insertion). One single strand of weft is known as a pick.

Rectangular in shape (Fig. 10.7), the shuttle is tapered at each end to allow it to easily enter or exit the shed that is just opening or closing while weaving the fabric. The main body of the shuttle is hollow. The hollow part



10.6 Interlacing of warp and weft.



10.7 A shuttle.

stores the package called pirn which contains the weft yarn. The pirn is held firmly inside the shuttle by shuttle jaws at the one end of the shuttle. At the other end of the shuttle is a unit known as the shuttle eye. There is an arrangement in the shuttle eye to control the weaving tension of the weft thread as it is delivered from the shuttle.

The reed fixed in the reciprocating sley pushes the newly inserted length of the weft yarn into its final position in the cloth, which is known as the fell. The weft insertion device cannot physically fit at the acute angle of the shed opening, so the newly inserted weft yarn has to be pushed to its final place in the warp sheet to form the fabric. The pushing of the last inserted weft yarn or pick to the cloth fell by the reed is known as beating-up.

After the last pick is woven, the take-up motion moves the fabric forward and passes it over the front-rest and winds on the take-up roller. The fabric take-up motion removes cloth from the weaving area at a constant rate to give the required pick density. Pick density is expressed as picks per inch or picks per centimetre. Pick density is determined by the weaving machine's speed expressed as picks per minute and the rate of fabric take-up expressed as inches per minute (ipm) or centimetres per minute (cm/min). From the take-up roller the fabric is wound onto the cloth roller.

Productivity of a loom is measured by the rate at which weft is inserted (metres per minute). It denotes the rate at which fabric is woven. The speed of the loom does not take into account the effect that loom width has on fabric production. The weft insertion rate (metres per minute) is the product of loom speed (picks per minute) and loom width (reed space in metres).

10.3.2 Weaving mechanism

To produce woven fabric, a loom requires three primary motions, shedding, picking and beating-up. Apart from these, there are two secondary motions in weaving, let-off and take-up motions. In an ordinary power loom all motions are operated by the main shaft called the crankshaft. The crankshaft is driven by an electric motor. One revolution of the crankshaft operates various functions of the loom at different time intervals.

Cam shedding

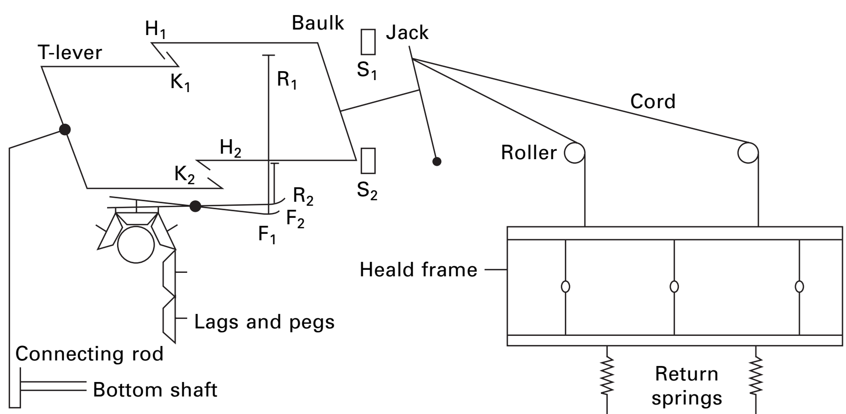
The shedding mechanism is operated by two shedding cams. The shedding cams are mounted on the bottom shaft in the case of plain weave design which needs to employ only two heald frames. However, wherever the design requires operating more than two heald frames, separate tappet shafts fitted to the bottom shaft are used. The shedding cams are mounted on the tappet shafts.

Plain simple twill and simple satin designs can be produced by the cam shedding mechanism, which can handle weave patterns that utilize up to as many as 14 different heald frames. This system is simple, inexpensive to design and reliable for producing fault-free fabric. Also, it does not restrict the weaving machine speed. The main disadvantage of the cam shedding mechanisms, however, is their restricted pattern possibilities. To overcome this constraint, more versatile shedding mechanisms, namely, dobby and jaquard, are utilized.

Dobby shedding

Dobby mechanisms can control up to 30 heald frames. There are two types of dobby mechanisms, the negative dobby and the positive dobby. In negative dobby shedding, the dobby lifts the heald frames which are lowered by a spring motion. In positive dobby shedding, the dobby raises and lowers the heald frames and the springs are eliminated. Negative or positive dobbies are further classified as single lift and double lift. The double lift dobby's cycle occupies two picks and therefore most of its motions occur at half the loom speed which allows higher running speeds. All modern negative dobbies are double lift dobbies. Although this type of dobby has been largely replaced by the positive dobby, it does illustrate the principles in a simple manner.

The double lift negative dobby has for each heald frame a baulk, a jack, cords, rollers, return springs, two hooks H_1 and H_2 and two feelers F_1 and F_2 (Fig. 10.8). The stop bars S_1 and S_2 and knives K_1 and K_2 extend the full depth of the dobby. The knives K_1 and K_2 reciprocate in slots and they complete one reciprocation every two picks. The dobby is driven from the bottom shaft of the loom via an eccentric which causes the knives K_1 and K_2, that are connected to a T-lever to move in and out alternately and so create a balanced double action.



10.8 Negative dobby.

The heald frame is connected by cords, rollers and a jack to the centre of the baulk and it is raised by stretched springs when the top end of the baulk is away from its stop bar S_1. The stop bar S_2 acts as a fulcrum. This action of moving the baulk away from S_1 happens when the T-lever pulls the knife K_1 outward along with the hook H_1. This was possible because K_1 had previously engaged hook H_1. The interlocking between K_1 and H_1 was made when a peg in the lag forming part of the pattern chain had raised the left-hand end of the feeler F_1 which thus allowed the rod R_1 to lower the hook H_1 and link onto the knife K_1.

In the next sequence of actions, as there is no peg to support the left-hand end of the feeler F_2, this end of F_2 will not be lifted and the rod R_2 will push the hook H_2 into a raised position and thereby no link will be formed between K_2 and H_2. As the action continues, the top end of the baulk will be returned to its stop bar S_1, and at the same time the bottom knife will move to the left without disturbing the bottom end of the baulk. The heald frame will therefore be lowered and will remain down for the next pick. In the absence of a peg, the frame remains down and both ends of the baulk are in contact with the stop bars.

The required pattern is represented in the pattern chain which has number of lags linked to form a continuous chain. The lags are pegged using small wooden pegs as per the pattern. Each lag corresponds to two picks. The pattern chain is turned intermittently by a wheel.

The need for higher speeds to improve productivity coupled with the demand for heavier lifts particularly on wider looms have led to the more widespread use of the positive dobby. In this system of shedding, the heald frames are both raised and lowered by the dobby mechanism and the springs are eliminated. A later development employs a rotary, instead of reciprocating action, to generate the lift given to the heald frame.

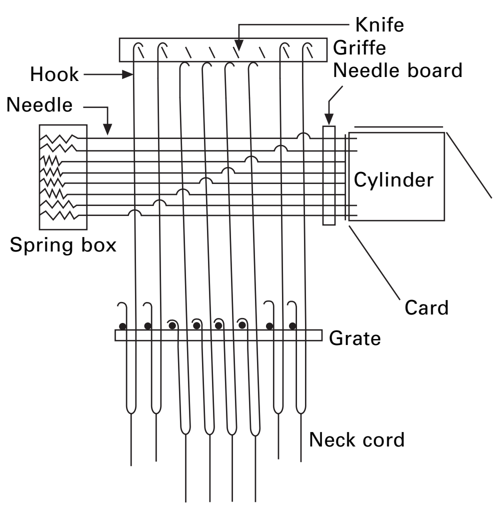
Jacquard shedding

The Jacquard machine originally invented by Joseph Marie Jacquard served as the prototype for a very wide range of weaving and knitting machines in the textile industry as well as those in lace making. When a big or complicated design is to be made in weaving, jacquard shedding is used. In this shedding the warp ends are controlled individually by harness cords and there are no heald frames. There will be as many cords as there are ends in the warp, which enables unlimited patterns to be woven.

Jacquard machines can be mechanical or electronic with single or double lift mechanisms. One of the simplest of these is the single lift single cylinder jacquard, with one needle and one hook for every end in the repeat. Common configurations have 200, 400 or 600 needles. For example, a 600-needle jacquard generally has 12 horizontal rows of needles, with each row having at least 50-needles plus a few extra needles. Each needle is kinked round a vertical hook, which it controls. Figure 10.9 shows one short row of needles and hooks.

Coil springs are provided to press the needles towards the pattern cylinder. Also, a lifting knife is provided for each long row of hooks. For a 600 needle machine, there would thus be 12 knives. The knives are fixed in a frame called a griffe. It reciprocates vertically once every pick and is normally driven either by a crank or by chain and sprocket from the crankshaft. The design is punched in pattern cards, one for each pick in the weave. The cards are laced together to form a continuous chain, and are presented to the needles by a card cylinder. After presenting a card to the needles, the cylinder shifts to present the next card. If there is a hole in the card opposite a particular needle, the needle will enter the hole (the cylinder being perforated to receive it), and the needle spring will cause the hook to engage its knife. As a result, the hook and the warp it controls will be lifted by the knife when the griffe rises. On the other hand, if there is no hole opposite a particular needle, it will be forced to the left as the cylinder moves inwards. The hooks it controls will be moved out of the path of its knife, so that the hooks and ends it controls will not be lifted.

The double lift, single cylinder jacquard has two sets of knives, each mounted in a griffe so that over a two-pick cycle the two griffes move up and down in opposition. The cylinder still has to reciprocate and turn every pick, but only at half the rates of reciprocation of the knives. These changes give a more balanced movement and also allow higher speeds to be attained. The double-lift double-cylinder machine represents a further advancement. In this machine, two needles and two hooks control each harness cord and each

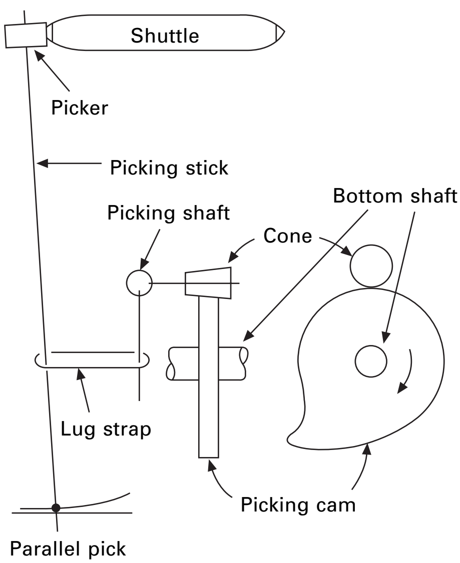


10.9 Single-lift and single-cylinder jacquard.

end in the repeat, so a machine which regulates 600 warp yarns would have 1200 needles and 1200 hooks to control 600 ends in the repeat. There are also two cylinders, one carrying the odd numbered cards and the other even numbered cards. Apart from this, its action is similar to that of the double-lift single-cylinder machine, and it also forms a semi-open shed. Further, this can run at a much higher speed as compared to the other two types. For many purposes, the double-lift double-cylinder jacquard has largely replaced both the single-lift single-cylinder and double-lift single-cylinder jacquards. Nowadays, electronic jacquards are available. These high-speed jacquards are suitable for use in high-speed shuttleless weaving machines, and are machines of choice for double-width weaving.

Picking

In shuttle weaving, the weft yarn is inserted by a shuttle which continuously moves back and forth across the width of the loom. A picking stick on each side of the loom activates the shuttle by hitting it and making it fly across the loom inside the open shed. Picking cams (Fig. 10.10) are mounted on the bottom shaft of the loom and are set at 180° to one another. When the picking cam rotates, it displaces the picking shaft via a cone. This makes the picking shaft pull the picking stick with a lug strap and by doing so the picking stick accelerates and hits the shuttle. Different mechanisms for picking operations are developed to suit the type of looms.



10.10 Cone-underpick.

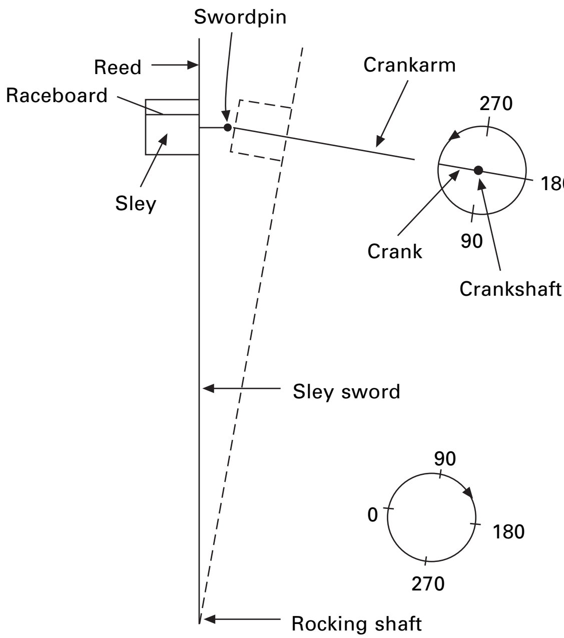
Beating-up

After it is picked, the shuttle travels on the race board. The lower portion of the warp yarns is in between the race board and the shuttle. The reed and race board are assembled together, and it is called a sley. The sley is mounted on two sley swords which are two levers that oscillate the sley back and forth (Fig. 10.11). The sley receives its motion from a crank on the crankshaft. The crank arm connects the crank to the sley by a sword pin mounted in the rear of the sley so that the rotating action of the crankshaft is converted to an oscillating action of the sley on its rocking shaft. The sley operates once every weaving cycle for beating-up the weft yarn by the reed and performs a continuous harmonic motion.

Let-off motion

As the yarn is woven, a let-off mechanism releases the warp yarn from the weaver's beam and at the same time maintains an optimum tension by controlling the rate of flow of warp yarns. If the tension of the warp yarn is not controlled at the desired level, then warp breakage rates increase, which will affect the dimensional and physical properties of the fabric.

Let-off mechanisms can be classified as negative and positive. The negative let-off mechanism is simple and less costly but suited only for non-automatic



10.11 Sley mechanism.

looms as it may cause short, medium and long period variations in warp tension when used in modern automatic looms. In the positive let-off mechanism the warp beam is rotated at a rate which tends to maintain a constant length of warp sheet between the fell of the cloth and the beam. An additional mechanism is used to maintain a constant tension on warp yarns as the warp is depleted. Modern weaving machines have electronic let-off mechanisms which provide a positive and controlled release of warp yarn from full to empty beams. This results in a consistent warp tension which, in turn, results in the best performance of the loom and good quality fabric.

Take-up motion

Once the reed recedes after beating up the weft, the woven cloth is removed from the weaving area by the take-up motion. The take-up roller removes the cloth at a rate that controls weft density and the woven cloth is wound onto a cloth roller. The take-up roller is covered with perforated steel fillet or hard rubber depending upon the type of fabric being woven. The drive to the take-up roller is by a series of gear wheels which control the pick density. Presently, many modern loom manufacturers use electronic take-up motion which gives better and more accurate control of the pick spacing by means of a servo motor.

Auxiliary functions

Apart from basic motions, in a loom there are many other auxiliary mechanisms that are used to improve productivity and enhance quality. Warp and weft stop motions will stop the loom almost instantaneously when a warp or weft thread breaks. Automatic pick finding devices reduce the loom down-time in case of weft yarn breakage. There are other devices to stop the loom when a shuttle is trapped in the shed, to replace automatically the weft package in the shuttle when weft yarn is exhausted in the package, and to select and insert suitable weft yarns for multi-type filling patterns. Modern looms incorporate a number of electronic devices that operate all the mechanisms of the loom with greater accuracy.

10.4 Woven fabric

10.4.1 Design and type

It is generally accepted that there are only three basic weave designs: (i) plain weave, (ii) twill weave and (iii) satin weave. Most of the other weave designs like honeycomb, leno, crepe velvet, etc., are derived from these basic patterns. Woven fabrics can be differentiated in many ways. They can be classified (i) by common names: denim, cheese-cloth, voile, etc., (ii) by weave type: plain, twill, satin, leno, etc. (iii) by weight: heavy fabrics and light fabrics, and (iv) by the end use: apparel fabrics, home furnishings, industrial fabrics, medical textiles, etc.

10.4.2 Properties of fabric

Woven fabric technology is deeply rooted in geometry. A fabric consists of millions of fibres assembled together in a particular geometry. The fabric properties depend on what raw material, fibre and yarn are used and the fabric structure. Some of the important fabric properties include fabric weight, cover factor, crimp, tensile strength, abrasion resistance, burst and impact resistance, and drape and hand. The test procedures for almost all cases have been standardized and testing instruments for all parameters are available. These tests are described in more detail in Chapter 12.

Fabric weight

Fabric weight is the weight of yarn per square metre in a woven fabric, which is the sum of the weight of the warp and the weight of the weft. The fabric weight is expressed as grams per square metre (g/m^2). This information is useful to determine the frequency with which new weft supplies and new beams will be required while weaving a fabric.

Cover factor

Cover factor is the area covered by yarn when compared to the total area of the fabric. The maximum cover factor is 1 when the yarns touch each other. Liquid and air permeability of the fabric depends on the cover factor to a large extent.

Crimp

Crimp refers to the extent of bending that warp and weft yarns undergo while weaving. The amount of warp and weft yarn tension maintained while fabric formation takes place governs the crimp of these yarns. Crimp affects thickness, weight, cover, flexibility and hand of the fabric.

Tensile strength

Tensile strength is an important property of fabric as it provides an indication of fabric quality and durability. The jaws of the tensile testing machine clamp the sample on both ends and a tensile load is applied until fabric breaks. Breaking strength and elongation at break are widely used for quality control.

Abrasion resistance

In certain end uses of fabric the abrasion resistance property plays an important role. Abrasion is the wearing away of any part of a material by rubbing against another surface. The twist level, yarn crimp, yarn structure and weave pattern together with raw material used affect the abrasion resistance of the fabric. The latest technology developments enable abrasion-resistant fibres to be arranged on the sheath, with high tensile strength fibres in the core.

Burst and impact resistance

Fabrics for some end uses like geotextiles, parachutes and filter fabrics must often withstand a high degree of pressure forces that act perpendicularly to the fabric plane. The burst resistance depends on the stretchability of the yarns as well as their strength. The type of fibre and yarn used in the fabrics also play a major role in bearing impact loading. Fabrics are designed to have equal properties in warp and weft for better burst resistance.

Drape and hand

Drape can be described as the ability of a fabric, when held vertically, to fall into pleats or folds under its own weight. This property is closely related to stiffness, one of the components of hand or handle. Hand or handle property comprises eight components, namely, flexibility, density, surface contour, thermal properties, surface friction, compressibility, extensibility and resilience. Drape and hand are extremely important for apparel fabrics.

10.5 Modern weaving machines

For centuries woven fabrics used to be made in shuttle looms. The advent of new technologies led to the development of shuttleless looms which fulfilled the ever-increasing demand for better quality and higher productivity. In conventional shuttle looms, a shuttle weighing about 400 g is used for inserting the weft yarn which weighs only less than 1/1000th of the shuttle weight. The mechanism used to insert the weft in this system limits the speed of the loom to 200–250 mpm. As a result, methods of weft insertions without a shuttle have been developed. They are air-jet, water-jet, projectile and rapier.

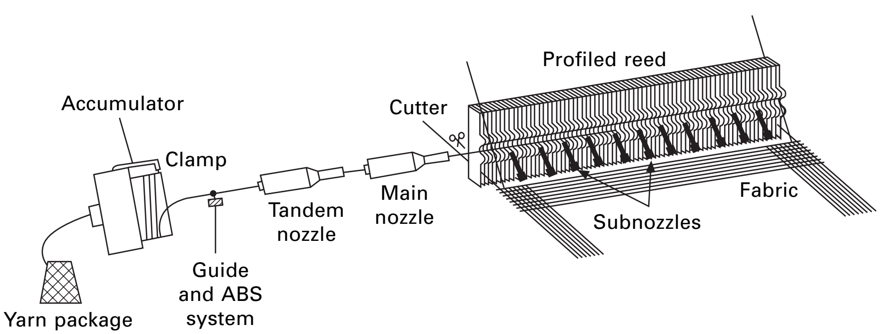
In practice these looms are named after their weft insertion system. To distinguish from shuttle looms, these machines are called shuttleless looms or shuttleless weaving machines which are considered to be the second generation of weaving machines. The first projectile weaving machine was introduced to the market in 1952. Production of rapier and air-jet weaving machines started in 1972 and 1975 respectively. The achievable production levels of various weaving technologies, as at present, are shown in Table 10.1.

10.5.1 Air-jet weaving

Air-jet weaving is a method of weaving in which a predetermined length of weft yarn is inserted into the warp shed by means of compressed air. The most popular configuration of air-jet weaving is the multiple nozzle system and profiled reed. The method of weft insertion is shown in Fig. 10.12. Yarn is drawn from the yarn package and stored in the accumulator. Due to high yarn velocity during insertion, it is difficult to unwind yarn intermittently from yarn package. Therefore, a yarn accumulator with feed systems is used between the tandem nozzle and yarn package. Yarn is released from the clamp of the accumulator as soon as the tandem and main nozzles are turned on. Upon release of the weft yarn from the clamp, it is fed into the warp shed

Table 10.1 Width and weft insertion rate of shuttleless looms

	Water-jet	Air-jet	Rapier	Projectile	Multiphase weaving
Loom width (cm)	150–230	150–540	190–360	390	189
Weft insertion rate (metres per minute)	2000–2100	2000–2500	1300–2000	1400–1500	4800–6000
Loom speed (picks per minute)	Up to 1050	450–1100	450–700	330–400	2430–2820



10.12 Air-jet filling insertion with profiled reed (courtesy of Sulzer).

via tandem and main nozzles. The combination of these two nozzles provides the initial acceleration for weft yarn to traverse across the warp shed. Subsequently, the sub or relay nozzles are activated to maintain the velocity of the leading end.

During weft insertion, the yarn is pulled by the air at the tip so as to avoid the possibility of buckling. A profiled reed guides the air and separates the weft yarn from the warp. A cutter is used to cut the yarn when the insertion is completed. The main advantage of the air-jet weaving machine is the high rate of weft insertion. These machines are ideal for cost-effective production of bulk fabrics with a wide range of styles. They are commonly used for weaving spun yarns, continuous filament yarns and textured yarns.

10.5.2 Water-jet weaving

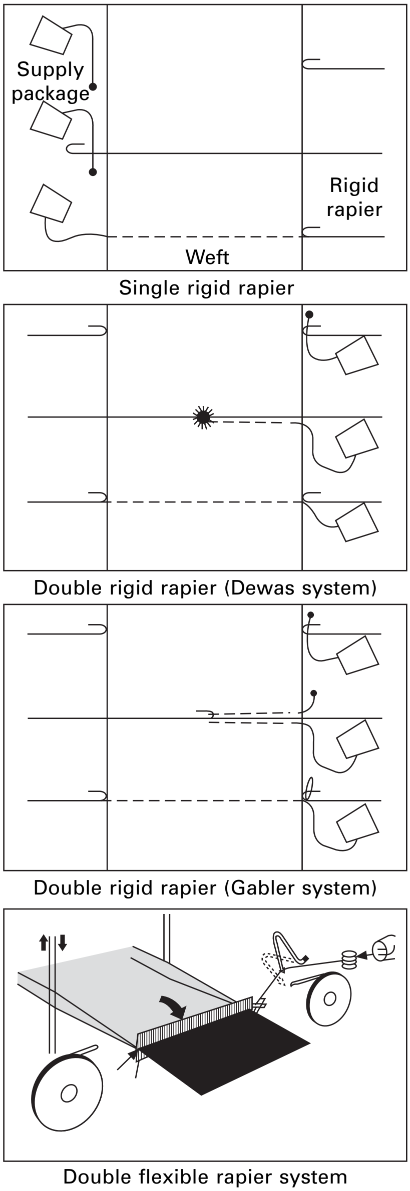
In water-jet weaving machines the weft yarn is inserted by highly pressurized water. These looms are similar in many ways to air-jet looms but they differ in construction, operating conditions and performance. Since water is used for weft insertion, warp and weft yarns must be water insensitive. The machine parts that get wet must be resistant to corrosion. The speed of weaving in this loom is high but the types of cloth that could be woven are somewhat limited due to the fact that yarn used for weaving should be wettable. These machines are commonly used for weaving synthetic filament yarns like polyester, nylon, etc.

10.5.3 Rapier weaving

In rapier weaving, a rigid or flexible rapier is used to insert the weft yarn across the warp sheet. The rapier head picks up the weft yarn and carries it through the shed. The rigid rapier is a metal bar generally with a circular cross-section. The flexible rapier has a tape-like structure that can be wound on a drum. Rapier weaving machines can be classified according to the method of weft insertion of single or double rapier system.

Single rapier machines

In single rapier machines, the rigid rapier enters the shed from one side and on reaching the other end grips the weft yarn tip and pulls it across the weaving machine while retracting (Fig. 10.13). This would mean that half of the rapier traverse is wasted and thus loom speeds are low. The single rapier length is equal to the width of the weaving machine. This would necessitate high mass and rigidity of the rapier to ensure straight movement of the rapier head. Due to some of these constraints the single rapier machines did not gain popularity in the industry.



10.13 Schematic of rapier systems.

Double rapier machines

Double rapier machines use two rapiers to insert the weft yarn and they can be rigid or flexible. In these machines, two rapiers enter the shed from opposite sides. One rapier takes the weft yarn from yarn accumulator on one side of the weaving machine, carries it to the centre of the machine and transfers it to the second rapier, which carries it to the opposite side of the machine. There are two types of double rapier, the Dewas system and the Gabler system. In the Dewas system, one rapier grips the tip of the yarn, takes it to the centre and transfers it to the other. The second rapier grips the yarn when transfer takes place and retracts carrying the yarn to the opposite side. In the Gabler system, one rapier from one end pushes the weft yarn into the shed in the form of a loop to the centre of the machine. The loop that is transferred to the second rapier is straightened during the rapier's reverse traverse. Double flexible rapier machines are more common in use than the rigid rapier machines since they save space. The weft yarn is gripped both by the giver and taker.

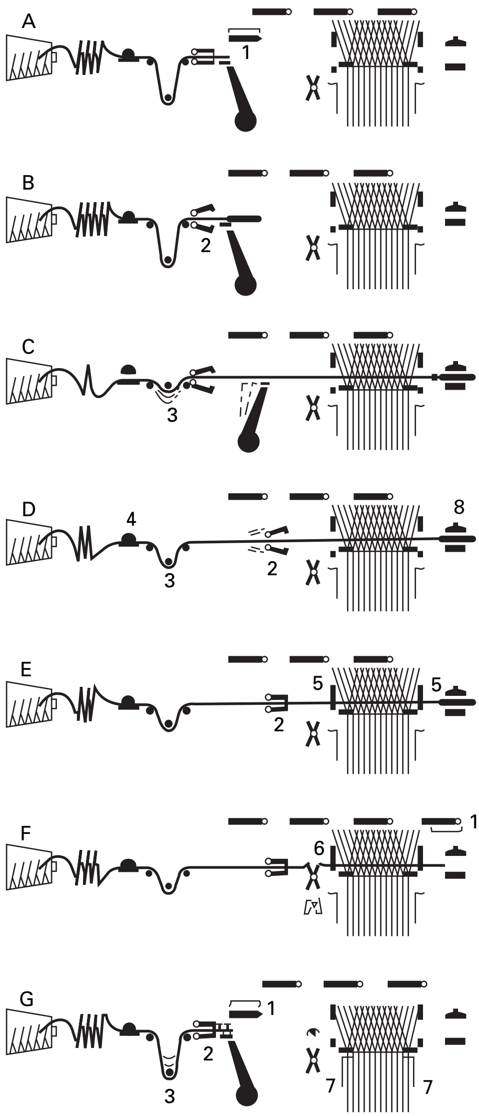
A very wide range of fabrics can be woven on rapier weaving machines. In these machines weft patterning is achieved more easily without reducing machine speeds, so rapier weft insertion is very popular in fancy weaving, where frequent pattern changes have to be made or when different types of yarn made from wool, cotton, man-made fibres, silk, etc., have to be used.

10.5.4 Projectile weaving

In a projectile weaving machine a projectile firmly holds the yarn by means of a gripper and traverses across the warp sheet. This system of filling insertion enables all yarns, whether fine or coarse, to be used as weft yarns. A variety of yarns made from cotton, wool, multifilaments, jute, and linen can be used as weft filling. This capability enables a variety of fabrics to be produced on these looms. The other important benefit in using a projectile weaving machine is that more than one width of fabric can be woven at a time.

The gripper projectile is picked across the warp shed at very high speed. The energy required for this operation is derived from the torsion rod which is twisted at a predetermined amount and released to give the projectile a high rate of acceleration by means of a picking lever. The projectile is ejected through the shed in a rake-shaped guide. It is stopped in the receiving unit and returned to its original position by a conveyor chain installed under the shed. Picking always takes place from one side and several projectiles are employed. These weaving machines can be single colour or multi-colour machines for any sequence of up to six different weft yarns.

The different phases of weft insertion are shown in Fig. 10.14. In positions A to C, the projectile 1 moves to picking position, grips the weft yarn from projectile feeder 2 and draws the yarn through the shed. During picking, the weft tensioner lever 3 and weft brake 4 operate to minimize the tension of the weft yarn. In position D, the projectile brake 8 in the receiving unit applies the brake, stops the projectile and pushes it back. In position E, the projectile feeder 2 takes over the weft yarn while grippers 5 hold it at both



1 Projectile
2 Projectile feeder
3 Weft tensioner lever
4 Weft brake
5 Weft end gripper
6 Weft cutter
7 Tucking needles
8 Projectile brake

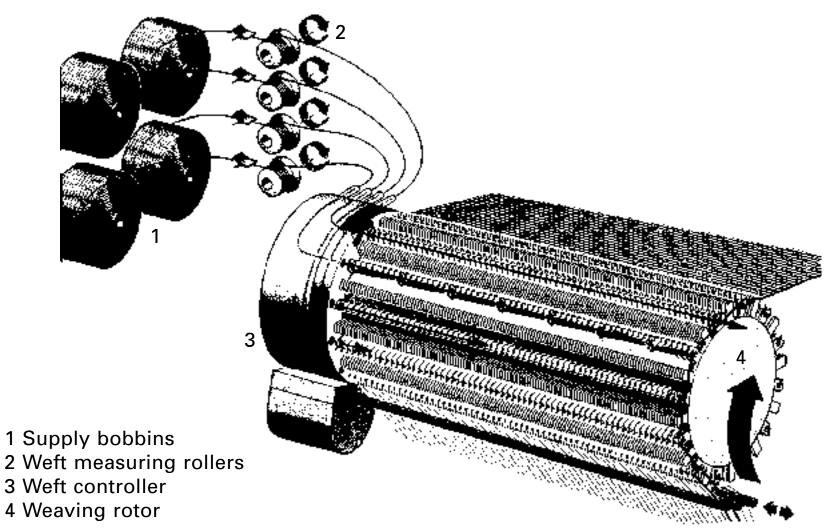
10.14 Filling insertion sequence with projectile (courtesy of Sulzer).

sides of the fabric. The yarn is released by the projectile on the receiving side in position F, and the projectile is carried back to the picking position by a conveyor chain. At the same time, the weft cutter 6 cuts the weft yarn on the picking side. In position G the weft is beaten up by the reed. Tucking needles 7 tuck the weft yarn tails into next shed. As the projectile feeder 2 returns, the weft tensioner lever 3 takes up the remaining length of yarn. The next projectile 1 is brought into the picking position for repeating the operations.

10.5.5 Multiphase weaving

Rapid developments have been taking place in recent years in the application of newer technologies to weaving. Speeds of weaving machines along with its more sophisticated patterning capabilities play a major role in the present developments. Thus shuttle looms gave way to shuttleless weaving machines. Both shuttle looms and shuttleless looms are single phase weaving machines in which the shedding, weft insertion and beating-up operations form the sequence. The necessity of waiting to insert one pick after another, limits the speed of single phase machines. In these machines, the weft insertion rate has reached a stagnation point of around 2000 m/min. Besides, the strain on the mechanisms employed and the stress on the yarns used for weaving have almost reached their optimum physical limits. All these factors led to the development of the multiphase weaving machine. In a multiphase weaving machine a number of weft yarns can be inserted simultaneously, unlike a single phase weaving machine where only one weft yarn at a time is placed in the fabric (Fig. 10.15).

In multiphase weaving several sheds are formed in the direction of warp, one behind the other and parallel to each other. These sheds are opened



10.15 The filling insertion elements of multiphase weaving (courtesy of Sulzer).

across the entire weaving width. A weft yarn is simultaneously inserted into each of these open sheds. The weft is inserted into the sheds by low pressure compressed air over the full width of the fabric. Relay nozzles are integrated in the shed forming elements at regular intervals. If four picks are inserted simultaneously, each with a speed of 1250 m/min, then the weft insertion rate of the machine is 5000 m/min. The weft insertion rate is the product of the weft carrier velocity and the phase number. In a multiphase weaving machine the stress and strain on warp and weft yarns are much lower than in a single phase weaving machine. This reduces lower end breaks both in warp and weft yarns.

10.6 Looms installed and weaving costs in selected countries

The number and percentage of shuttle looms and shuttle-less looms installed in different countries are shown in Table 10.2. The table covers all the countries that have looms accounting for over 2% of the world total. Even though India has the largest number of looms at over 38% of world total, shuttle-less looms make up around 1% of this total. In comparison, China has an installed capacity of 20% of the looms in the world, of which 14% are shuttle-less looms.

The manufacturing costs of weaving in selected countries are shown in Table 10.3. The labour cost expressed as percentage of total manufacturing cost is highest in Italy at 49%, closely followed by USA at 48%. In comparison the labour cost is low in developing countries and it ranges between 7% and 11% in China, Brazil, India and Turkey. The lower labour costs in China, India and Turkey are offset to some extent by the higher power cost which is about 24% in these countries. The auxiliary material cost and interest are

Table 10.2 Number and percentage of shuttleless looms to total looms in selected countries (2002)

Country	Shuttle looms	Shuttle-less looms	Total as % of world total	Shuttle-less looms as % of total
Russia	27,824	96,057	2.60	77.54
Brazil	93,500	38,794	2.78	29.32
Thailand	128,217	52,507	3.80	29.05
China	808,796	134,173	19.82	14.23
Japan	117,490	19,241	2.87	14.07
Indonesia	234,520	27,356	5.50	10.45
Pakistan	260,100	18,507	5.86	6.64
India	1,803,755	21,468	38.37	1.18

Source: ITMF (International Textile Machinery Shipment Statistics, 2002).

lowest in Italy and USA as compared to other countries. However, this effect is not reflected in the total cost of these two countries as the contribution by these two components to total manufacturing cost is small. When total manufacturing cost is considered, Italy and USA rates the highest whilst it does not vary much in other developing countries shown in the table.

It can be inferred from the figures in the table that in future more and more weaving capacity is likely to be created in developing countries like Brazil, China, India and Turkey, largely driven by the comparative cost advantage these countries enjoy in manufacturing fabrics for apparel and home furnishing.

10.7 Future of weaving

In recent times, there has been an increasing penetration of textiles into newer areas, broadly termed as technical textiles. Technical textiles fall into different categories like automobile textiles (seat-belts, air bags and interior fabrics), medical textiles (orthopaedic and hygiene products), protective textiles (bullet-proof and fire-resistant fabrics and heat-, water- and chemical-resistant fabrics), geotextiles (fabrics used in building and pavement constructions), agricultural textiles (plant nets, sun screens and wind shields), industrial textiles (conveyor belts, hoses and filter cloth), sports textiles (footwear and parachute fabrics) and packing textiles (soft luggage and bags). Some proportion of these newer types of fabrics will be of woven types and the remaining will be from non-woven processes. To meet the exacting demands of fabric versatility, weaving machines for complex three-dimensional (3D woven

Table 10.3 Manufacturing costs of ring/OE yarn weaving (2003)

USD/yard

Cost element	Brazil	China	India	Italy	Korea	Turkey	USA
Labour	0.02	0.02	0.03	0.23	0.08	0.03	0.17
	10%	7%	11%	49%	28%	11%	48%
Power	0.03	0.05	0.06	0.08	0.04	0.05	0.04
	14%	23%	25%	17%	14%	24%	12%
Auxiliary material	0.04	0.04	0.06	0.06	0.09	0.06	0.04
	19%	17%	24%	13%	31%	24%	13%
Depreciation	0.05	0.09	0.05	0.07	0.06	0.07	0.07
	28%	45%	22%	15%	20%	29%	21%
Interest	0.06	0.02	0.04	0.03	0.02	0.03	0.02
	29%	8%	18%	6%	7%	12%	6%
Total manufacturing costs	0.20	0.22	0.24	0.47	0.29	0.24	0.34
Index (Italy = 100)	(41)	(45)	(50)	(100)	(60)	(51)	(73)

Source: ITMF (International Production Cost Comparison, 2003).

fabrics) and circular weaving for tubular fabrics, have been developed. The process of 3D-weaving is done through the shedding operation whereby it becomes possible to interlace a grid-like multiple layer warp with vertical and horizontal sets of wefts to produce a fully interlaced 3D fabric. In circular weaving the warp is arranged in circular manner and there are continuously circulating shuttles running around the periphery in a weave.

The introduction of electronics in weaving has contributed to a great extent to the increase in productivity of looms over the years. It is to be expected that more advanced electronic devices than the existing ones will be incorporated into many of the weaving operations. This will not only increase the speeds and enhance productivity, but will also control and monitor the various functions of weaving machines more closely and precisely. Efforts to reduce vibration, noise levels and energy requirements of weaving machines will continue.

Advances in nanotechnology are also expected to give considerable push to innovations of new products and processes in textiles. Research and development activities are going on all over the world to explore the possibility of application of nanotechnology in the production of high-performance textiles through modification of fibres, yarns or fabrics. Recent public awareness of environment-friendly textiles will demand some changes in the existing products and processes. As a beginning, biodegradable fibres, eco-friendly dyes and cleaner manufacturing technology are being introduced in the industry.

In the present global market for textiles, two particularly different trends in the manufacturing of textiles stand out. First, apparels and furnishing fabrics will be largely manufactured by developing countries, since the capital investment required for machinery for these products will be at affordable levels in developing countries. Second, the major portion of technical textiles, particularly those involving high technology, will be produced by developed nations. The main reason for this is that the capital investment required for machinery and processes of such high technological levels and sophistication will be too prohibitive for developing countries.

As the use of textiles is becoming more and more diversified, the development of newer fibres, yarns, fabrics and suitable machinery for manufacturing them will expand business opportunities all over the world.

10.8 Sources of further information

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11
Dyeing of cotton and cotton products

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11.1 Introduction

The coloration of cotton textiles is a mature and highly efficient industrial technology. Worldwide the consumption of cotton dyes is some 360,000 tonnes per year comprising a major part of the $6 billion dollar dye industry. Unlike other textile fibres, there is very little coloration of cotton prior to spinning and the great majority of cotton products are dyed and printed in fabric form. A number of distinct cotton dyeing processes and classes of cotton dye have been developed and are particularly suited to certain product types. This chapter discusses these different dyes and dyeing techniques.

11.2 General principles

There are a number of general scientific aspects of cotton dyeing which have a major influence on the dyeing process used. These will be discussed briefly before progressing to examine the technology of the dyeing process.

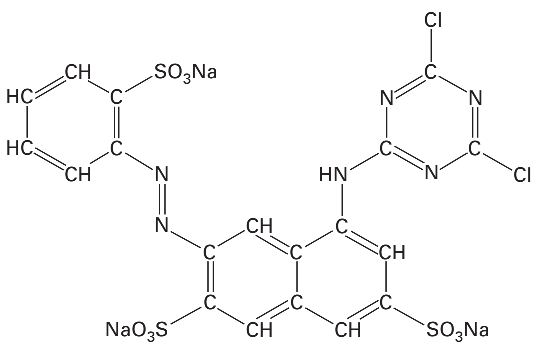
11.2.1 Equilibrium and dye structure

The absorption of dyes by cotton during the dyeing process can be described as a chemical equilibrium as in eqn 11.1 below.

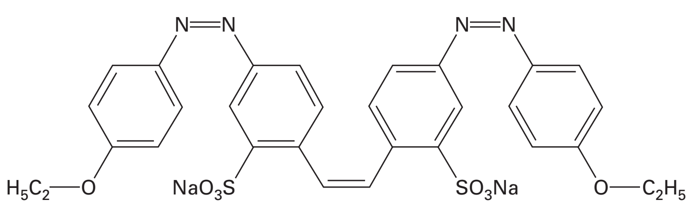
$$D_{bath} \rightleftarrows D_{fibre} \qquad 11.1$$

In this simplified model, dyes are generally described as substantive if at the end of the dyeing process D_{fibre} (the concentration of dye on the fibre) is much larger than D_{bath} (the concentration of dye in the dyebath). Substantivity is favoured by the formation of multiple dye-fibre bonds. This bonding in the case of cotton dyes is hydrogen bonding between suitable hydrogen donor groups on the dyes and lone pairs on the oxygen atom of the cellulosic hydroxyl group. The necessity for the formation of a number of these bonds combined with the highly crystalline structure of cotton, places very specific requirements on the structure of cotton dyes, in particular on the higher molecular weight, direct and reactive dyes. In general the most useful dyes are found to be those that can adopt an elongated and coplanar configuration in which the number of hydrogen bonds is maximised and the cellulose crystal structure is not disrupted (McCleary, 1953). Figure 11.1 shows typical cotton dyes that demonstrate these structural properties. The hydrogen bonds formed between these dyes and the cellulose molecule confer a level of durability (fastness) of colour during the life of the cotton article and especially fastness to washing.

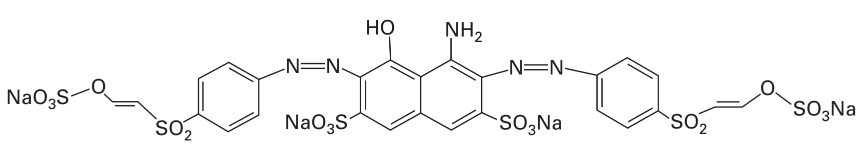
The alternative approaches to attaining acceptable fastness are the formation of an insoluble coloured complex within the fibre (azoic, sulphur and vat dyes) or the formation of dye-fibre covalent bonds (reactive dyes). These dyes will be discussed later in the chapter, however, the same



CI Reactive Red 1



CI Direct Yellow 12



CI Reactive Black 5

11.1 Typical cotton dyes.

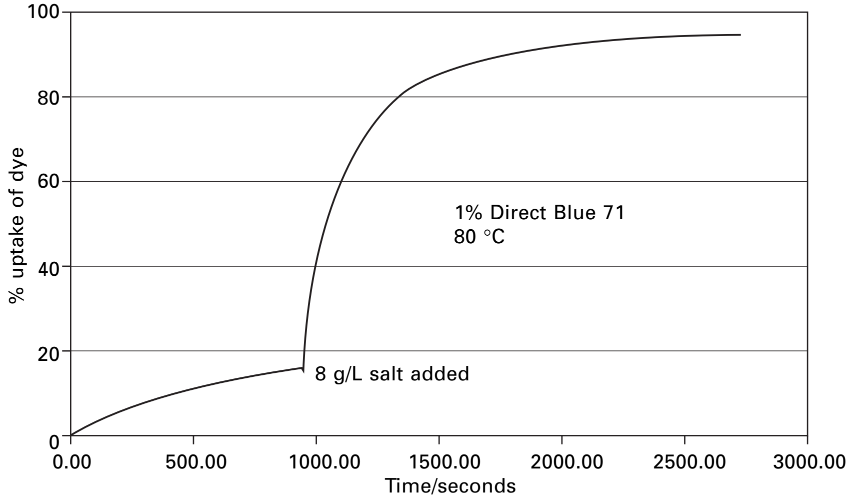
principles apply to the dye absorption process regardless of subsequent chemical reactions.

11.2.2 Electrostatic effects and the use of salt

When textile fibres are immersed in an aqueous dyebath there is a rearrangement of charge groups at the interface between the fibre and the aqueous environment. This invariably leads to the fibre surface acquiring an initial negative charge, the so-called zeta potential (Ribitsch, 1998). Since most textile dyes are sulfonated to provide aqueous solubility they also have a negative charge in solution and there is an electrostatic barrier to overcome in order for the dyes to diffuse through the fibre-water interface.

In cotton dyeing, the only widely used method of overcoming this electrostatic barrier is the addition to the dyebath of large quantities of ‘salt’, generally sodium chloride or sodium sulphate. The presence of electrolyte is well known to reduce the extent of the electrostatic field around a charged surface (Hunter, 1981). The mechanism of the salt effect is the dynamic adsorption of counterions (e.g. sodium), which leads to a reduction in the effective surface charge of the fibre. Figure 11.2 shows the effect of salt addition on the uptake by cotton of a typical dye.

It can be seen that there is an initial adsorption of dye, but dye uptake approaches approximately 20% asymptotically. The addition of salt results in rapid exhaustion of dye to yield a much higher and commercially practical uptake. The addition of salt, as well as affecting the rate of dyeing by reducing the electrostatic repulsion, increases the overall uptake of dye by reducing its solubility in the dyebath.

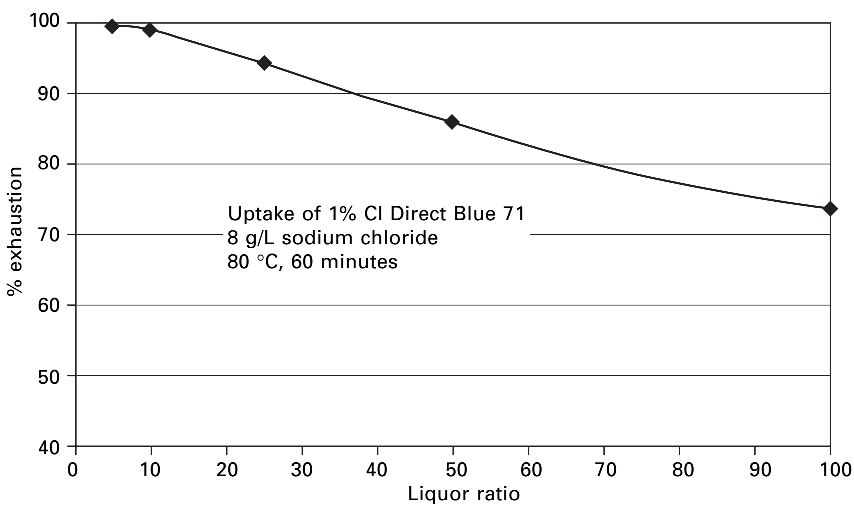


11.2 Exhaustion of direct cotton dye – effect of salt addition.

11.2.3 Equilibrium and liquor ratio

As previously referred to, the cotton dyeing process is an approach to equilibrium, and at the completion of the process there is a distribution of dye between the fibre and the dyebath. The equilibrium concentration of dye in each of the two phases is governed by various physical effects such as the amount of electrolyte in the dyebath and the 'substantivity' of the particular dye structure. One practical consequence of the equilibrium between dyebath and fibre is the effect of the relative amounts of the two phases, the so-called 'liquor to goods ratio' or 'liquor ratio'. Higher liquor ratios allow more dye to remain in the dyebath at the completion of the dyeing process; the implication of this is a lesser depth of shade and more dye in the effluent from the dyehouse. Figure 11.3 shows the effect of liquor ratio on the uptake of a typical direct dye.

It can be seen that there are high levels of dye uptake only at quite low liquor ratios and that the exhaustion of the dye varies significantly with small changes in liquor ratio. In order to get reproducible shades in cotton dyeing, liquor ratio is one of the many aspects that have to be consistent from laboratory to bulk and from one dyeing to the next. The lowest liquor ratios are those obtained in modern jet dyeing equipment and these are claimed to be as low as 2:1. Typical package dyeing liquor ratios are between 10 and 20 to 1. In continuous and semi-continuous dyeing methods the liquor ratios are typically less than one and thus even higher fixation levels are obtained.



11.3 Effect of liquor ratio on exhaustion of cotton dye.

11.2.4 The effect of temperature on dyeing

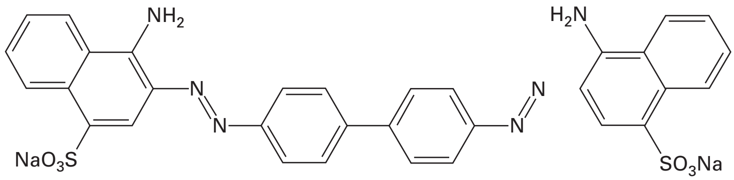
Studies of dyeing have shown that the absorption of dyes by cotton is an exothermic process. The implication of this fact is that if dyeing is carried out to equilibrium, then lower temperatures favour higher exhaustion of dyes. One might conclude from this that dyeing should be carried out at room temperature, however, the other effect of dyeing temperature is on the rate of dye uptake; this kinetic effect has more practical significance, although the thermodynamic effect should not be neglected. The rate of dye uptake increases appreciably with temperature and approximately doubles for every ten degree temperature rise. The dyeing temperature must be high enough for equilibrium and fixation to occur in a short enough time for practical operation of the dyehouse. An additional constraint is that if the rate of dyeing is too rapid, severely unlevel dyeing can occur. This is due to the fact that timescale of dyeing will be similar to the time in which dye liquor circulates in the dyeing machine. Thus the choice of dyeing temperature is a compromise (Perkins, 1996); all dye manufacturers provide recommended dyeing temperature profiles for particular dyes based on studies in their research laboratories and practical experience.

11.3 Direct dyes

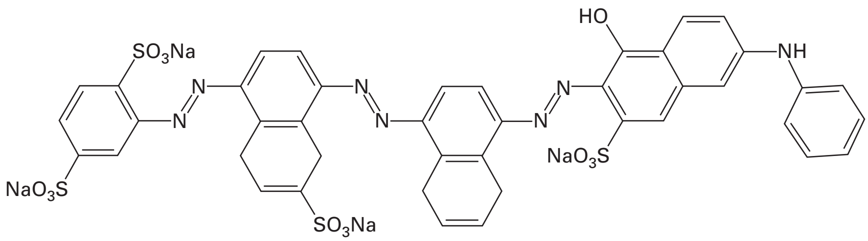
In 1884 Bottiger discovered that the diazo dye, Congo Red, coloured cotton without the necessity for pre-treatment with a metal salt (a so-called 'mordant'). This finding led to the synthesis of related dyes which were referred to as the 'direct' dyes due to their ease of application. The dyes are generally sulfonated poly-azo compounds although other structures such as metal complexes and anthraquinones are utilised to complete the shade palette (Fig. 11.4).

The levels of wash-fastness achieved using direct dyes is generally not as high as the vat dyes (discussed later), but their ease of application and broader palette led to this dye class being of great importance until the discovery of the reactive dyes. The direct dyes generally have better lightfastness than the corresponding reactive dyes (Esche, 2004) and so find particular use in applications where laundering is infrequent but resistance to fading is desirable, e.g., curtains.

The direct dyes have differing affinities for cotton and as such require different dyeing conditions to ensure that sufficient colour yield is obtained and the resultant dyeing is level. Manufacturers generally group direct dyes into two or three groups, each group having a recommended dyeing procedure. Typically the dyeing process is commenced at 40 °C and after circulation of the dyebath for approximately ten minutes, the dyes are added and the temperature raised to 100 °C over 45 minutes and held at that temperature for 30–45 minutes. The dyebath is cooled and drained and the goods are



CI Direct Red 28 (Congo Red)



CI Direct Blue 73

11.4 Typical direct dye structures.

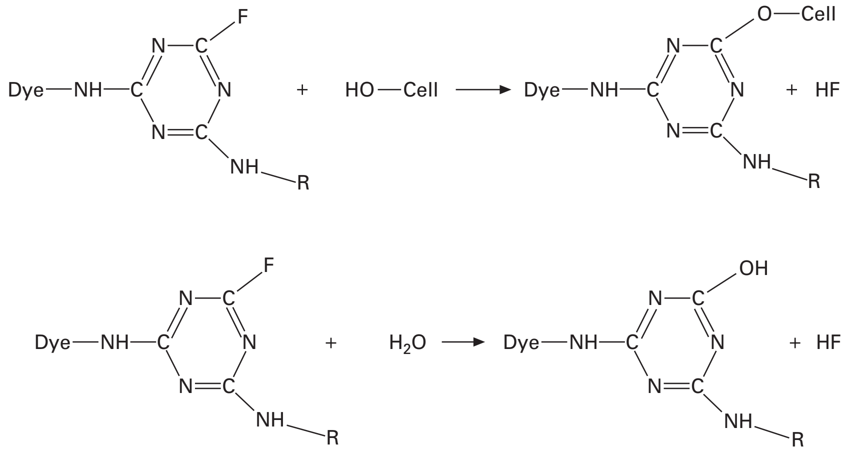
rinsed. There are a number of possible stages at which salt can be added to the dyebath during the dyeing process, generally either at the commencement of dyeing or during the high-temperature stage, depending on the affinity of the particular dye.

All manufacturers generally recommend an aftertreatment to improve the wet fastness of direct dyes. These aftertreatments consist of application of proprietary compounds which are cationic in nature. The development and mechanism of these aftertreatment compounds has been discussed (Cook, 1982). The main disadvantage of the use of these compounds is a tendency to reduce the lightfastness of the shade.

11.4 Reactive dyes

Reactive dyes are dyes that form a covalent bond with cotton fibres. The key parts of the dye molecule are the chromophore and the reactive group. ICI released the first range of reactive dyes, the Procions, in 1956 with dyes based on the dichlorotriazinyl reactive group. This event was closely followed by Ciba's monochlorotriazinyl based Cibacron dyes. These dyes were enthusiastically embraced by cotton processors, and there followed an intense research and development effort which led to all the major textile dye manufacturers producing ranges of cotton reactive dyes.

These dyes combined ease of application, previously unobtainable shades and very high levels of fastness. A representative reaction of dye and cellulose is shown in Fig. 11.5. The side-reaction with the hydroxyl ion is undesirable as the hydrolysed dye will have a lower fastness on the fibre, being the



11.5 Reaction of dye with cellulose (fixation) and water (hydrolysis).

equivalent of a direct dye. The typical exhaust process for dyeing cotton with reactive dyes is similar to that for direct dyes. The goods are loaded in the machine with appropriate auxiliary chemicals and the dyes are added after equilibration. Salt is added and the temperature raised according to manufacturers' recommendations which are quite varied. Typically the dyebath temperature is raised from 40 °C to 80–90 °C over 45 minutes and held for 60–90 minutes. The dyebath is drained and the fabric is rinsed extensively and 'soaped off'. The latter process describes the use of a detergent and alkali solution to remove unfixed dye and is very important for attaining high fastness levels.

Globally the market share of reactive dyes for cotton is approximately 10% although it appears that at the higher-value end of the market, use of reactives may be as high as 30%. Rattee has discussed the enduring preference for direct dyes over the technically superior reactives (Rattee, 1984) and identifies the cost of the dyes and the more complex washing off required as the main impediment to greater dominance of the cotton dyes market. It is estimated that almost two-thirds of reactive dyes are applied to cotton by exhaust processes (section 11.6). Although as described in a later section (11.7), the pad batch process has been developed specifically to exploit the reactivity of these dyes.

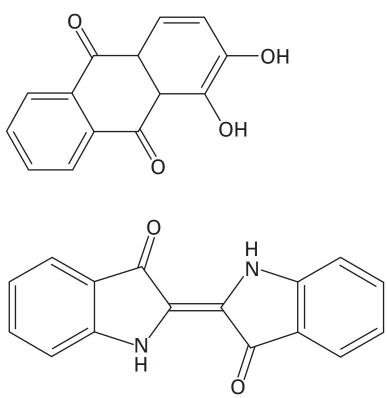
11.5 Vat, sulphur and azoic dyes

The dyes discussed in this section have in common the property that they are applied by a two-step process in which water-soluble forms of the dye are absorbed by cotton and subsequently aftertreated to yield insoluble dyes in the fibre. These dyeing processes lead to dyed cotton goods with very high fastness and comprise a very significant part of the cotton coloration industry. Vat dyes derived from natural sources are the oldest dyes known. Synthetic vat dyes and modern versions of the vat dyeing process are highly important for the coloration of cotton. The application of sulphur dyes has similarities to the vat dyeing process and is particularly important for deep shades. Azoic dyes are insoluble dyes formed *in situ* by the same reactions used to synthesise azo dyes.

11.5.1 Vat dyes

The principal ancient natural dyes were those derived from anthraquinones and those based on indigoid structures (Fig. 11.6); we would now classify these dyes as vat dyes. Alizarin is a red dye found in the roots of the madder plant and the powdered roots are used directly in the dyeing process. The plant is native to India and parts of Indonesia and was widely traded and cultivated from ancient times. The precursors to the indigo dye molecule are found in the leaves of the indigo and woad plants. These plants were very important crops until the early 20th century when BASF and Hoechst began manufacturing synthetic indigo. Understanding of the structure and synthesis of these natural dye molecules led to the synthesis of new vat dyes. Figure 11.7 shows typical examples of synthetic vat dyes. Early examples were derivatives of the natural dye structures, but many new chromophores have been developed by dye manufacturers.

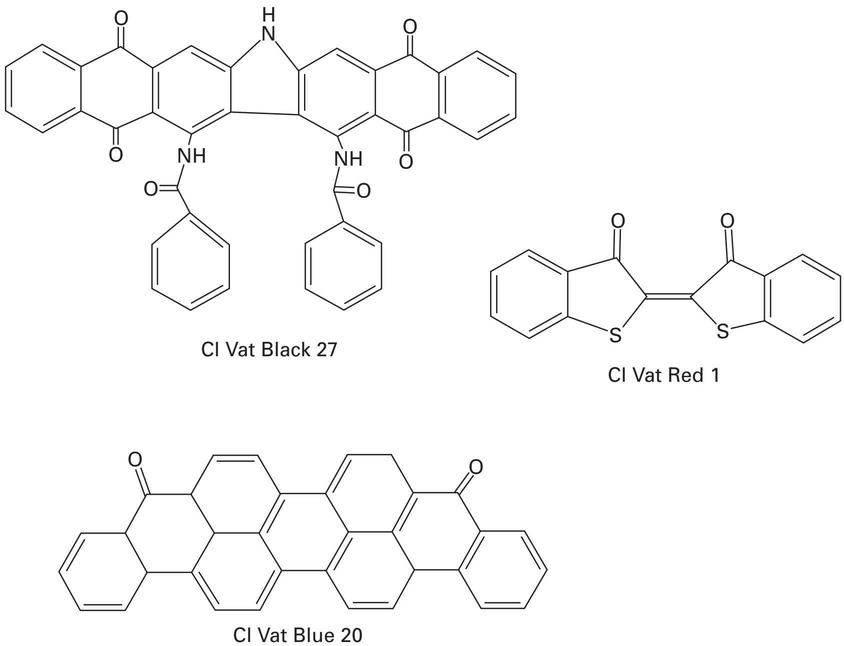
A feature of most vat dyes is that, unlike the majority of textile dyes, they are not soluble in water. The first stage of the dyeing process consists of 'vatting'; the conversion of the dye to a water soluble 'leuco' form by reduction. The reducing agent used almost exclusively is sodium dithionite which in combination with alkali rapidly converts vat dyes to the required form (see Fig. 11.8). The leuco form of the dye is generally only faintly coloured but



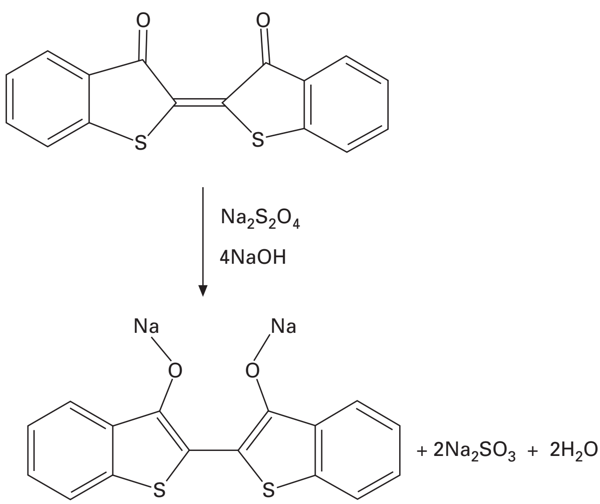
Alizarin

Indigo

11.6 Traditional vat dyes.



11.7 Modern vat dyes.



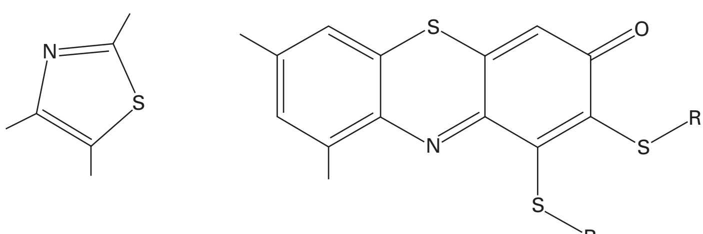
11.8 Vat dyes: conversion to leuco form.

has good substantivity for cotton and is absorbed readily by cotton. Once the dye exhaustion process has reached equilibrium, the next stage of the operation is oxidation of the dye to return it to the coloured, insoluble form. Traditional practice was to hang the dyed fabrics and allow atmospheric oxygen to re-oxidise the dyestuff, a process known as skying. Modern industrial practice is to oxidise in the dyeing machine after refilling the dyebath. Oxidising agents used are generally hydrogen peroxide or other proprietary peroxy compounds. The final stage of the dyeing process is to soap off the fabric by treatment with surfactants at high temperature. This step is important to remove poorly fixed dye and achieve maximum fastness.

11.5.2 Sulphur dyes

Sulphur dyes are one of the highest volume dyestuffs for cotton due to their generally low price and good fastness properties (Phillips, 1996). The hue range is quite dull and it is estimated that 75–80% of the market for sulphur dyes is in the production of black shades (Guest, 1989). It was estimated in 1972 that production of CI Sulphur Black 1 amounted to 10% of world dye production (Rys, 1972). The dyes were originally discovered as the product of heating wood products with sulphides, but with the analysis of their structure, industrial production of dyes of a more consistent constitution developed. In a typical process a melt of sodium polysulphide and 2,4-dinitrophenol is heated under reflux for 2–3 days at 110 °C to yield the dye CI Sulphur Black 1. The dyes consist of complex heterocyclic compounds linked by di- and multi-sulphide linkages. Typical structures identified are shown in Fig. 11.9.

The application method for sulphur dyes is analogous to that for vat dyes; the dyes as supplied are insoluble in water. The leuco form is produced by reduction with a sulphur compound (traditionally alkaline sodium sulphide). This form is soluble and has substantivity for cotton. The deeply coloured, high molecular weight dye is reformed in the fibre by oxidation. Sulphur dyes can be applied to yarn and fabric in all varieties of exhaust dyeing machinery. The process consists of preparing the reduced dye in the dyebath, adding salt and raising the temperature to exhaust the leuco form. The goods are generally rinsed prior to oxidation in the dyeing machine; subsequent rinsing and soaping is required to achieve the highest fastness. By far the most important processing route for sulphur dyeing of cotton is the continuous



Thiazole Thiazone

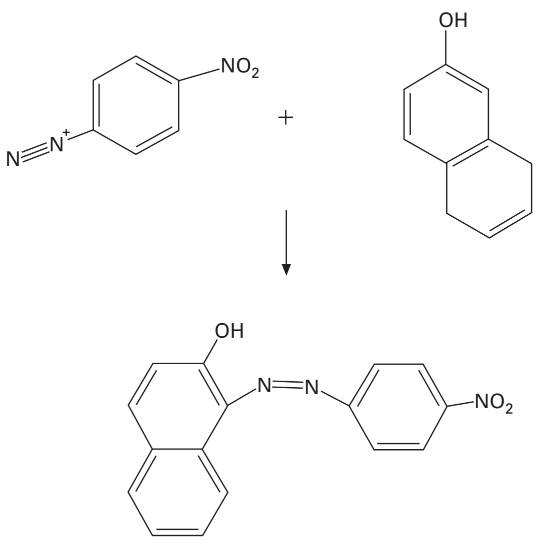
11.9 Heterocyclic groups found in sulphur dyes.

pad-steam process. The fabric is padded with a solution containing the leuco form of the dye and extra reducing agent to act as an anti-oxidant. The fabric passes through a steaming chamber in which dye exhausts into the fibre. The oxidation is carried out in one bath of a subsequent continuous open width washing range. The sulphur dyeing process for cotton can be adapted to other continuous dyeing processes such as pad-bake.

11.5.3 Azoic dyes

The synthesis of azo dyes through the reaction of aromatic diazo compounds with coupling compounds was discovered by Griess in 1858 and forms the basis of the synthesis of the majority of textile dyes today. The British dye company Read Holliday discovered a method of forming azo dyes within cotton fibres in 1880 (McClaren, 1983). In the original method the cotton fabric was first treated with β-naphthol and dried. The fabric was then treated with a diazotised amine to yield an insoluble azo dye. Figure 11.10 shows the reaction leading to one of the most important early azoic dyes; Para Red.

The technology of azoic dyeing has developed considerably since their discovery. More substantive alternatives to β-naphthol type compounds, which do not necessarily require drying, have been developed along with a range of stabilised diazo compounds which eliminate the need for forming these compounds under dyehouse conditions. The most important methods for dyeing azoic combinations are continuous treatment of fabrics. For example, fabric can be padded with coupling component, dried and padded with diazo



11.10 Formation of Para Red from coupling of p-nitro azobenzene with β-naphthol.

component followed by washing off. The azoic dyeing method has declined significantly in popularity and it is estimated that the consumption of azoic dyes has fallen from 28,000 tonnes in 1988 to 13,000 tonnes in 2004 (Phillips, 1996); this is probably due to substitution with reactive dyes.

11.6 Exhaust dyeing of cotton

The traditional image of dyeing is that of vessels containing large volumes of dye solution into which textile goods are placed and dyed through the application of heat and various chemicals. The modern embodiment of these 'long liquor' processes is what we refer to here as exhaust dyeing, the 'exhaustion' being the depletion of dye from the dyebath due to its absorption by the textile. Typical, but not mandatory, aspects of modern exhaust dyeing equipment are

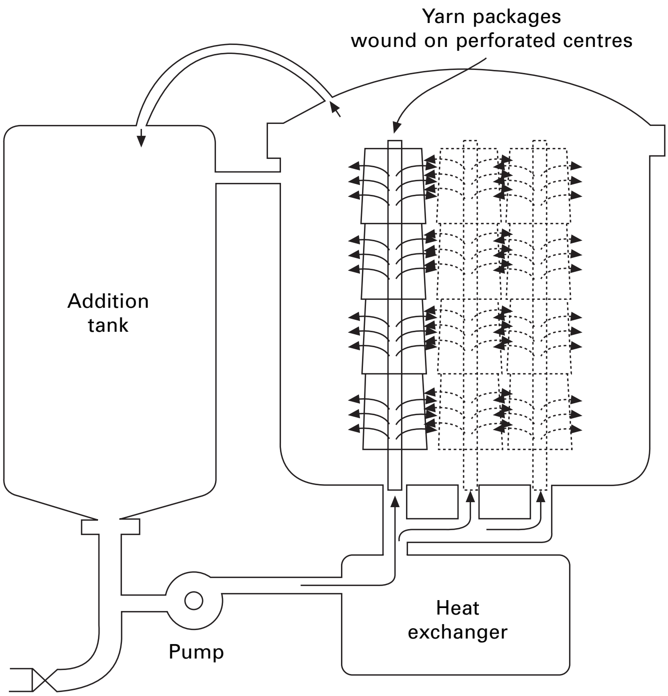
- pumped circulation of the dye liquor
- a sealed system which can be pressurised
- microprocessor control of heating and flow.

An example of modern exhaust dyeing machinery is the package dyeing machine shown schematically in Fig. 11.11. Yarn wound onto perforated centres is loaded onto a central shaft and compressed to a uniform density. The liquor is circulated via a uniform radial flow from the perforated shaft, through the yarn package into the main part of the vessel and recirculated via the pump; this flow direction can be reversed and is usually alternated during the course of a dyeing to ensure uniform contact between the yarn and the dye liquor.

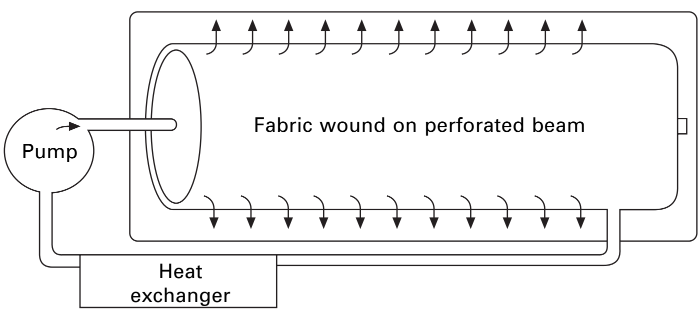
The other major types of exhaust dyeing machinery are those used for dyeing cotton in fabric form. There are four main types, the beam, beck, jet and jig. A typical beam dyeing machine is shown in Fig. 11.12; fabric is wound onto a perforated shaft and the dye liquor is pumped radially through the fabric roll in a similar manner to the package dyeing machine discussed above. This is referred to as an 'open width' process because the fabric is constrained at its full width and a flat appearance is thus maintained.

The jig is also an open-width fabric dyeing machine in which the fabric is passed back and forth between two take-up rollers via the dye liquor which is in an intermediate trough (Fig. 11.13). Older style jigs (jigs very much pre-date beam dyeing machines) placed considerable lengthways tension on the fabric which may not be desirable; tensionless versions are now widely available and give these machines broader applicability.

A schematic representation of a beck or winch is shown in Fig. 11.14 in which the fabric in a continuous loop form (referred to as a 'rope' due to the twisted configuration it tends to adopt) is circulated over two rollers and through the dyeing liquor, spending most of the time in the dyeing liquor.



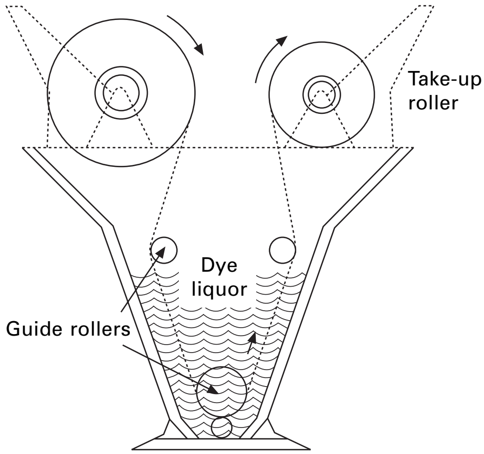
11.11 Package dyeing machine.



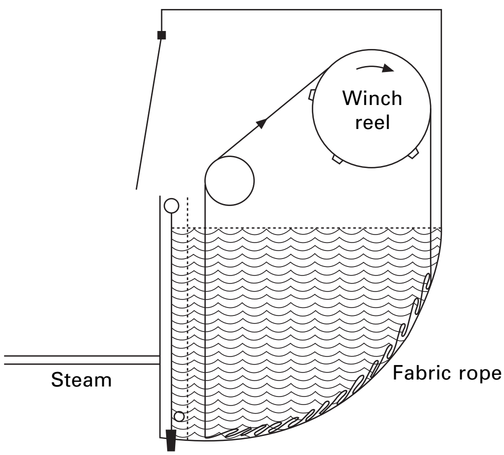
11.12 Beam dyeing machine.

These machines are the original fabric dyeing equipment with much of the construction being made of wood prior to the advent of stainless steel.

The jet dyeing machine was developed in the early 1950s and is based on the principle that the fabric rope is transported by the liquor which is circulated though a venturi nozzle and tube arrangement. Fortress and Ward list some 15 advantages of jet dyeing machines over beck type machines (Fortress,



11.13 Jig dyeing machine.



11.14 Winch dyeing machine.

1962). The greater contact between fabric and liquor enables a lower liquor ratio to be used which is important for good dye exhaustion on cotton. There is less mechanical action on the fabrics reducing the occurrence of creasing and similar deleterious effects. The penetration of the fabric by the liquor is more efficient which has benefits in even dye application and also in the rinsing and soaping of dyed fabrics which is crucial to attaining high fastness. A schematic diagram of a typical modern jet machine is shown in Fig. 11.15. Jet dyeing machines have become very widespread with many variations on the original concept. The partially flooded versions find the greatest application to cotton due to their ability to achieve very low liquor ratios.

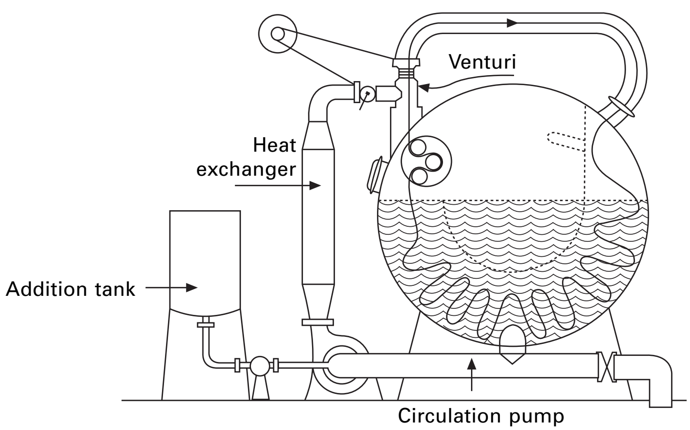
11.7 Semi-continuous dyeing

In the early 1960s the cold pad-batch process was developed for the application of reactive dyes to cotton (Raper, 1962) and has since found extensive adoption in the dyeing of cotton fabrics. The cold pad-batch process (or simply pad-batch) takes advantage of the ability of many reactive dyes to react with cotton at room temperature in practical time scales (Capponi, 1961). In this method the fabric is impregnated ('padded') with a dye paste and stored ('batched') for up to 24 hours at ambient temperatures to allow fixation to take place. The dyed fabric is then washed off (see Fig. 11.16). A typical procedure is as follows:

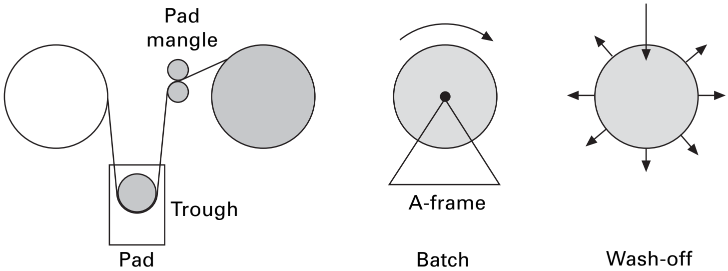
X g/L reactive dye (up to 100 g/L)
1–2 g/L wetting agent
<70 g/L sodium silicate
5–30 g/L caustic soda
pad on at 60–80% pickup, room temperature
store for up to 24 hours
rinse

The pH of the pad liquor is of the order 11–12 due to the alkali content.

A great deal of technical development that has gone into the design of modern padding equipment and the factors involved in obtaining high-quality dyeings are largely understood (Wyles, 1983). In particular the tendency of the dye to hydrolyse in the alkaline pad liquor is minimised by having



11.15 Jet dyeing machine.



11.16 Cold pad-batch process.

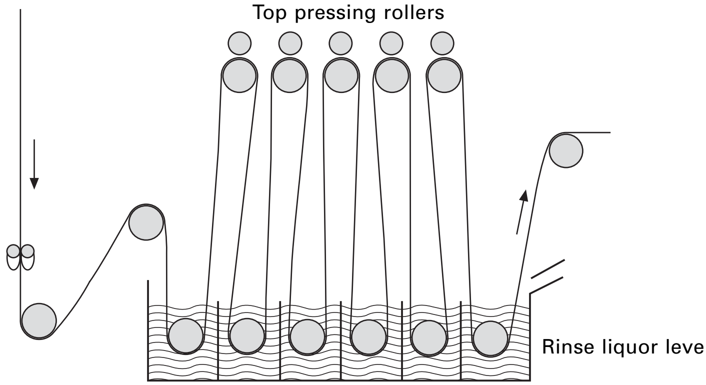
separate alkali and dye solutions which are mixed in the padding trough. The design of padding troughs and mechanisms to use minimum volumes of liquor also reduces the risk of excessive hydrolysis. For batching, fabric is generally wound onto beams which are stored on an A-frame, a device which slowly rotates the roll of fabric. This rotation avoids drainage effects in which the liquor settles under gravity producing unevenness. The fabric is usually wrapped in plastic to avoid the effects of the atmosphere on the dye-fibre reaction.

After an appropriate period the fabric is washed off to remove unfixed dyes and associated chemicals. In some cases the design of the A-frame beam will permit rinsing by connection of a water supply to the central shaft. In this method, referred to as 'trickle washing' the rinsing waters permeate the fabric roll radially until dye and chemicals have been removed and the maximum fastness obtained. The alternative procedure is to wash off on a continuous open width washing range. This procedure is more rapid and flexible. In an open width washing range the fabric is transported through a series of chambers referred to as boxes. In each box the fabric makes multiple passes through treatment liquor in the lower part of the box (Fig. 11.17). The successive dipping and expressing of the liquor leads to a very efficient washing process.

11.8 Continuous dyeing of cotton fabrics

Continuous dyeing is a method of dyeing fabrics in which, in an uninterrupted sequence, they are first impregnated with dyes and chemicals followed by a fixation step and rinsing and drying. The impregnation of fabric with dye is generally carried out in a padder as described in the previous section. Fixation can occur by a number of mechanisms such as steaming, baking or simply exposure to the atmosphere. Steaming is a very common component of continuous dyeing ranges for cotton fabrics, the aqueous high-temperature environment allowing the diffusion of dyestuff molecules into the fibre.

Continuous dyeing methods are suited to high production volumes and respond quickly to the demands of fashion. Virtually all cotton dyes can be



11.17 Wash-box.

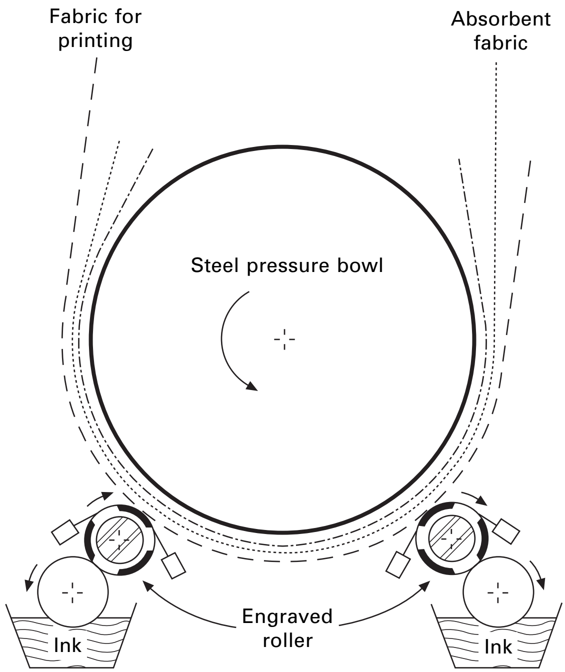
applied by continuous methods and, as mentioned in previous sections, it is the most important process for application of vats, sulphur dyes and azoic combinations.

11.9 Printing of cotton fabrics

Printing has always been an important process for producing fashion effects on cotton fabrics. The total annual production of printed fabric is approximately 15,000 million metres and it is estimated that around 50% of all printed fabric is 100% cotton (van Bergen, 1999). The technology of printing has changed over the years and is currently experiencing a period of rapid development.

The use of carved wooden blocks for printing fabrics has been known since antiquity (Robinson, 1969). The technique was used on a craft or semi-industrial basis and techniques were highly varied and regional therefore it is difficult to make general statements about the methods used. Multi-step processes included the printing of metal salts (mordants) or alternatively waxes and other 'dye resist' compounds. Subsequent dyeing yielded a print in which the dye fixed to mordanted regions and areas printed with dye resist remained undyed. The technique of applying dyes onto fabrics to obtain printed fabrics directly was a relatively late development. Block printing is very slow and labour intensive by modern standards. Block printing was the principal technique used until the 18th century but declined rapidly with Bell's invention of the engraved roller printing machine.

Roller printing is a continuous method in which the fabric is passed between a pressure cylinder and a series of engraved rollers which pick up dye pastes (also referred to as inks) of different colours (Fig. 11.18). The technology of roller printing became highly refined, although the original arrangement of rollers persisted as the dominant design. The roller printing

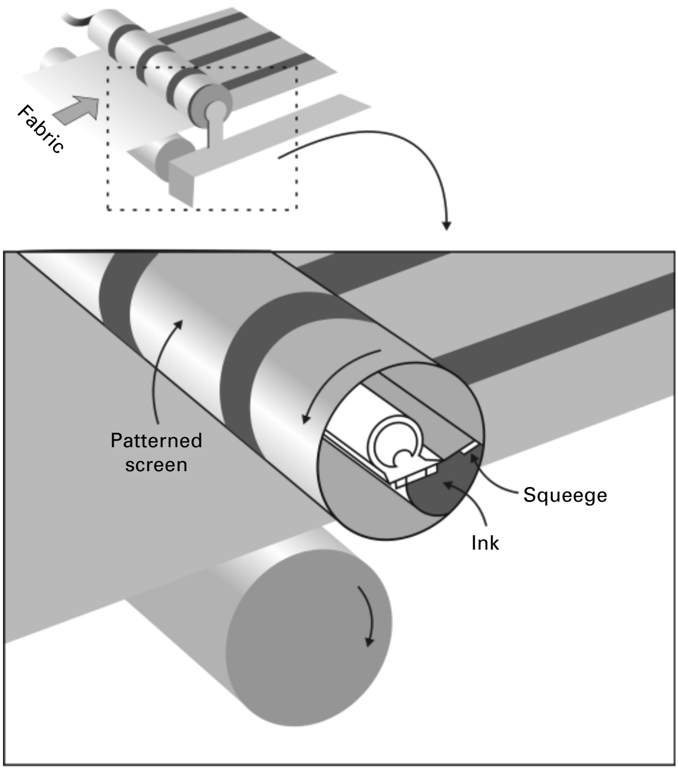


11.18 Two-colour roller printing machine.

process is capable of high productivity and the production of very finely detailed designs. Disadvantages of the process are the expense and time required to engrave rollers and the machine downtime involved in changing designs. The use of engraved roller printing has declined to a very large degree due to the advent of rotary screen printing.

Screen printing was introduced into the textile industry in the west during the early part of the twentieth century. The technique involves the use of a stencil pattern supported on a tightly stretched screen. Dye paste is forced through the design by the use of a squeegee. The original flat bed screen system was largely carried out by hand for speciality products and short runs. The efficiency and economy of the process gradually led to the development of industrial machinery with a greater level of automation. Automated flat bed screen printing is still an important part of the printing industry but its successor, rotary screen printing, is now used for the majority of printed cotton (Dawson, 2000).

Rotary screen printing is now the predominant technique and is estimated to account for at least 60% of printed fabrics (van Bergen, 1999). The principle involved is shown in Fig. 11.19; the cylindrical screen is formed from a perforated nickel cylinder which has a pattern applied to it. The patterns are applied by two main methods, in the former a polymer lacquer forms the



11.19 Rotary screen printing.

pattern and allows printing ink to flow through the perforations in the areas to be coloured. In the latter method the pattern is applied electrochemically as a fine metal coating. The printing ink is expressed from the part of the screen in contact with the fabric by either a flexible stainless steel blade or a rod of circular cross-section.

Ink-jet printing was discovered more or less at the same time by Canon and Hewlett Packard (Gregory, 2000). In the process solutions of dyes or pigments are applied as droplets from printing heads which are scanned across a moving substrate. The technique has become commonplace in home and office computing for printing on paper. Since the mid-1990s there has been an increasing interest in using ink-jet technology for textile printing. The potential benefits have led to a great deal of interest from the coloration industry and many manufacturers are making machinery tailored to textile production. Some of the key advantages are:

- the ability to print runs of variable length, especially short print runs, economically

- rapid production with reduced time between computer-based design, sample preparation and production
- less wastage of ink.

Ink-jet printing has become reasonably common for sample preparation and the printing of speciality items such as banners. It was estimated that in 2003 some 300 million metres of fabric was printed by this method and growth was rapid (Owen, 2003). At the present time, the technology has made very little inroad into full-scale textile production. The prime reason for this is the slower production speed compared to rotary screen printing.

A further process used in printing of cotton is that of discharge printing. In this printing method, dyed fabric is printed with a chemical that destroys the dye in printed regions to give a dark ground and an undyed figure. This printed pattern is usually a bleached white, however if a resistant dye is included in the print paste then two colour (so-called 'illuminated') effects are possible. The prints are steamed and washed off to remove reduced dyestuff as well as printing chemicals. Sodium formaldeheyde sulfoxylate and related salts are the most commonly used discharging chemical and the dyes used come from the reactive, direct and azoic classes. Dyestuff manufacturers provide data about the 'dischargeability' of dyes indicating their suitability for this process.

11.10 Environmental aspects of dyeing cotton

The management of waste and effluent is an integral part of modern dyehouse operations. In the case of cotton dyeing the key issues are salt and unfixed dyes, so-called 'colour in effluent'. As discussed previously, salt (sodium chloride or sodium sulphate) is used in substantial quantities in dyeing of cotton in order to improve dye uptake. It can be estimated that approximately 2.8 million tonnes of salt is used in cotton dyeing each year to dye 21 million tonnes of cotton worldwide. The use of large quantities of salt in cotton dyehouses poses a major problem; dyehouses which discharge into freshwater or municipal sewage treatment plants are generally expected to meet quite strenuous limits on the salinity of effluent. Typical salt levels allowed in dyehouse effluent are between 1–2 g/L. Given that reactive dye process liquor can contain between 40 and 100 g/L salt, considerable dilution is required and this creates operational difficulties.

A substantial effort has been put into solving the problem of high salt consumption in cotton dyeing. Within the bounds of the conventional exhaust dyeing process there are a number of straightforward approaches to reducing salt consumption, they include:

- the use of low liquor ratios
- the use of dye ranges optimised for their salt requirements
- concentration and re-use of brine (Anon., 2005).

As discussed previously, the use of low liquor ratios leads intrinsically to better uptake of dye. In addition to this the absolute quantity of salt required is less due to the lower liquor volumes. The major dye companies have responded to the concerns over salt usage by developing specific selections of reactive dyes that require less salt for the dyeing process. Ciba were the first to market such a range with their Cibacron LS dyes which were developed for their substantivity and high fixation. Dystar have a range based on similar principles under the brand name Levafix OS and Clariant have recommended dyes from their Drimarene range. Whilst the initial capital outlay is significant, the reuse of dyebaths can lead to a reduction in salt usage and discharge. The additional benefits of such a system are savings in water and energy.

The issue of colour in effluent is the other major issue facing many cotton dyers. In a comparison of the degree of fixation of textile dyes (Easton, 1995) the three dye classes with the lowest fixations were all cotton dyes, viz., the direct, reactive and sulphur dyes. The coloration industry worldwide is estimated to have to deal with 40,000 tonnes of waste dye per annum (Brown, 1987). It is generally accepted that most dyes have a low environmental toxicity and the major concern is the aesthetic problem posed by the presence of unnatural colours in waterways. Accordingly most water authorities set discharge limits on the basis of visible colour.

There are a range of approaches to managing colour in effluent and clearly the best solution is to optimise dyeing processes to obtain the highest levels of exhaustion. The use of dyeing methods which lead to high fixation of dyes, such as pad-batch (Smith, 1989) or very low liquor ratio piece dyeing machinery is one approach along with the use of high fixation dyes. Treatment of coloured effluent is often required and there are a number of references that discuss and compare the technologies available. Settling tanks with the use of flocculants have been the traditional choice due to the additional requirement to reduce solids and biological oxygen demand (BOD) from waste water. Many firms have invested in more elaborate technologies including membrane filtration, oxidation based treatment plants and specific dye adsorbents. Whilst these technologies generally involve a bigger capital outlay, there are savings involved in sludge disposal costs and big savings if the clean water produced is reused (Skelly, 2000).

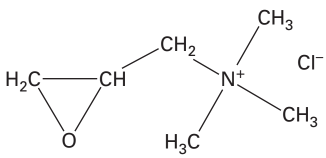
11.11 Future trends

One of the main research avenues pursued in order to improve the affinity of dyes for cotton (and to use less salt) has been pre-treatment with cationic compounds. There have essentially been two approaches:

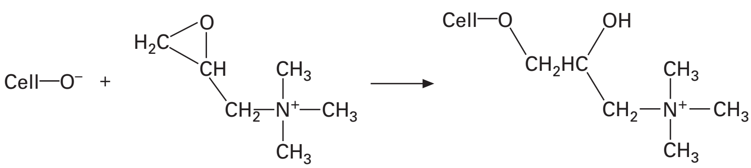
1. The use of low molecular weight chemicals which form covalent bonds to the cotton fibre.
2. The use of cationic resins.

Figure 11.20 shows a typical reactive agent used for introducing covalently bound cationic groups into cotton. This chemical was marketed for a number of years by Protex of France under the tradename Glytac A. The epoxide group undergoes cleavage by the nucleophilic celluloside anion formed under basic conditions (Fig. 11.21).

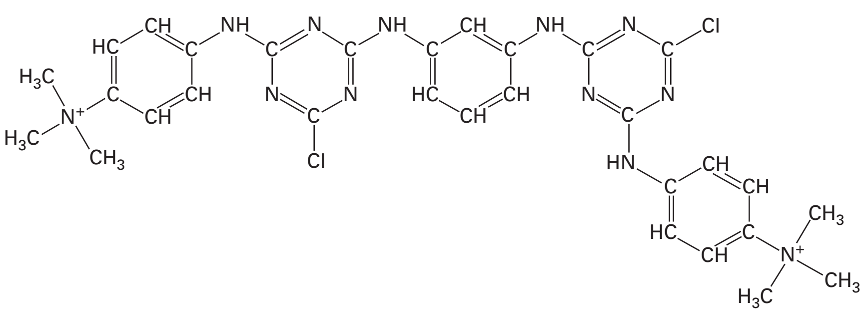
The main benefit claimed was increased colour yield, and presumably less colour in effluent, although normal levels of salt appear to have been used (Rupin, 1970). One research group studied the use of this compound in various cotton dyeing processes and found benefits, although they found unacceptable performance of some of the resulting dyed cotton, particularly in wet contact fastness tests (Herbert, 1983). Further problems with the use of such compounds have been identified (Evans, 1984), particularly the requirement to have a separate pad bake process to get the best cationisation result and avoid the problems of precipitation of a dye-cationic complex in the dyebath. Compounds (especially that shown in Fig. 11.22) that had structural similarities to cotton reactive dyes have been investigated while these compounds were more easily applied, and gave good fastnesses, there was a



11.20 N-2,3-epoxy propyl trimethylammonium chloride (Glytac).



11.21 Reaction of Glytac compound with cellulose under alkaline conditions.



11.22 Cationic cotton dye analogue.

tendency to produce unevenness, ring dyeing and differences in shade (Evans, 1984).

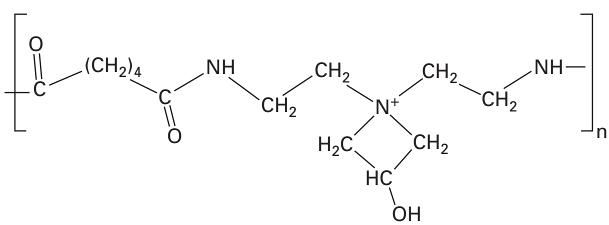
The alternative approach to the use of low molecular weight reactive compounds is to use high molecular weight polymers containing cationic groups. The polyamide-epichlorohydrin resin Hercosett (Fig. 11.23) was applied by a pad-bake process and led to very good exhaustion of reactive dyes under salt free conditions, although only the bifunctional (more reactive) dyes, such as Levafix E and Procion MX dyes gave high fixation as well (Burkinshaw, 1989).

There were several problems identified which prevent this method and other cationisation processes having practical application.

1. The lightfastness of dyes is significantly reduced by the treatment.
2. Cationising agents generally do not penetrate the individual yarns well and this will lead to colour changes on wearing and is probably a cause of the low light fastness.
3. The necessity for a pre-treatment in separate equipment is undesirable.
4. Cationising agents are difficult to apply in a level manner and do not penetrate denser fibre assemblies such as yarn packages well.

It appears that the ideal cationic pre-treatment which solves these problems has not been identified yet.

The dyestuff companies are continually active in the development of new dyes for cotton. In particular heterobifunctional reactive dyes in which there are two reactive groups of different chemical nature, are now part of many dyestuff ranges. Sumitomo were one of the pioneers in this field with the production of the Sumifix Supra dyes which have two different reactive groups; a monochlorotriazine and a sulfatoethylsulfone (Matsui, 1988). The presence of two reactive groups not only improves the overall fixation of reactive dyes, but broadens the application conditions, leading to greater reproducibility. The Cibacron C dye range is based on a similar concept and is particularly suited for high fixations at low temperature, as in the pad-batch process. It is likely that bi- and multi-functional dyes will become even more common in reactive dye ranges. Lewis has summarised recent



11.23 Repeat unit of Hercosett resin. The commercial form is partially cross-linked.

developments in the field of reactive dyes and gives an insight into the innovation still occurring (Lewis, 2004).

Ink-jet printing will undoubtedly continue to grow in volume, but it appears that further innovation is required to bridge the big gap in production speed required to displace rotary screen printing.

11.12 Sources of further information

There are a number of useful reference books which provide more extensive information than is possible in this chapter. In particular Shore's book (Shore, 1995) provides comprehensive information on the chemical aspects of cotton dyeing, the final chapter of which provides a unique discussion of the relationship between textile product attributes and dye selection. Trotman's book (Trotman 1984) provides further information on dyeing of textiles including the mechanical design of dyeing equipment.

There are two important professional organisations dealing with coloration. The Society of Dyers and Colorists based in Bradford, England (www.sdc.org.uk) publishes the journal *Coloration Technology* (formerly *Journal of the Society of Dyers and Colorists*) and the annual *Review of Progress in Coloration* which are key sources of information. SDC publications also have a range of specific textbooks concerning all aspects of the dyeing industry. The American Association of Textile Chemists and Colorists (www.aatcc.org) which is based in Raleigh, North Carolina publishes the informative monthly journal *AATCC Review* which was formed from the merger of two other magazines, the *Textile Chemist and Colorist* and *American Dyestuff Reporter*. Both the AATCC and SDC run conferences and training programs.

Key research groups in cotton dyeing include CSIRO Textile and Fibre Technology, Geelong Australia (www.tft.csiro.au), The Colour Chemistry Department at Leeds University England (www.colour.leeds.ac.uk) and the College of Textiles at North Carolina State University (www.tx.ncsu.edu). The major textile dye companies provide comprehensive support to customers for their dye ranges through their technical information 'pattern cards' and other material.

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